EXTENDED RANGE FORECAST OF ATLANTIC SEASONAL HURRICANE ACTIVITY AND LANDFALL STRIKE PROBABILITY FOR 2021

We anticipate that the 2021 Atlantic basin hurricane season will have above-normal activity. Current weak La Niña conditions may transition to neutral ENSO by this summer/fall, but the odds of a significant El Niño seem unlikely. Sea surface temperatures averaged across the tropical Atlantic are currently near average, while subtropical Atlantic sea surface temperatures are warmer than normal. We anticipate an above-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 8 April 2021)

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 2021

Forecast Parameter and 1981–2010 Average* (in parentheses)	Issue Date 8 April 2021
Named Storms (NS) (12.1)	17
Named Storm Days (NSD) (59.4)	80
Hurricanes (H) (6.4)	8
Hurricane Days (HD) (24.2)	35
Major Hurricanes (MH) (2.7)	4
Major Hurricane Days (MHD) (6.2)	9
Accumulated Cyclone Energy (ACE) (106)	150
Net Tropical Cyclone Activity (NTC) (116%)	160

* CSU will change its climatology from 1981–2010 to the new climatology that NOAA decides to use with its seasonal hurricane outlooks.

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 - 69% (average for last century is 52%)

2) U.S. East Coast Including Peninsula Florida - 45% (average for last century is 31%)

3) Gulf Coast from the Florida Panhandle westward to Brownsville - 44% (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) 58% (average for last century is 42%)

ABSTRACT

Information obtained through March 2021 indicates that the 2021 Atlantic hurricane season will have activity above the 1981–2010 average. We estimate that 2021 will have about 8 hurricanes (average is 6.4), 17 named storms (average is 12.1), 80 named storm days (average is 59.4), 35 hurricane days (average is 24.2), 4 major (Category 3-4-5) hurricanes (average is 2.7) and 9 major hurricane days (average is 6.2). The probability of U.S. major hurricane landfall is estimated to be about 130 percent of the long-period average. We expect Atlantic basin Accumulated Cyclone Energy (ACE) and Net Tropical Cyclone (NTC) activity in 2021 to be approximately 140 percent of the 1981–2010 average.

This forecast is based on an extended-range early April statistical prediction scheme that was developed using 38 years of past data. Analog predictors are also utilized. We also include a statistical/dynamical model based off of 40 years of data from the ECMWF SEAS5 model. Our statistical model, our statistical/dynamical model and our analog model all call for an active Atlantic hurricane season in 2021.

The tropical Pacific is currently characterized by weak La Niña conditions. At this point, there is a relatively good chance that the tropical Pacific will revert to neutral ENSO conditions during this summer, but it seems unlikely that El Niño conditions will occur during this year's hurricane season. El Niño typically reduces Atlantic hurricane activity through increases in vertical wind shear. The tropical Atlantic currently has near average sea surface temperatures, while most of the subtropical Atlantic is warmer than normal.

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. We also now present probabilities of exceedance for hurricanes and Accumulated Cyclone Energy to give interested readers a better idea of the uncertainty associated with these forecasts.

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 ~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 also now include probabilities of exceedance to provide a visualization of the uncertainty associated with these predictions.

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. We acknowledge a grant from the G. Unger Vetlesen Foundation for additional financial support.

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 would like to acknowledge assistance from Louis-Philippe Caron and the data team at the Barcelona Supercomputing Centre for providing data and insight on the statistical/dynamical models. We would like to thank Ethan Gibney for assistance developing the new landfall probability methodology outlined later in this manuscript. 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 1981–2010 average value of this parameter is 106 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 hPa (approximately 40000 feet or 12 km) and 850 hPa (approximately 5000 feet or 1.6 km).

1 knot = 1.15 miles per hour = 0.515 meters per second

1 Introduction

This is the 38th 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 model as well as output from the SEAS5 statistical/dynamical model from the European Centre for Medium Range Weather Forecasts (ECMWF). These models show skill at predicting TC activity based on ~40 years of historical data. We also select analog seasons, based on currently-observed conditions as well as conditions that we anticipate for the peak of the Atlantic hurricane season. Qualitative adjustments are added to accommodate additional processes which may not be explicitly represented by 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

We are currently using an April statistical forecast scheme that was developed on data from 1982–2019 and yielded a successful forecast in real-time in 2020. The model uses the ECMWF Reanalysis 5 (ERA5) (Hersbach et al. 2020) as well as NOAA Optimum Interpolation (IO) sea surface temperature (SST) (Reynolds et al. 2002). The ERA5 reanalysis currently extends from 1979 to near-present with a preliminary version now extending back to 1950. A benefit of the ERA5 reanalysis is that it is the first reanalysis from ECMWF that provides updates in near real-time, allowing for the same reanalysis product to be used for both hindcast model development as well as real-time analysis. The NOAA Optimum Interpolation (OI) SST (Reynolds et al. 2002) is available from 1982–present. This new model showed significant skill in cross-validated (e.g., leaving the year out of the developmental model that is being predicted) hindcasts of Accumulated Cyclone Energy (ACE) (r = 0.66) over the period from 1982–2020.

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 1982–2020 hindcast/forecast period. All predictors correlate significantly at the 5% level using a two-tailed Student's t-test and assuming that each year represents an individual degree of freedom. Table 2 displays the 2021 observed values for each of the three predictors in the statistical forecast scheme. Table 3 displays the statistical model output for the 2021 hurricane season. The two SST predictors call for increased Atlantic hurricane activity, while the 200 hPa zonal wind predictor calls for a below-average season.

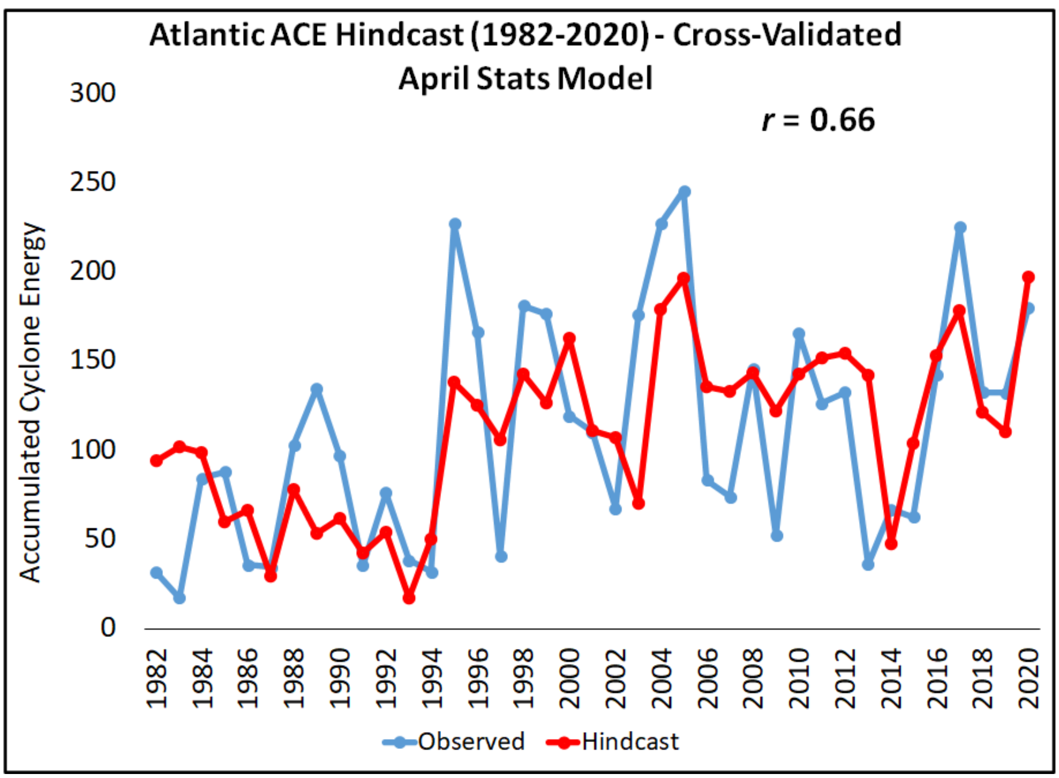

Figure 1: Observed versus early April cross-validated hindcast values of ACE for the statistical model for 1982–2020.

April Forecast Predictors

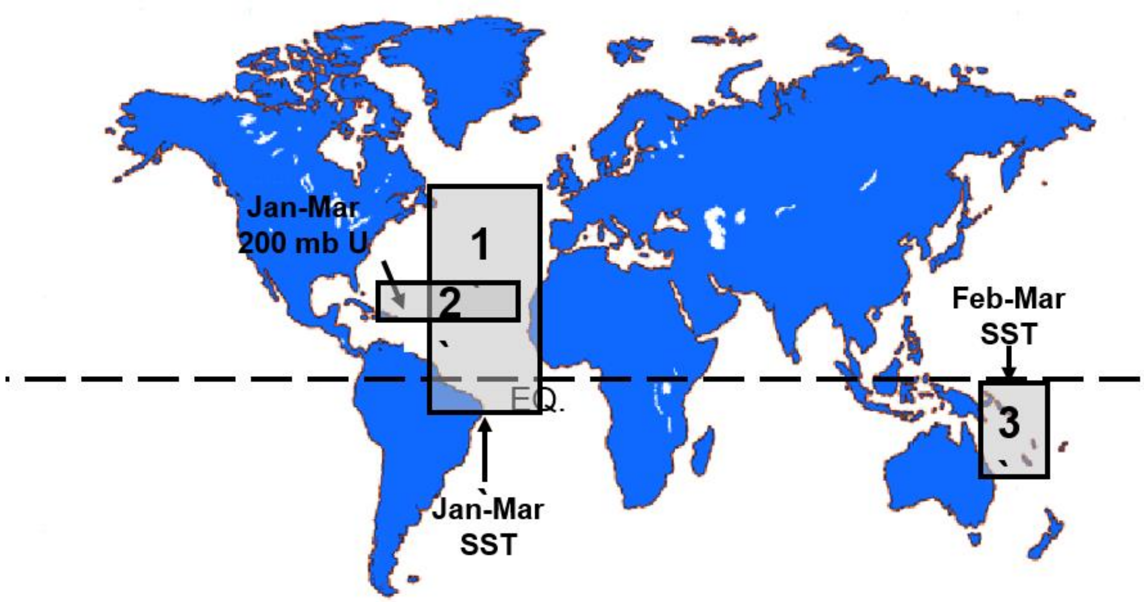

Figure 2: Location of predictors for our early April extended-range statistical prediction for the 2021 hurricane season.

Table 1: Linear correlation between early April predictors and ACE over the period from 1982–2020.

Predictor	Correlation w/ ACE
1) January–March SST (5°S–50°N, 40°W–10°W) (+)	0.56
2) January–March 200 hPa U (17.5°N–27.5°N, 60°W–20°W) (+)	0.45
3) February-March SST (20°S–0°, 145°E–170°E) (+)	0.52

Table 2: Listing of early April 2021 predictors for the 2021 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	2021 Forecast Value	Impact on 2021 TC Activity
1) January–March SST (5°S–50°N, 40°W–10°W) (+)	+1.3 SD	Enhance
2) January–March 200 hPa U (17.5°N–27.5°N, 60°W–20°W) (+)	-0.7 SD	Suppress
3) February-March SST (20°S–0°, 145°E–170°E) (+)	+1.6 SD	Enhance

Table 3: Statistical model output for the 2021 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)	15.5	17
Named Storm Days (NSD) (59.4)	77.1	80
Hurricanes (H) (6.4)	8.0	8
Hurricane Days (HD) (24.2)	31.1	35
Major Hurricanes (MH) (2.7)	3.7	4
Major Hurricane Days (MHD) (6.2)	8.9	9
Accumulated Cyclone Energy (ACE) (106)	141	150
Net Tropical Cyclone Activity (NTC) (116%)	153	160

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.

