QUALITATIVE DISCUSSION OF ATLANTIC BASIN SEASONAL HURRICANE ACTIVITY FOR 2021

We provide qualitative discussions of the factors which will likely determine next year's Atlantic basin hurricane activity with our December outlook. Two big questions with the upcoming hurricane season are how the tropical Pacific will trend given the current La Niña event as well as what North Atlantic sea surface temperatures will look like.

Our first quantitative forecast for 2021 will be issued on Thursday, April 8.

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In Memory of William M. Gray[4]

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

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ABSTRACT

We are providing a qualitative discussion of features likely to impact the 2021 Atlantic basin hurricane season rather than a specific number forecast. This outlook for 2021 will give our assessment of the probability of five potential scenarios for Accumulated Cyclone Energy (ACE).

The current way that we assess the following year's activity in the December outlook is in terms of two primary physical parameters:

1. the strength of the Atlantic Multi-Decadal Oscillation (AMO)

2. the phase of ENSO

The Atlantic had three quiet hurricane seasons from 2013-2015, followed by a slightly above-average season in 2016, near record-breaking levels of activity in 2017 slightly above-average seasons in 2018 and 2019 and an extremely active season in 2020. Five above-average seasons lends high confidence that the AMO remains in a positive phase, although the far North Atlantic has generally been characterized by below-average sea surface temperatures (SSTs), especially during the winter. Another big question for 2021 is how El Niño-Southern Oscillation (ENSO) will trend over the next few months. As is typically the case at this time of year, there is considerable model disagreement as to what the phase of ENSO will look like for the summer and fall of 2021.

For the 2021 hurricane season, we anticipate five possible scenarios with the probability of each as indicated on the next page:

1. AMO becomes very strong in 2021 and no El Niño occurs (resulting in a seasonal average Accumulated Cyclone Energy (ACE) activity of ~ 170) – **25% chance**.

2. AMO is above average and no El Niño occurs (ACE ~ 130) – **35% chance**.

3. AMO is above average and El Niño develops (ACE ~ 80) – **20% chance**.

4. AMO is below average and no El Niño occurs (ACE ~ 80) – **10% chance**.

5. AMO is below average and El Niño develops (ACE ~ 50) – **10% chance**.

Typically, seasons with the above-listed ACE values have TC activity as follows:

170 ACE – 14-17 named storms, 9-11 hurricanes, 4-5 major hurricanes
130 ACE – 12-15 named storms, 6-8 hurricanes, 2-3 major hurricanes
80 ACE – 8-11 named storms, 3-5 hurricanes, 1-2 major hurricanes
50 ACE – 5-7 named storms, 2-3 hurricanes, 0-1 major hurricane

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.

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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 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.

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 40-50 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, 20-75°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.

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 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 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. These forecasts are based on statistical and statistical-dynamical methodologies derived from 30-60 years of past data. Qualitative adjustments are added to accommodate additional processes which may not be explicitly represented by our quantitative analyses. These evolving forecast techniques are based on a variety of climate-related global and regional predictors previously shown to be related to the forthcoming seasonal Atlantic basin TC activity and landfall probability. We believe that seasonal forecasts must be based on methods that show significant hindcast skill in application to long periods of prior data. It is only through hindcast skill that one can demonstrate that seasonal forecast skill is possible. This is a valid methodology provided that the atmosphere continues to behave in the future as it has in the past.

The best predictors do not necessarily have the best individual correlations with hurricane activity. The best forecast parameters are those that explain the portion of the variance of seasonal hurricane activity that is not associated with the other forecast variables. It is possible for an important hurricane forecast parameter to show little direct relationship to a predictand by itself but to have an important influence when included with a set of 2-3 other predictors. This is the nature of the seasonal or climate forecast problem where one is dealing with a very complicated atmosphere-ocean 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. 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 some of the climate system's non-linear interactions. Any seasonal or climate forecast scheme must show significant hindcast skill before it is used in real-time forecasts.

2 The Influence of the Atlantic Ocean Thermohaline Circulation (THC) and the Strength of the Atlantic Gyre on Atlantic Hurricane Activity

Over the next few pages, we discuss two large-scale physical features which we posit are fundamental for how active the 2021 Atlantic hurricane season is likely to be.

The longer-period SST changes which the Atlantic Ocean experiences are due primarily to variations in the strength of the southwest to northeast upper branch of the THC in the high latitude Atlantic, which are then reflected in changes in the AMO. The THC (which is observed and modeled to vary considerably in strength on multi-decadal timescales) is strong when there is an above-average poleward advection of warm tropical waters to the high latitudes of the Atlantic. This poleward-moving water can then sink to deep levels if it has high enough salinity content. This sinking process is known as North Atlantic Deep Water Formation (NADWF). The deep water then moves southward into the Southern Hemisphere. The amount of North Atlantic water that sinks is roughly proportional to the water's density which at high latitudes, where water temperatures are low, is primarily dependent on salinity content. The strong association between our proxy for the AMO and North Atlantic salinity in the far North Atlantic (50-60°N, 50-10°W) is shown in Figure 1. High salinity implies higher rates of NADWF. When the salinity rates are lower, less NADWF formation occurs. During these periods, the water tends to recirculate and increase the ocean's clockwise circulating gyre motion.