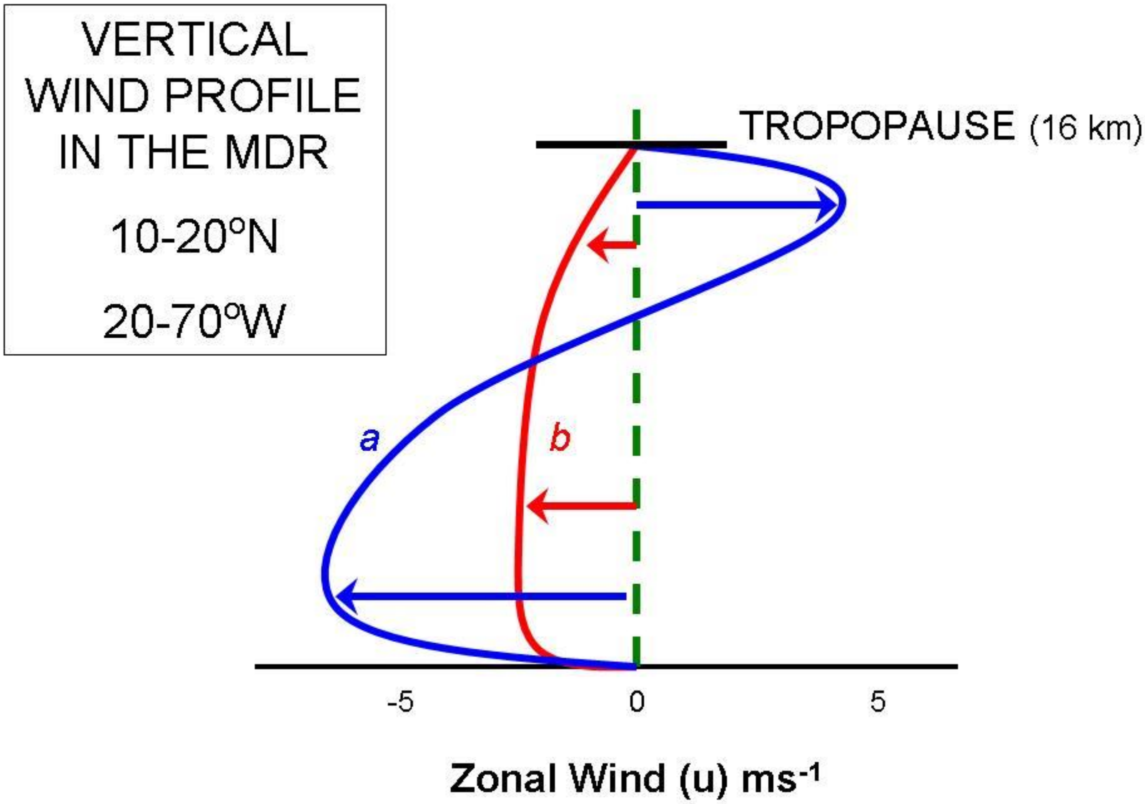

Figure 3: Vertical wind profile typically associated with (a) inactive Atlantic basin hurricane seasons and (b) active Atlantic basin hurricane seasons. Note that (b) has reduced levels of vertical wind shear.

For each of these predictors, we display a four-panel figure showing linear correlations between values of each predictor and August–October values of SST, sea level pressure (SLP), 200 hPa zonal wind, and 850 hPa zonal wind, respectively, during 1982–2019. In general, higher values of SSTs, lower values of SLP, anomalous westerlies at 850 hPa and anomalous easterlies at 200 hPa are associated with active Atlantic basin hurricane seasons. SST correlations are displayed using the NOAA Optimum Interpolation (OI) SST, while atmospheric field correlations are displayed using ERA5.

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

(5°S–50°N, 40°W–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 (r =0.54) with ACE from 1982–2020. Predictor 1 also strongly correlates (r = 0.61) with August–October values of the Atlantic Meridional Mode (AMM) (Kossin and Vimont 2007) over the period from 1982–2020. 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. January–March 200 hPa U in the Subtropical North Atlantic (+)

(17.5°N–27.5°N, 60°W–20°W)

Anomalously strong winds at upper-levels in the subtropical North Atlantic are associated with anomalously low pressure in the tropical and subtropical Atlantic during January–March. Stronger-than-normal westerly winds at upper levels in the subtropics are also associated with reduced anticyclonic wavebreaking (and associated reduced vertical wind shear) during the peak of the Atlantic hurricane season (Jones et al. 2021, manuscript submitted to *Journal of Climate*). As has been shown in prior work (Knaff 1997), when the Azores High is weaker than normal, Atlantic trade winds are also weaker than normal. These weaker trades inhibit ocean mixing and upwelling, thereby causing anomalous warming of tropical Atlantic SSTs. These warmer SSTs are then associated with lower-than-normal sea level pressures which can create a self-enhancing feedback that relates to lower pressure, weaker trades and warmer SSTs during the hurricane season (Figure 5) (Knaff 1998). All three of these factors are associated with active hurricane seasons. This predictor is also negatively correlated with tropical central Pacific SSTs during August–October, indicating that La Niña-like conditions are favored during the boreal summer when anomalously strong upper-level winds predominate over the Atlantic during January–March.

Predictor 3. February–March SST in the Coral Sea (+)

(20°S–0°, 145°E–170°E)

Anomalous warmth in the Coral Sea is associated with lower pressure in the western tropical Pacific and higher pressure in the eastern tropical Pacific, thereby driving stronger trade winds across the tropical Pacific that inhibit El Niño development. The development of anomalously high pressure in the eastern tropical Pacific then drives anomalously weak trade winds in the tropical Atlantic, feeding back into both reduced shear and anomalously warm SSTs in the tropical Atlantic by the peak of the Atlantic hurricane season (August–October) (Figure 6).

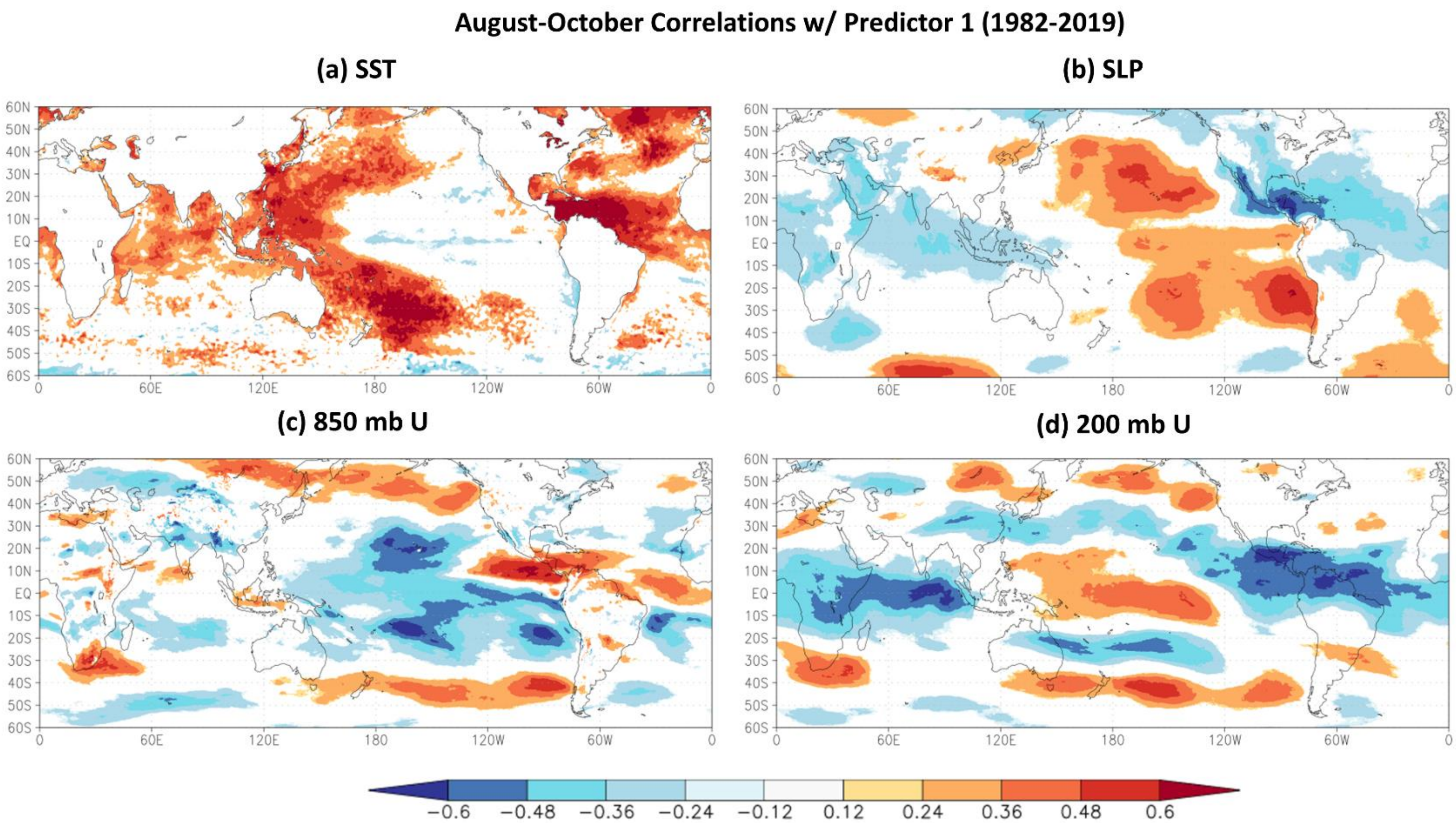

Figure 4: Rank correlations between January–March SST in the tropical and subtropical Atlantic (Predictor 1) and (panel a) August–October sea surface temperature, (panel b) August–October sea level pressure, (panel c) August–October 850 hPa zonal wind and (panel d) August–October 200 hPa zonal wind.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

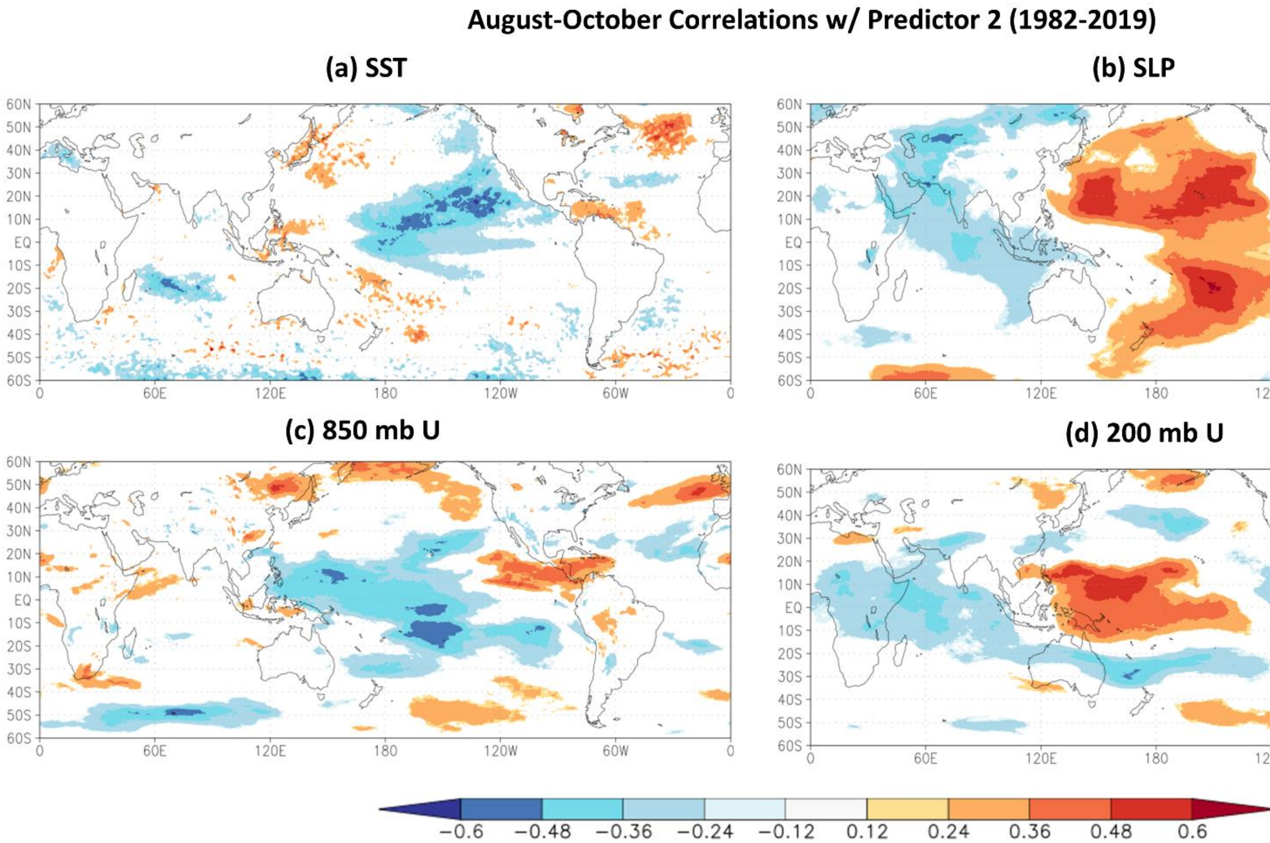

Figure 5: As in Figure 4 but for January–March 200 hPa zonal wind in the subtropical North Atlantic.

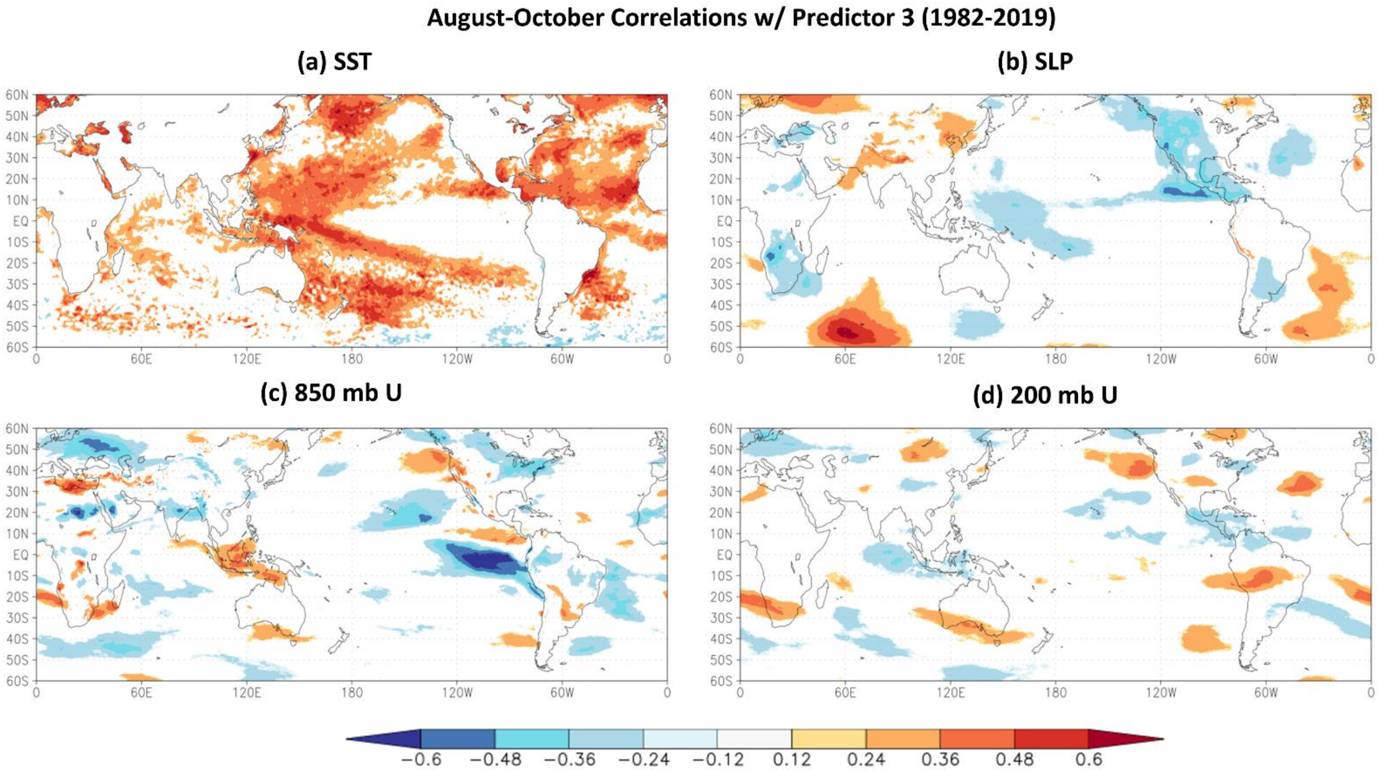

Figure 6: As in Figure 4 but for February-March SST in the Coral Sea.

2.2 April Statistical/Dynamical Forecast Scheme

We developed a statistical/dynamical hybrid forecast model scheme that we used for the first time in 2019. This model, developed in partnership with Louis-Philippe Caron and the data team at the Barcelona Supercomputing Centre, uses output from the ECMWF SEAS5 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 SEAS5 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 2021 season. All other predictands (e.g., named storms, major hurricanes) are calculated based on their historical relationships with ACE. It typically takes about two weeks after the initialization date to obtain SEAS5 output, so the results displayed here are from the model output from the 1 March forecast. We recently published a paper discussing this scheme in detail (Klotzbach et al. 2020, https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2020GL089357).

Figure 7 displays the parameters used in our early August statistical model, while Table 4 displays SEAS5's forecasts of these parameters for 2021 from a 1 March initialization date. Two of the three parameters call for well above-normal activity, while the trade wind predictor in the Caribbean/tropical Atlantic indicates near-normal activity. However, the trade wind predictor has much less weight at the 1 March initialization time than the other two predictors, and consequently, the SEAS5 statistical/dynamical model is calling for a very active season. Figure 8 displays cross-validated hindcasts for SEAS5 forecast of ACE from 1981–2020, while Table 5 presents the forecast from SEAS5 for the 2021 Atlantic hurricane season.

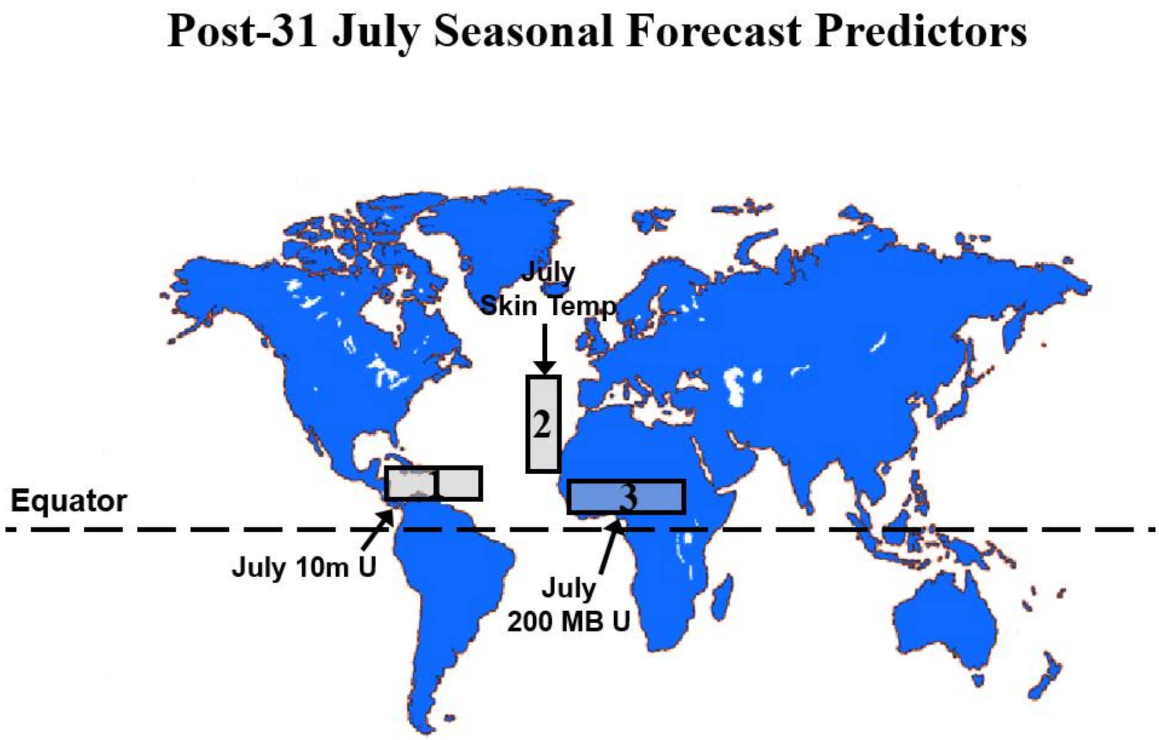

Figure 7: Location of predictors for our early April statistical/dynamical extended-range statistical prediction for the 2021 hurricane season. This forecast uses the ECMWF SEAS5 model to predict July conditions in the three boxes displayed and uses those predictors to forecast ACE.