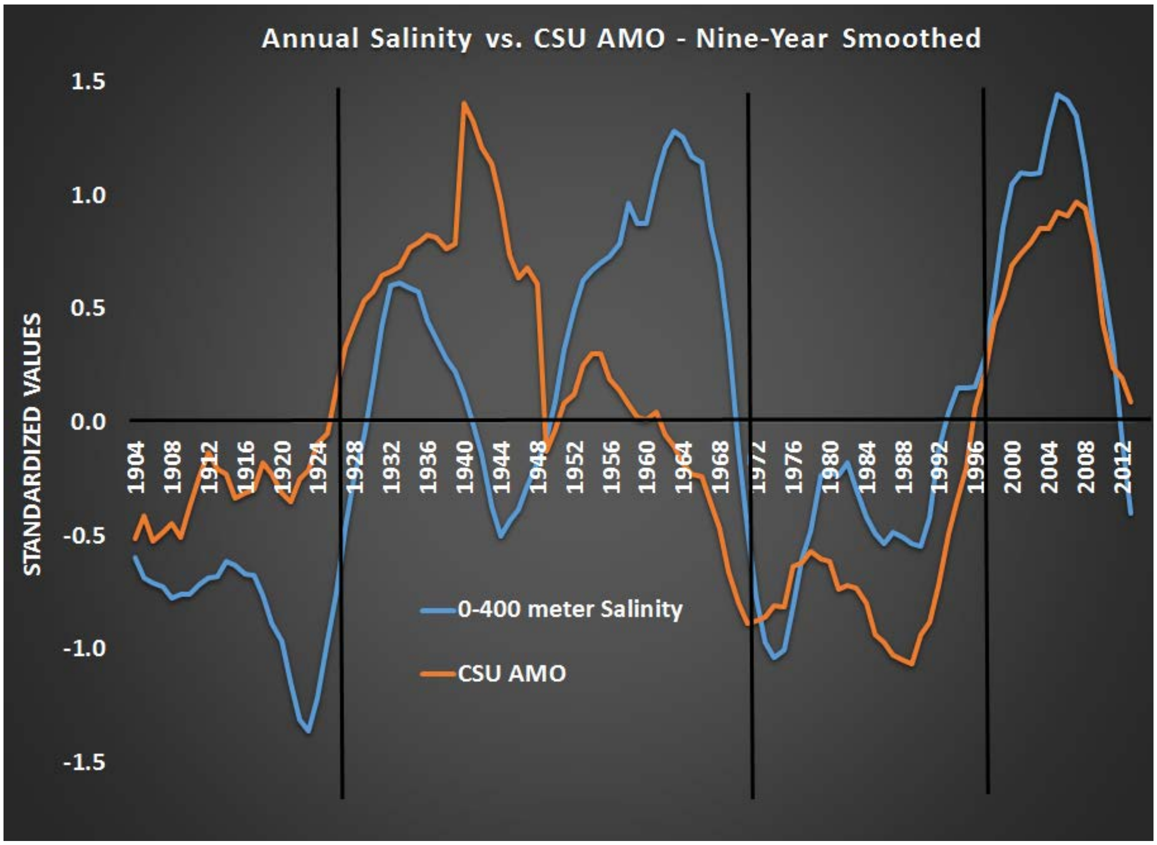

Figure 1: Illustration of the strong association of the AMO with North Atlantic salinity content from 1900-2018.

Through a progression of relationships, the strength of the NADWF and inverse strength of the Atlantic gyre is hypothesized to bring about alterations of the tropospheric vertical wind shear, trade wind strength, SSTs, middle-level water vapor, and other conditions in the Atlantic <u>M</u>ain <u>D</u>evelopment <u>R</u>egion (MDR – 7.5-22.5°N; 20-75°W). Changes of SST in the MDR are a consequence of a combination of the AMO's influences on a variety of other parameters in the MDR (Figure 2). A stronger than average THC causes more ocean sinking in area 1. This in turn reduces the strength of the Atlantic gyre. There is then a change in the other conditions shown in Figure 2 to bring about more or less favorable parameters in the MDR for TC formation and intensification. This figure illustrates how the changing rate of southward advection of cold water in the east Atlantic (2) brings about alterations of SLP (3), SST (4), and rainfall (5). These changes in turn lead to changes in trade wind strength (6) and 200 mb zonal wind (7). Changes in hurricane activity and especially major hurricane activity follow (8). It is also found that in periods with a positive AMO, El Niño frequency and intensity is typically reduced (9) and tropical South Atlantic SSTs are decreased (10).

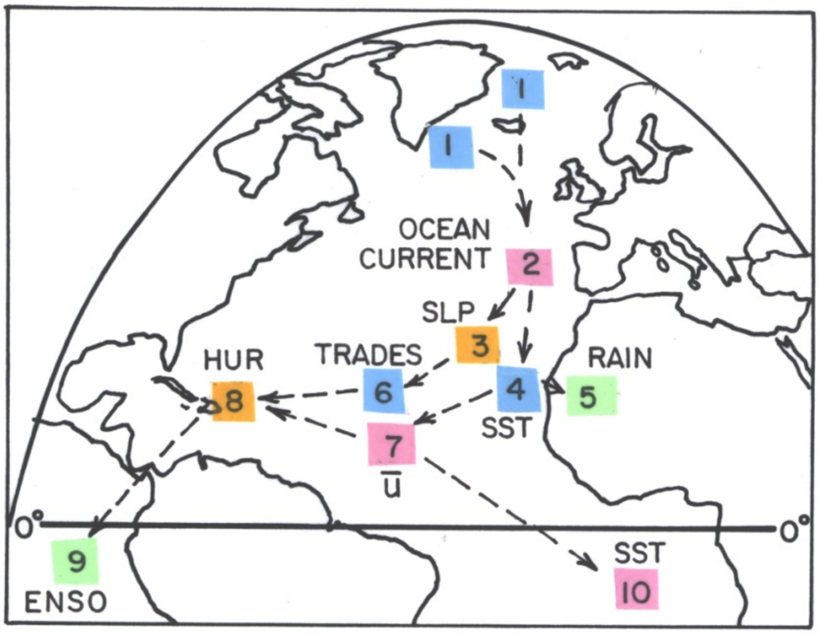

Figure 2: Idealized analysis of how changes in North Atlantic SST and salinity (area 1) lead to progressive ocean current, wind, pressure, SST, vertical shear and rain changes as portrayed in nine areas. It is this complete package of Atlantic/eastern Pacific Ocean/atmosphere parameter changes on multi-decadal time scales which cause large changes in Atlantic major hurricanes on this time scale.