Table 4: Listing of predictions of July large-scale conditions from ECMWF SEAS5 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 2021 Forecast	Effect on 2021 Hurricane Season
1) ECMWF Prediction of July Surface U (10–20°N, 90–40°W) (+)	+0.1 SD	Neutral
2) ECMWF Prediction of July Skin Temperature (20–40°N, 35–15°W) (+)	+1.7 SD	Enhance
3) ECMWF Prediction of July 200 hPa U (5–15°N, 0–40°E) (-)	-0.7 SD	Enhance

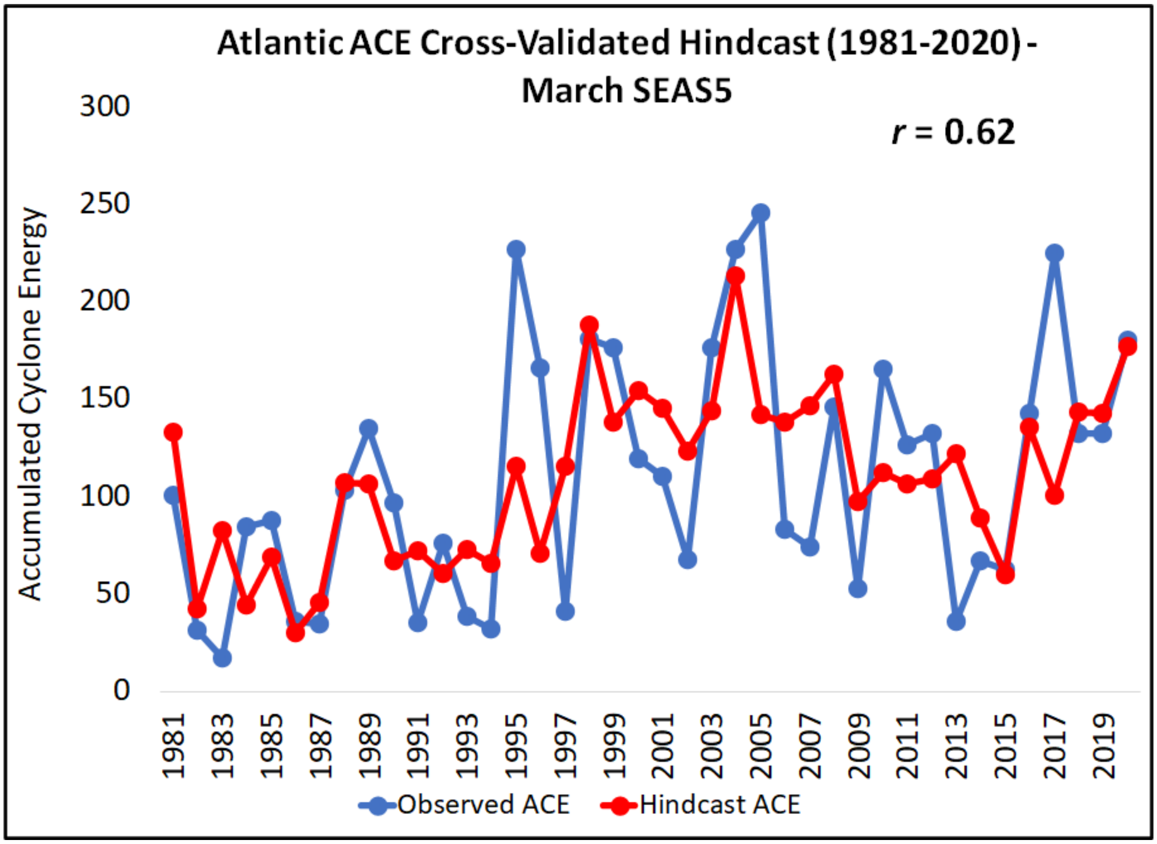

Figure 8: Observed versus cross-validated statistical/dynamical hindcast values of ACE for 1981–2020 from SEAS5.

Table 5: Statistical/dynamical model output from SEAS5 for the 2021 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)	16.9	17
Named Storm Days (59.4)	92.0	80
Hurricanes (6.4)	9.6	8
Hurricane Days (24.2)	41.0	35
Major Hurricanes (2.7)	4.6	4
Major Hurricane Days (6.2)	12.2	9
Accumulated Cyclone Energy Index (106)	180	150
Net Tropical Cyclone Activity (116%)	189	160

By combining the statistical model forecast and the statistical/dynamical model forecast from SEAS5, we can increase the hindcast skill from either model individually.

As noted earlier, the statistical model has a cross-validated hindcast with ACE of r = 0.65, while the statistical/dynamical model has a cross-validated hindcast with ACE of r = 0.62. By simply averaging the forecasts from the two models together, we can improve the cross-validated hindcast variance explained to r = 0.70 – or ~50% of the variance in ACE (Figure 9).

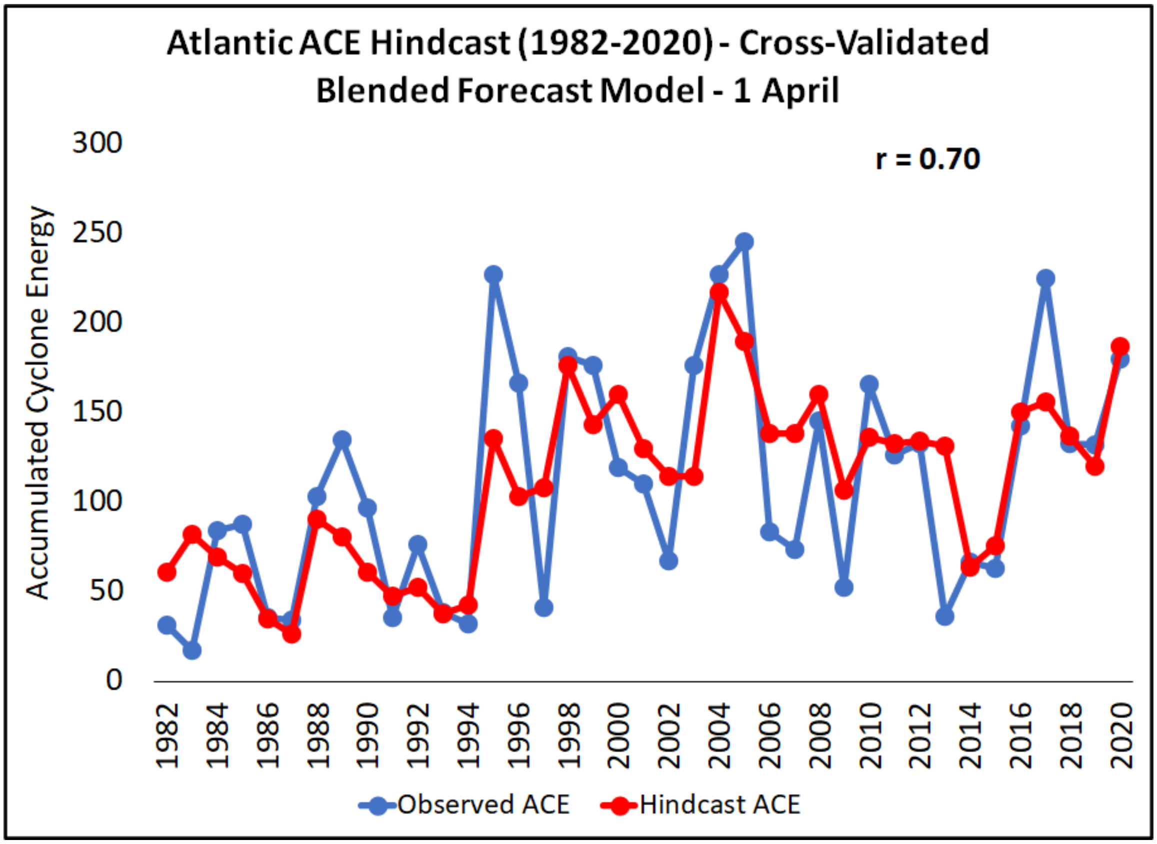

Figure 9: Observed versus early April blended (e.g., statistical and statistical/dynamical) model cross-validated hindcast values of ACE for 1982–2020.

2.3 April Analog Forecast Scheme

Certain years in the historical record have global oceanic and atmospheric trends which are similar to 2021. These years also provide useful clues as to likely levels of activity that the forthcoming 2021 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 2021 conditions and, more importantly, projected August–October 2021 conditions. Table 6 lists our analog selections.

We searched for years that were generally characterized by La Niña conditions the previous winter and had neutral ENSO or weak La Niña conditions during the peak of the Atlantic hurricane season (August–October). We also selected years that had near- to above-average SSTs in the tropical Atlantic. We anticipate that the 2021 hurricane season will have activity near the average of our five analog years.

Table 6: Analog years for 2021 with the associated hurricane activity listed for each year.

Year	NS	NSD	H	HD	MH	MHD	ACE	NTC
1996	13	79.00	9	45.00	6	13.00	166	192
2001	15	68.75	9	25.50	4	4.25	110	135
2008	16	88.25	8	30.50	5	7.50	146	162
2011	19	89.75	7	26.00	4	4.50	126	145
2017	17	93.00	10	51.75	6	19.25	225	232
Average	16.0	83.8	8.6	35.8	5.0	9.7	155	173
2021 Forecast	**17**	**80**	**8**	**35**	**4**	**9**	**150**	**160**

2.4 April Forecast Summary and Final Adjusted Forecast

Table 7 shows our final adjusted early April forecast for the 2021 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 of our schemes call for above-average Atlantic hurricane activity this year. Our forecast is near the average of the three schemes and calls for an above-normal season, due to both anticipated neutral ENSO or weak La Niña conditions as well as anomalously warm SSTs in the tropical Atlantic 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 2021 hurricane season.

Forecast Parameter and 1981–2010 Average (in parentheses)	Statistical Scheme	SEAS5 Scheme	Analog Scheme	3-Scheme Average	Adjusted Final Forecast
Named Storms (12.1)	15.5	16.9	16.0	16.1	17
Named Storm Days (59.4)	77.1	92.0	83.8	84.3	80
Hurricanes (6.4)	8.0	9.6	8.6	8.7	8
Hurricane Days (24.2)	31.1	41.0	35.8	36.0	35
Major Hurricanes (2.7)	3.7	4.6	5.0	4.4	4
Major Hurricane Days (6.2)	8.9	12.2	9.7	10.3	9
Accumulated Cyclone Energy Index (106)	141	180	155	159	150
Net Tropical Cyclone Activity (116%)	153	189	173	172	160

3 Forecast Uncertainty

One of the questions that we are asked regarding our seasonal hurricane predictions is the degree of uncertainty that is involved. This season we continue to use probability of exceedance curves as discussed in Saunders et al. (2020). In that paper, we outlined an approach that uses statistical modeling and historical skill of various forecast models to arrive at a probability that particular values for hurricane numbers and ACE would be exceeded. Here we display probability of exceedance curves for hurricanes and ACE (Figures 10 and 11), using the error distributions calculated from both normalized cross-validated statistical as well as the cross-validated statistical/dynamical hindcasts from SEAS5. Hurricane numbers are fit to a Poisson distribution, while ACE is fit to a Weibull distribution. Table 8 displays one standard deviation uncertainty ranges (~68% of all forecasts within this range). This uncertainty estimate is also very similar to the 70% uncertainty range that NOAA provides with its forecasts. We use Poisson distributions for all storm parameters (e.g., named storms, hurricanes and major hurricanes) while we use a Weibull distribution for all integrated parameters except for major hurricane days (e.g., named storm days, ACE, etc.). We use a Laplace distribution for major hurricane days.