One of the primary physical drivers for active versus inactive Atlantic basin hurricane seasons is the strength of the AMO (Gray et al. 1996, Goldenberg et al. 2001, Klotzbach and Gray 2008). A positive phase of the AMO (or strong phase of the THC) typically leads to 3-5 times more major Atlantic basin hurricane activity than does a negative phase. The typical period of the AMO is about 60 years, with the period length varying between as short as 40-50 years and as long as 70-80 years. This means that we typically have 25-35 years of above-average Atlantic basin major TC activity and similar length periods with considerably reduced amounts of major TC activity. We had three quiet Atlantic hurricane seasons in a row (e.g., 2013-2015) which led us to question whether we had moved out of the active era that began in 1995 (Klotzbach et al. 2015). However, the Atlantic has since had five active seasons in a row, causing us to believe that the AMO remains in its positive phase.

While the AMO typically remains in an above-average or in a below-average state for periods of 25-35 years, there can be monthly, seasonal or longer breaks up to a year or two within these decadal periods when the AMO conditions of features such as SST, salinity, pressure, wind, and moisture become substantially weaker in positive AMO phases or stronger during negative AMO phases.

There is a strong inverse relationship between the strength of the AMO and the strength of the Atlantic gyre (Bermuda-Azores High). This has been well documented in our analysis of various yearly and seasonal gyre and AMO proxy variations. Hurricane activity, particularly the most intense hurricane activity, is much more frequent when the Atlantic Bermuda-Azores gyre circulation system is weak and the Atlantic Ocean THC system is strong. Hurricane activity is generally reduced when the reverse conditions occur. Increased gyre strength acts to bring about cooler air (and reduced moisture) and cooler ocean water advection in the eastern half of the Atlantic. This acts to increase the strength of the trade winds and increase the low latitude (5-20°N) south to north tropospheric temperature gradient and the upper tropospheric westerly winds. These changes are inhibiting factors for hurricane formation and intensification.

We currently maintain an AMO proxy that utilizes SST in the region from 50-60°N, 50-10°W and SLP in the region from 0-50°N, 70-10°W (Figure 3). The index is created by weighing the two parameters as follows: 0.6*SST – 0.4*SLP. Our AMO index is currently running at below-normal levels (Figure 4). The far North Atlantic is much cooler than normal (Figure 5).

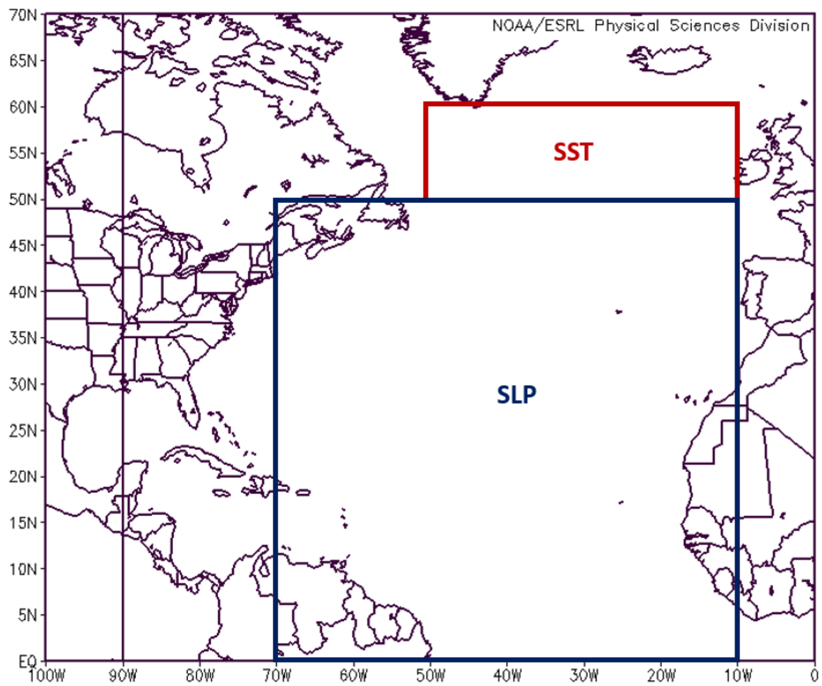

Figure 3: Regions which are utilized for calculation of our THC/AMO index. These regions are as defined in Klotzbach and Gray (2008).

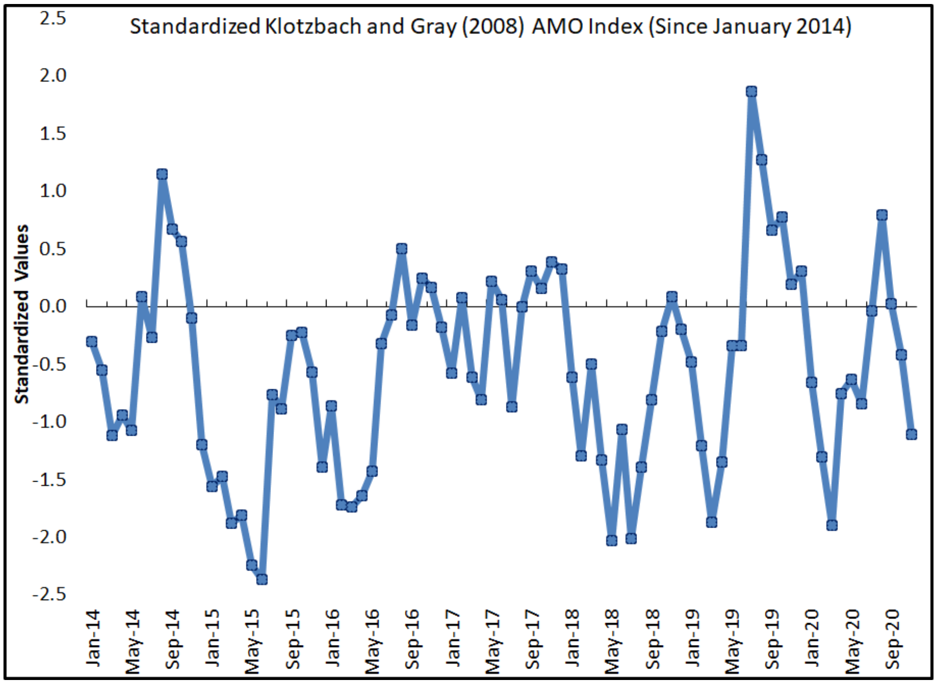

Figure 4: Standardized values of the CSU AMO index by month since January 2014.