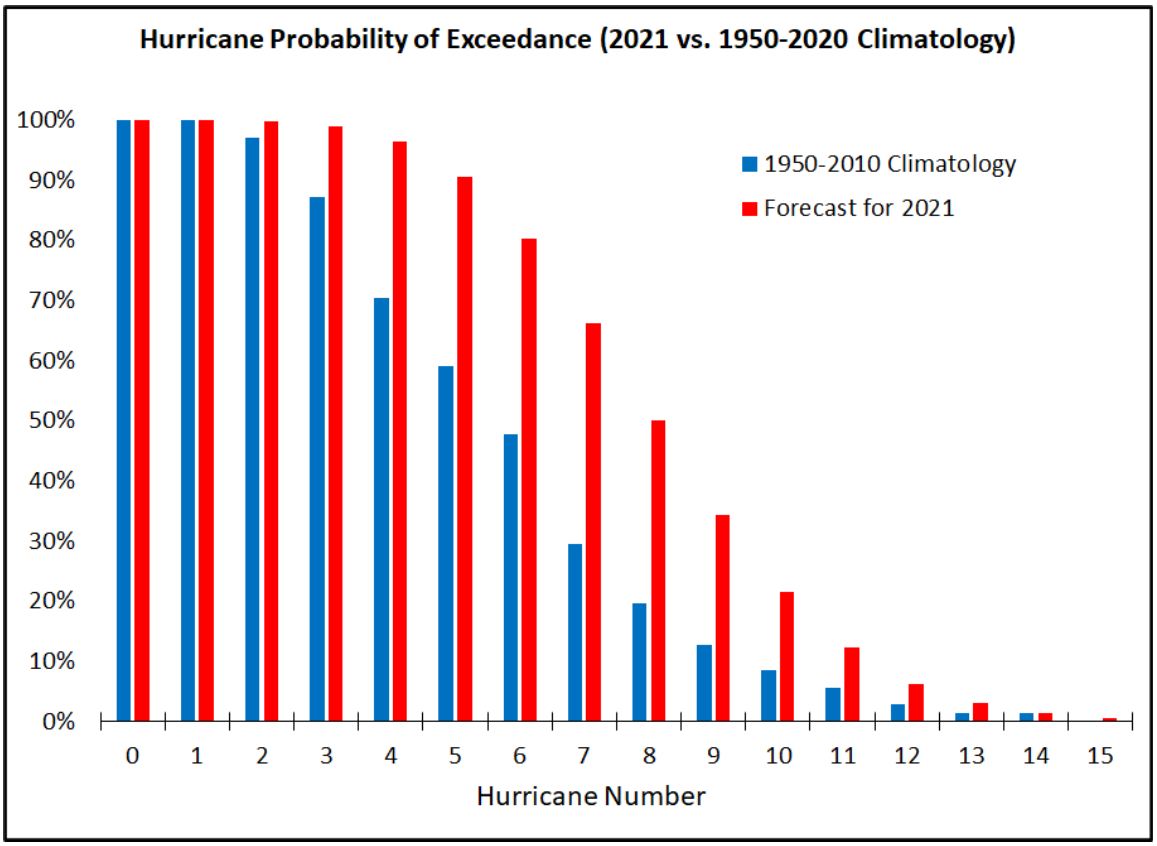

Figure 10: Probability of exceedance plot for hurricane numbers for the 2021 Atlantic hurricane season. The values on the x-axis indicate that the number of hurricanes exceeds that specific number. For example, 97% of Atlantic hurricane seasons from 1950-2020 have had more than two hurricanes.

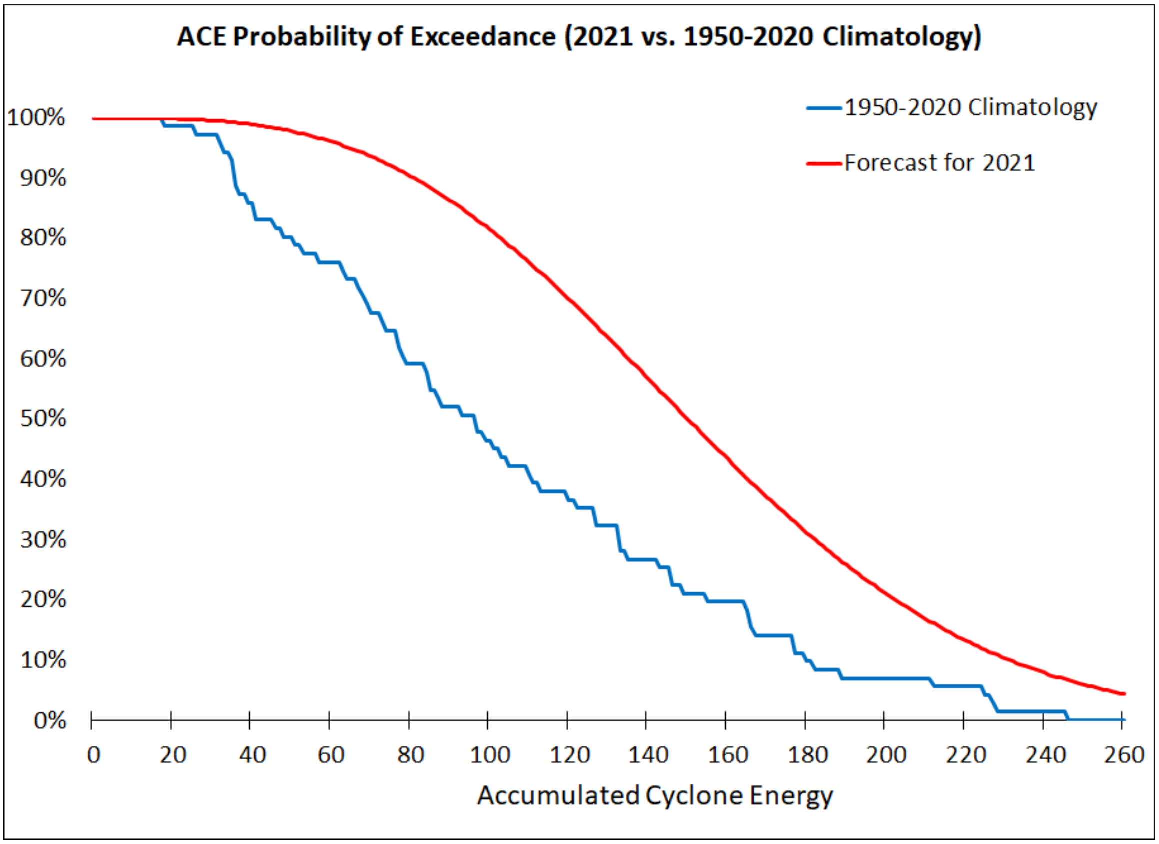

Figure 11: As in Figure 10 but for ACE.

Table 8: Forecast ranges for each parameter. Note that the forecast spread may not be symmetric around the mean value, given the historical distribution of tropical cyclone activity.

Parameter	2021 Forecast	Uncertainty Range (68% of Forecasts Likely to Fall in This Range)
Named Storms (NS)	17	14 – 20
Named Storm Days (NSD)	80	57 – 104
Hurricanes (H)	8	6 – 10
Hurricane Days (HD)	35	22 – 50
Major Hurricanes (MH)	4	2 – 6
Major Hurricane Days (MHD)	9	6 – 14
Accumulated Cyclone Energy (ACE)	150	97 – 200
Net Tropical Cyclone (NTC) Activity	160	108 – 217

4 ENSO

Over the past several months, the tropical Pacific has been characterized by a weak to moderate La Niña event (Figure 12). ENSO events are partially classified by NOAA based on SST anomalies in the Nino 3.4 region, which is defined as 5°S–5°N, 170–120°W. Weak La Niña events are typically defined to be those where SST anomalies are between -0.5°C – -1.0°C and moderate La Niña events are defined to be those were SST anomalies are between -1.0°C – -1.5°C. Over the past several weeks, SST anomalies have begun to increase across most of the tropical Pacific, indicating a potential transition towards neutral ENSO conditions.

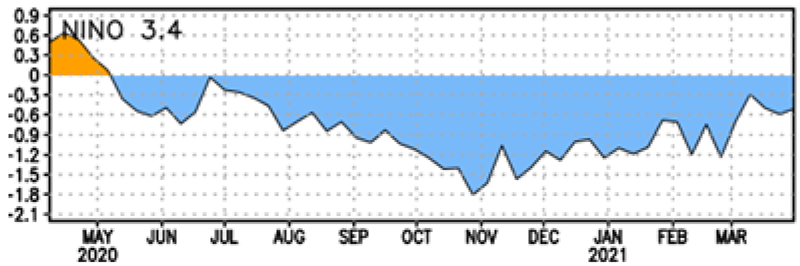

Figure 12: Nino 3.4 SST anomalies from April 2020 through March 2021.   Figure courtesy of Climate Prediction Center.

Upper-ocean heat content anomalies in the eastern and central tropical Pacific bottomed out in late October and have generally increased since that time (Figure 13). These anomalies have recently become positive, also indicating a potential transition away from La Niña conditions.

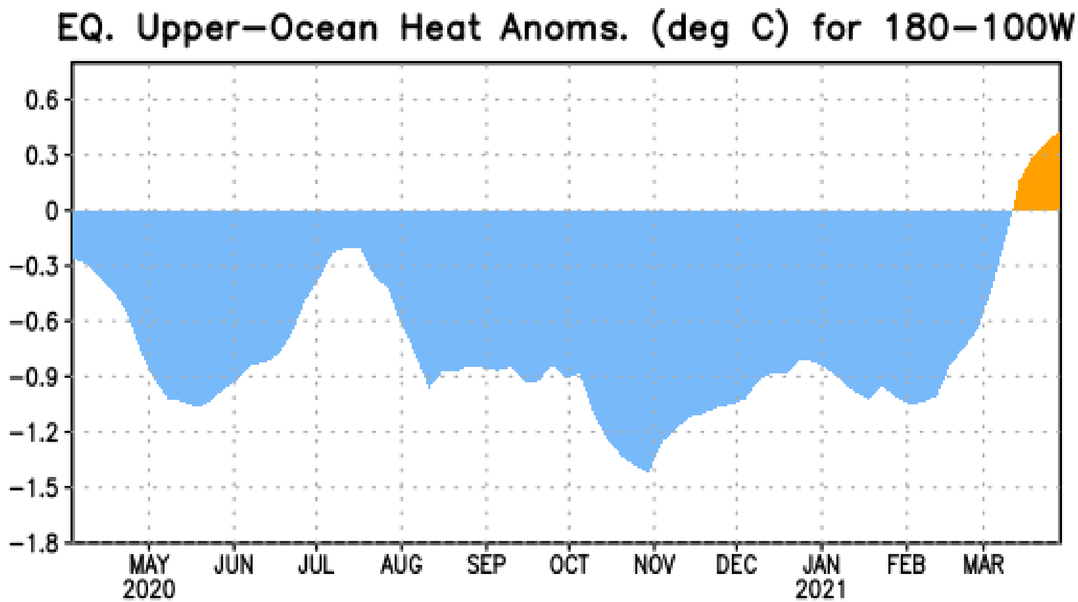

Figure 13: Central and eastern equatorial Pacific upper ocean (0-300 meters) heat content anomalies over the past year. Upper ocean heat content anomalies have generally increased since late October 2020.

SSTs are currently below normal across most of the eastern and central equatorial Pacific (Figure 14). The western North Pacific is warmer than normal, while the current spatial pattern of SSTs in the North Pacific (e.g., warm anomalies off of Japan and cold anomalies off of California) are indicative of a negative phase of the Pacific Decadal Oscillation.

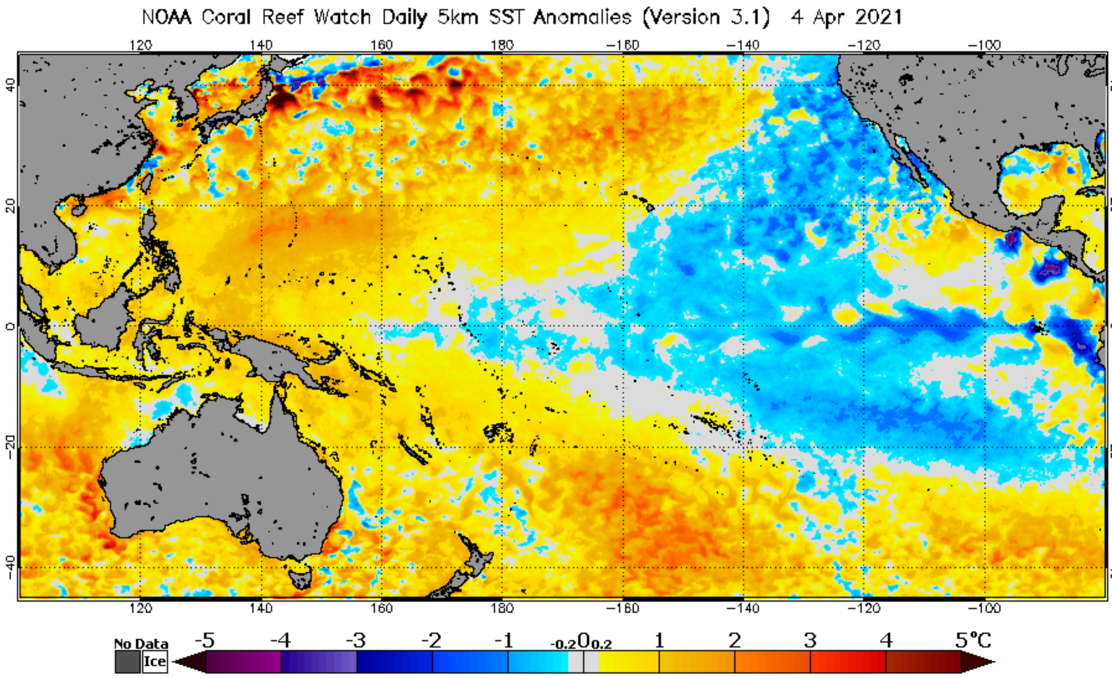

Figure 14: Current SST anomalies across the tropical and subtropical Pacific.

Table 9 displays January and March SST anomalies for several Nino regions. As would be expected given the weakening La Niña, anomalies have increased over the past couple of months in the eastern and central tropical Pacific.

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	-0.6	-0.3	+0.3
Nino 3	-0.6	-0.4	+0.2
Nino 3.4	-1.0	-0.5	+0.5
Nino 4	-1.3	-0.6	+0.7

The tropical Pacific is currently experiencing a downwelling (warming) Kelvin waves (denoted by the long dashed line) (Figure 15). These downwelling Kelvin waves are typically triggered by anomalous low-level westerly winds in the tropical Pacific. While it does not happen on every occasion, often downwelling (warming) Kelvin waves are followed by upwelling (cooling) Kelvin waves, as indicated by the short, dashed lines in Figure 15.

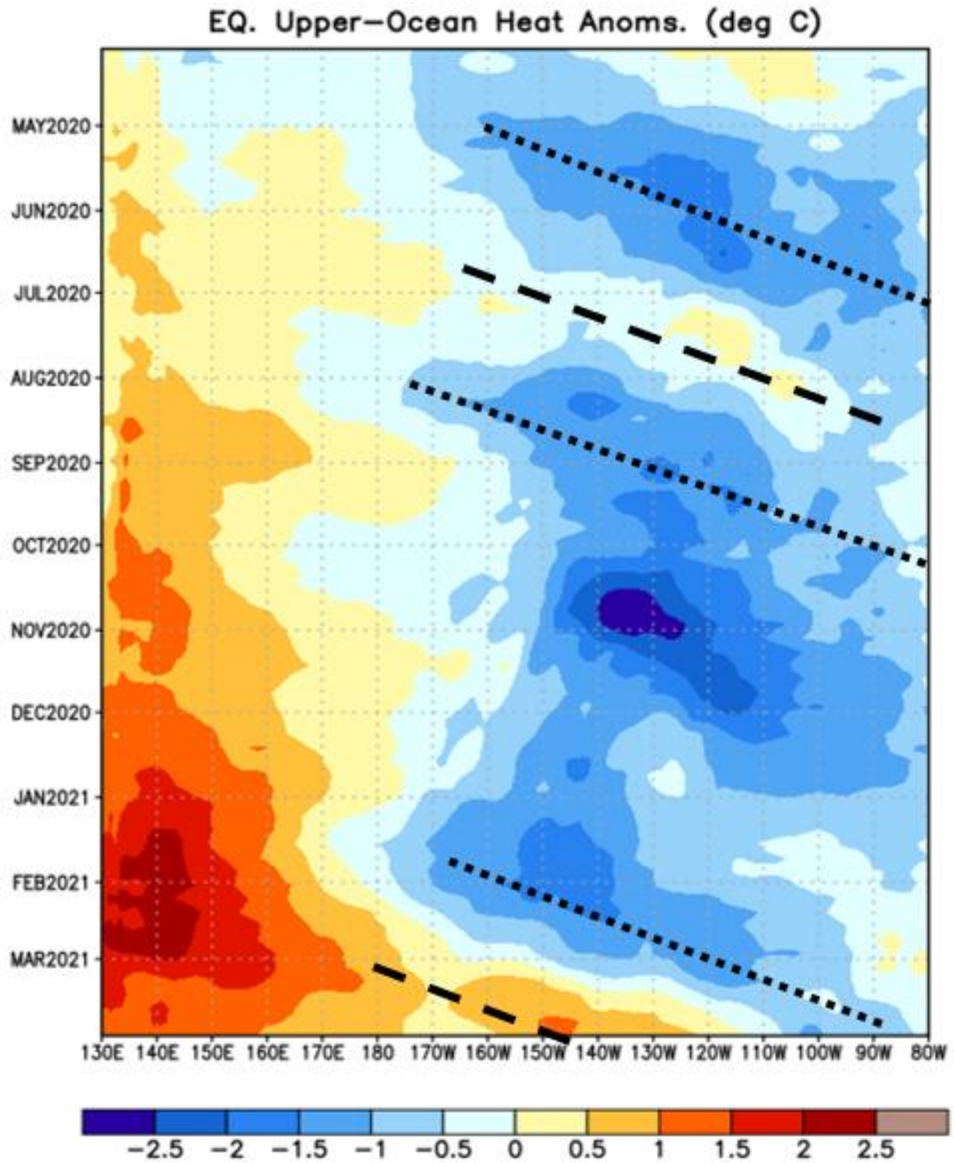

Figure 15: Upper-ocean heat content anomalies in the tropical Pacific since April 2020. Dashed lines indicate downwelling Kelvin waves, while dotted lines indicate upwelling Kelvin waves. Downwelling Kelvin waves result in upper-ocean heat content increases, while upwelling Kelvin waves result in upper-ocean heat content decreases.

Over the next several months, we will be closely monitoring low-level winds over the tropical Pacific. Anomalous easterlies are currently observed across the central tropical Pacific, and the ECMWF is forecasting anomalous easterlies near the International Date Line for the next several days, followed by anomalous westerlies associated with a Madden-Julian oscillation event (Figure 16). If these anomalous westerlies occur as forecast, that could potentially lead to some additional anomalous warming of the tropical Pacific, but we believe that the odds of a significant El Niño event for the 2021 Atlantic hurricane season are quite small.

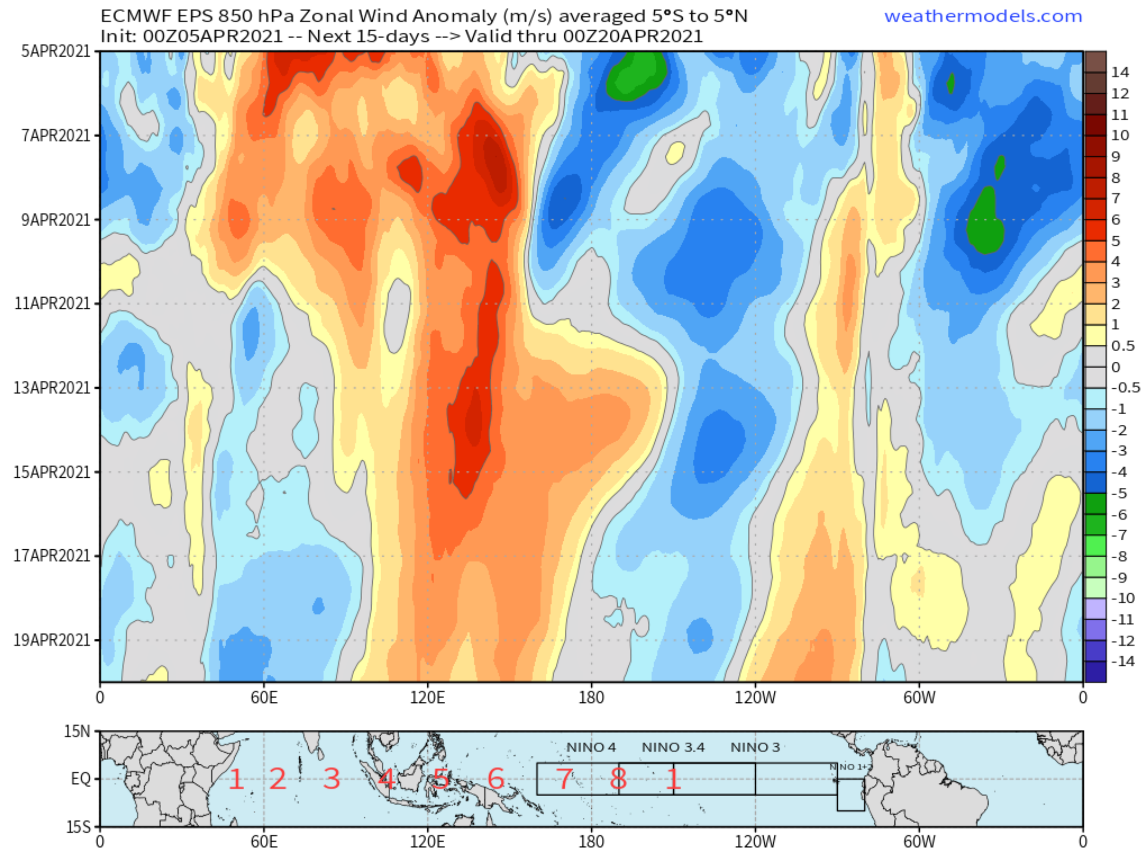

Figure 16: Forecast 850-hPa zonal equatorial winds for the next 15 days. Figure courtesy of weathermodels.com.

There is always considerable uncertainty with the future state of El Niño during the Northern Hemisphere 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 17). While there is a large spread, most models call for either La Niña or neutral ENSO conditions for the next several months.

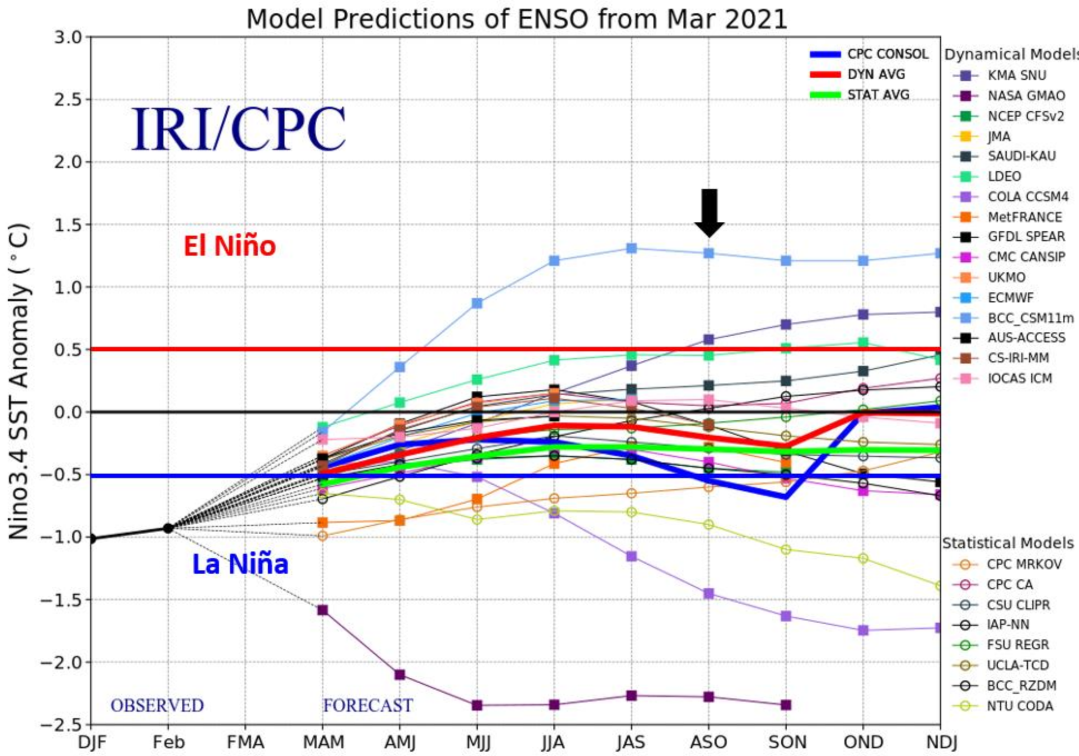

Figure 17: ENSO forecasts from various statistical and dynamical models for Nino 3.4 SST anomalies based on late February to early March initial conditions. Most models are calling for either La Niña or ENSO neutral conditions for August–October. Figure courtesy of the International Research Institute (IRI).

The latest official forecast from NOAA also indicates that the chances of El Niño are quite low for August–October. NOAA is currently predicting a 10% chance of El Niño, a 46% chance of ENSO neutral conditions and a 44% chance of La Niña for the peak of the Atlantic hurricane season (Figure 18).

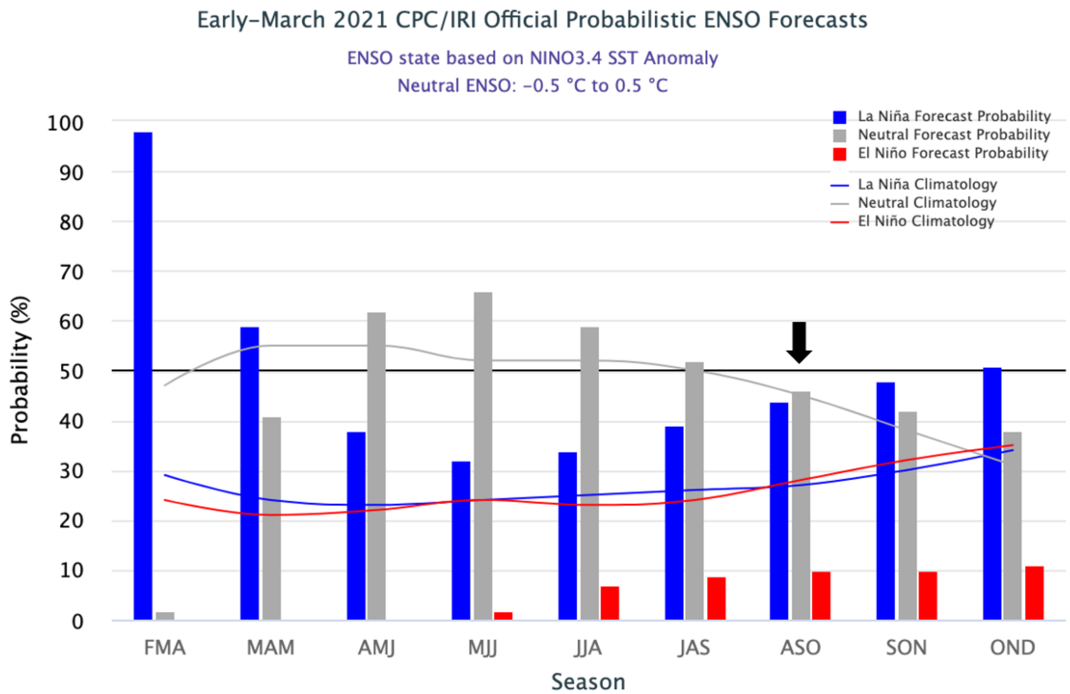

Figure 18: Official NOAA forecast for ENSO.

Based on the above information, our best estimate is that we will likely not have El Niño conditions for the peak of the Atlantic hurricane season. Even if El Niño does not develop, there remains considerable uncertainty as to whether the tropical Pacific will have neutral ENSO conditions or continue to have La Niña conditions. We will have much more to say with our next forecast release on 3 June.

5 Current Atlantic Basin Conditions

Currently, SSTs are near normal in the tropical Atlantic, while they are well above normal in the subtropical North Atlantic (Figure 19). The Atlantic had a similar SST pattern across the tropical Atlantic in late December 2020 (Figure 20), although SST anomalies were slightly higher during late December 2020. Unlike the past few years, the Atlantic has not experienced a strongly positive North Atlantic Oscillation (NAO) this past winter (Figure 21). A positive NAO tends to force 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. The NAO was generally negative during the first part of the winter and positive during the second part of the winter, which has led to some anomalous cooling of the tropical Atlantic in recent weeks. However, the NAO has since trended back towards more neutral conditions. Overall, the current SST anomaly pattern correlates relatively well with what is typically seen in active Atlantic hurricane seasons, with anomalous warmth in the subtropical eastern Atlantic (Figure 22). We will be closely monitoring trends in Atlantic SST conditions over the next several months.

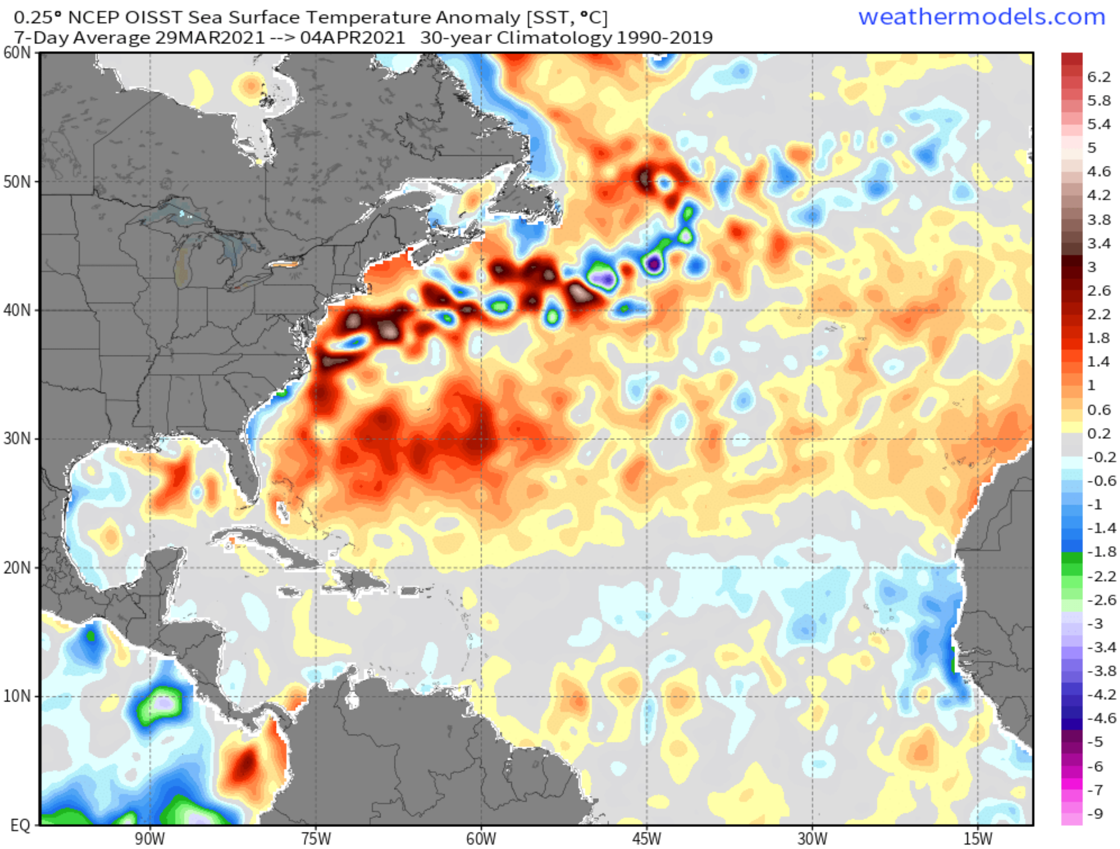

Figure 19: Late March 2021 SST anomaly pattern across the Atlantic Ocean.

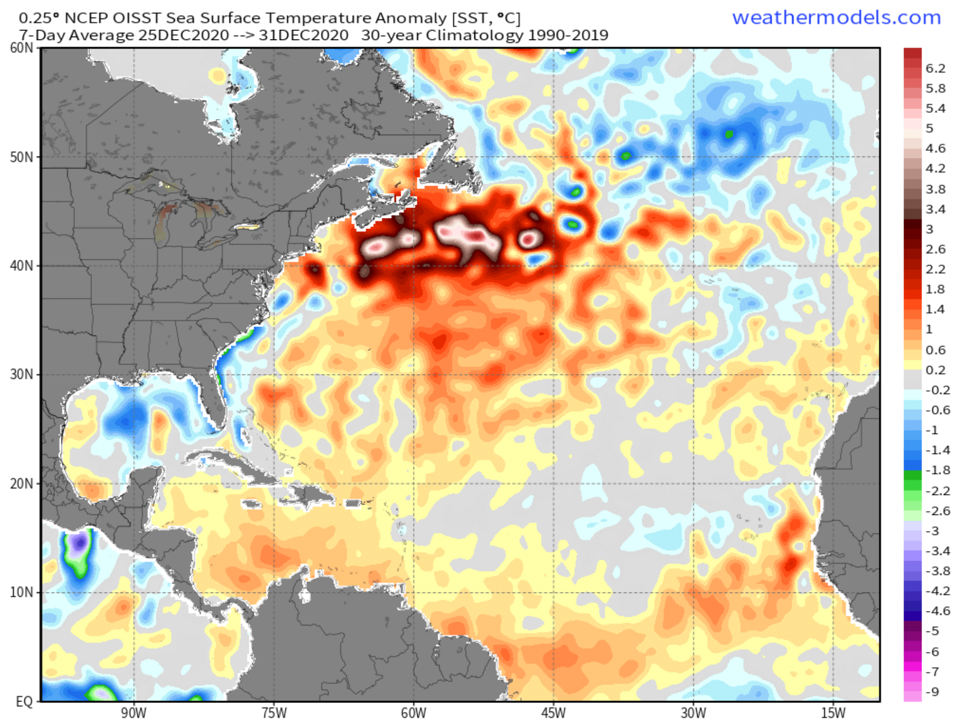

Figure 20: Late December 2020 North Atlantic SST anomalies.

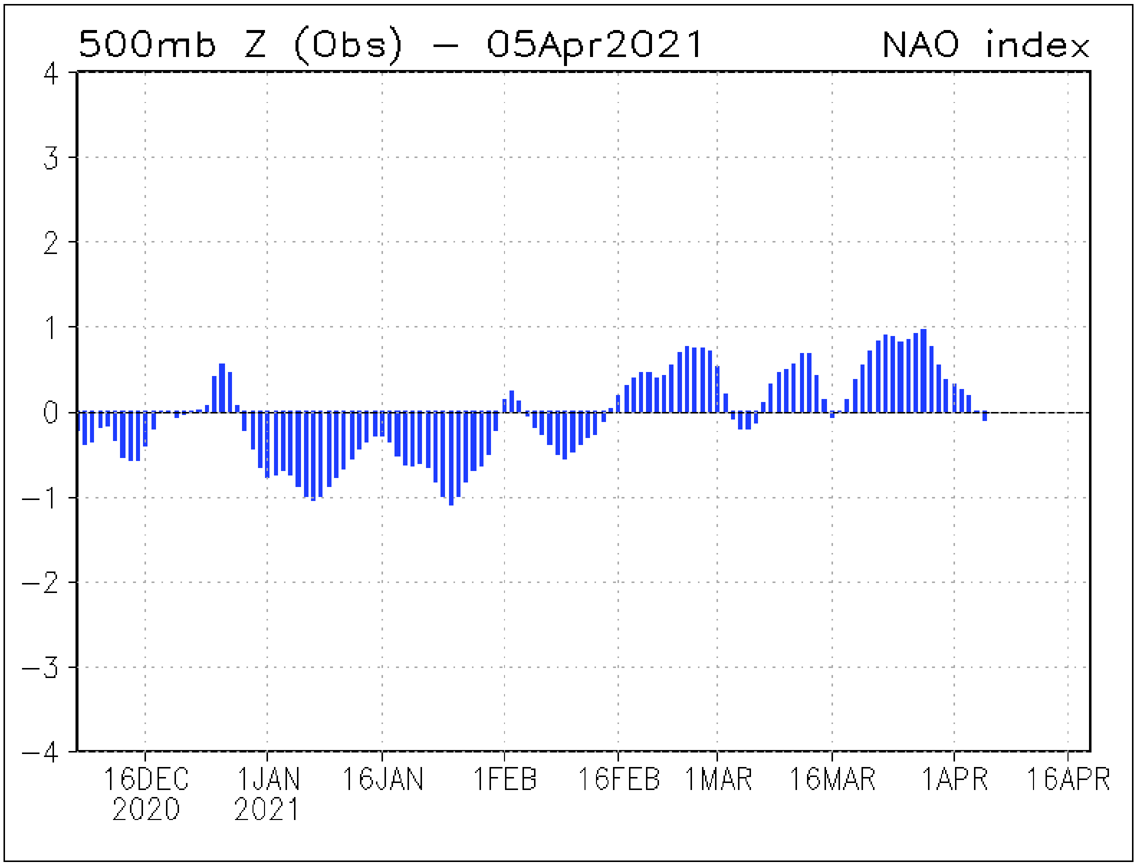

Figure 21: Observed standardized values of the daily NAO since mid-December 2020. The NAO was generally negative in January through mid-February and positive from mid-February through the end of March.

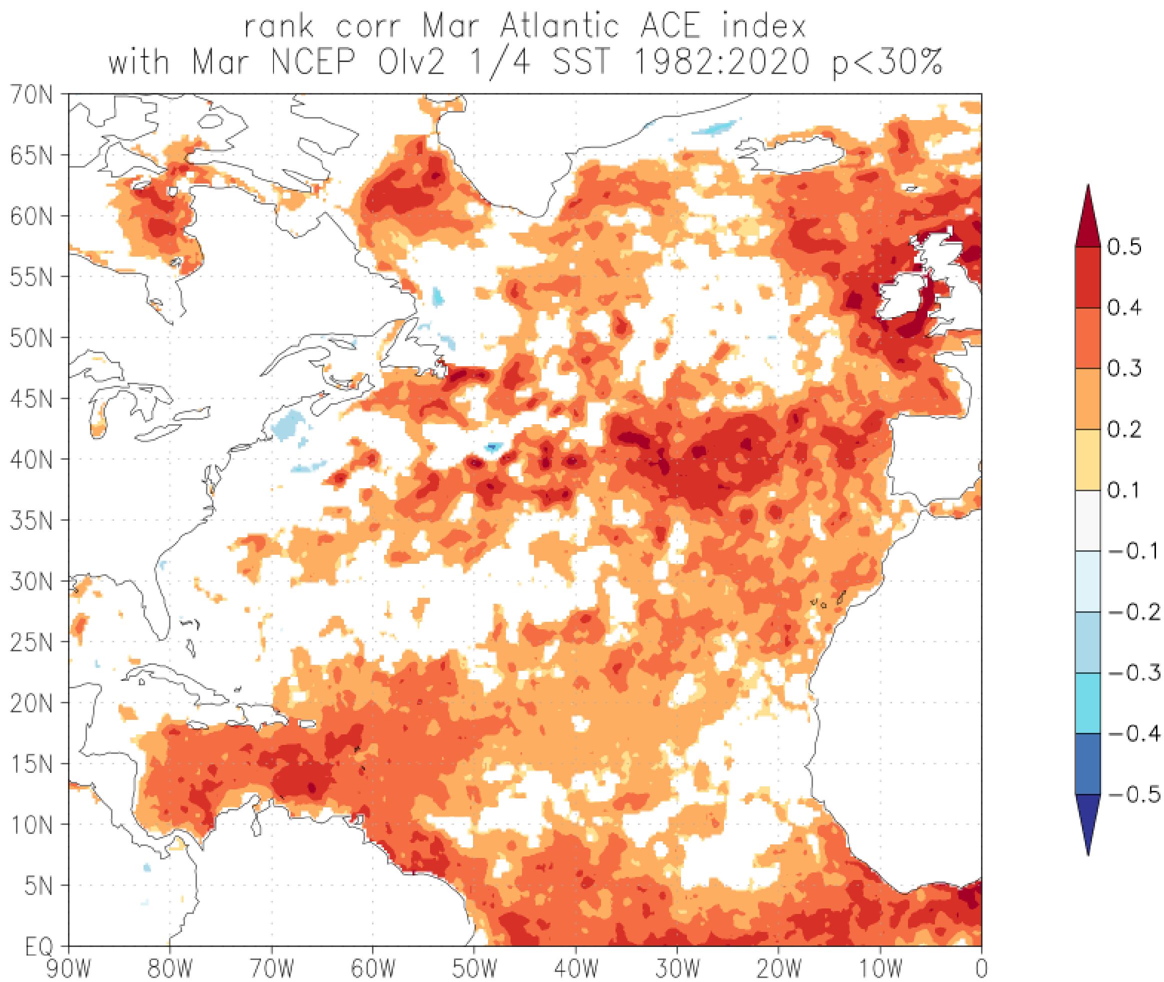

Figure 22: Rank correlation between March North Atlantic SST anomalies and seasonal Atlantic ACE from 1982–2020.

6 Tropical Cyclone Impact Probabilities for 2021

This year, we are debuting a new methodology for calculating the impacts of tropical cyclones for each state and county/parish along the Gulf and East Coasts, tropical cyclone-prone provinces of Canada, islands in the Caribbean and countries in Central America. We have used NOAA's Historical Hurricane Tracks website and selected all named storms, hurricanes and major hurricanes that have tracked within 50 miles of each landmass from 1851-2019. This approach allows for tropical cyclones that may have made landfall in an immediately adjacent region to be counted for all regions that were in close proximity to the landfall location of the storm. We then fit the observed frequency of storms within 50 miles of each landmass using a Poisson distribution to calculate the climatological odds of one or more events within 50 miles.

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 displays the climatological odds of storms tracking within 50 miles of each state along the Gulf and East Coasts along with the odds in 2021. Given that the seasonal forecast is for above-average hurricane activity, the odds of tropical cyclone impacts are also elevated. Probabilities for other Atlantic basin landmasses are available on our website.

Table 11: Probability of >=1 named storm, hurricane and major hurricane tracking within 50 miles of each coastal state from Texas to Maine. Probabilities are provided for both the 1851–2019 climatological average as well as the probability for 2021, based on the latest CSU seasonal hurricane forecast.

		2021 Probability				**Climatology**	
	Probability >=1	**event within**	**50 miles**		**Probability >=1**	**event within**	**50 miles**
State	Named Storm	Hurricane	Major Hurricane		Named Storm	Hurricane	Major Hurricane
Texas	75%	49%	21%		58%	35%	14%
Louisiana	80%	53%	23%		63%	37%	15%
Mississippi	69%	39%	12%		52%	26%	8%
Alabama	75%	41%	14%		58%	28%	9%
Florida	96%	75%	41%		86%	58%	28%
Georgia	79%	45%	11%		63%	31%	7%
South Carolina	73%	41%	12%		56%	28%	7%
North Carolina	84%	52%	11%		68%	37%	7%
Virginia	63%	28%	3%		46%	19%	2%
Maryland	47%	16%	2%		33%	11%	1%
Delaware	33%	8%	<1%		22%	5%	<1%
New Jersey	34%	11%	1%		23%	7%	1%
New York	40%	15%	4%		27%	10%	2%
Connecticut	33%	13%	3%		22%	8%	2%
Rhode Island	33%	13%	4%		22%	8%	2%
Massachusetts	49%	23%	6%		34%	15%	3%
New Hampshire	28%	10%	3%		18%	6%	2%
Maine	34%	12%	3%		23%	8%	2%

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 2021 should have above-normal activity. The big question marks with this season's predictions revolve around what phase ENSO will be, as well as what the configuration of SSTs will look like in the Atlantic Ocean during the peak of the Atlantic hurricane season.

8 Forthcoming Updated Forecasts of 2021 Hurricane Activity

We will be issuing seasonal updates of our 2021 Atlantic basin hurricane forecasts on **Thursday 3 June**, **Thursday 8 July, and Thursday 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 2021 forecasts will be issued in late November 2021. 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 2016-2020.

2016	18 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

2019	4 April	Update 4 June	Update 9 July	Update 5 August	Obs.
Hurricanes	5	6	6	7	6
Named Storms	13	14	14	14	18
Hurricane Days	16	20	20	20	23.50
Named Storm Days	50	55	55	55	70.00
Major Hurricanes	2	2	2	2	3
Major Hurricane Days	4	5	5	5	9.50
Accumulated Cyclone Energy	80	100	100	105	132
Net Tropical Cyclone Activity	90	105	105	110	141

2020	2 April	Update 4 June	Update 7 July	Update 5 August	Obs.
Hurricanes	8	9	9	12	13
Named Storms	16	19	20	24	30
Hurricane Days	35	40	40	45	34.75
Named Storm Days	80	85	85	100	118
Major Hurricanes	4	4	4	5	6
Major Hurricane Days	9	9	9	11	8.75
Accumulated Cyclone Energy	150	160	160	200	180
Net Tropical Cyclone Activity	160	170	170	215	225