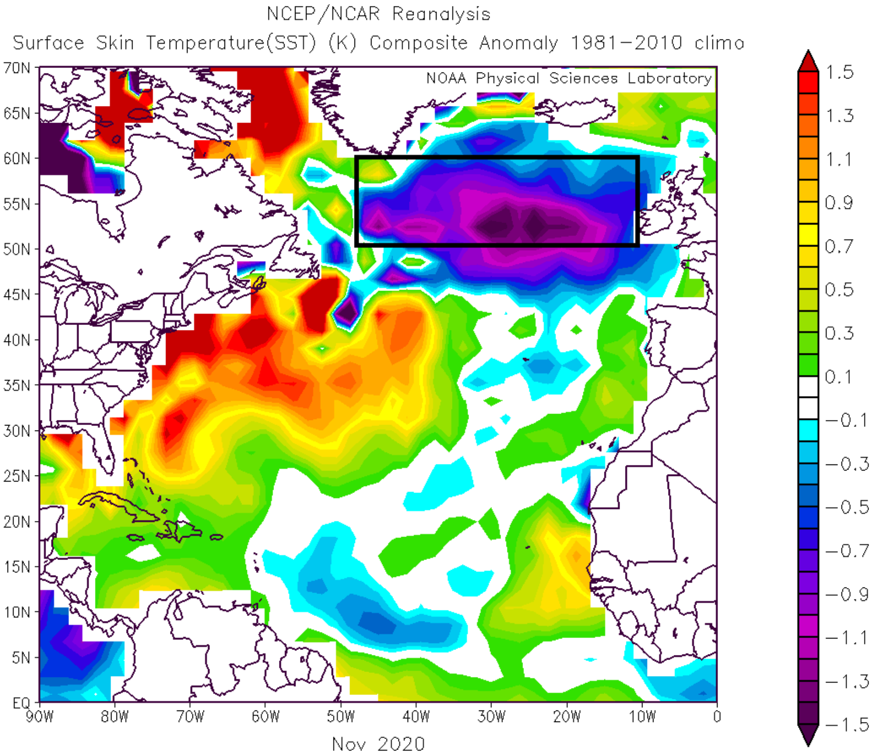

Figure 5: November 2020 SST anomalies across the North Atlantic Ocean. The black box highlights the region where SSTs are measured for the CSU AMO index.

One of the big scientific questions that we have been trying to better understand over the past few years is the predominant trend to a negative horseshoe of SST anomalies in the North Atlantic (including anomalously cold SSTs in the tropical Atlantic) during the winter, but the persistence of above-normal SSTs in the tropical Atlantic during the peak of the Atlantic hurricane season. Figure 6 displays January-March-averaged SSTs during 2014-2020 minus 1995-2012 – the likely peak of the positive AMO phase. Figure 7 displays the same data but plotting August-October-averaged SSTs. SSTs have remained well above the 1981-2010 average across the tropical Atlantic during the peak of most hurricane seasons (August-October) since 2013 (Figure 8). The negative horseshoe of SST observed during the winter months has likely been a result of the predominantly positive North Atlantic Oscillation and associated stronger zonal winds blowing across the Atlantic. However, these zonal wind anomalies have not persisted through the summer, leading to anomalous winter to summer warming of the tropical Atlantic. Consequently, despite the current negative value of the AMO index, we believe that the AMO will likely be trending more positive by next year's hurricane season.

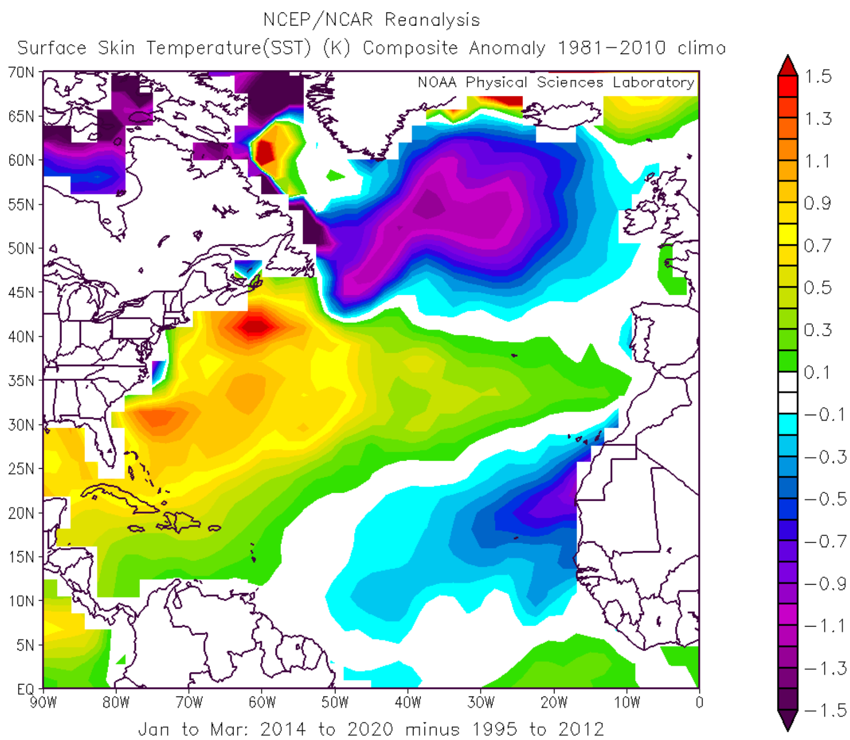

Figure 6: January-March-averaged SSTs from 2014-2020 minus 1995-2012.

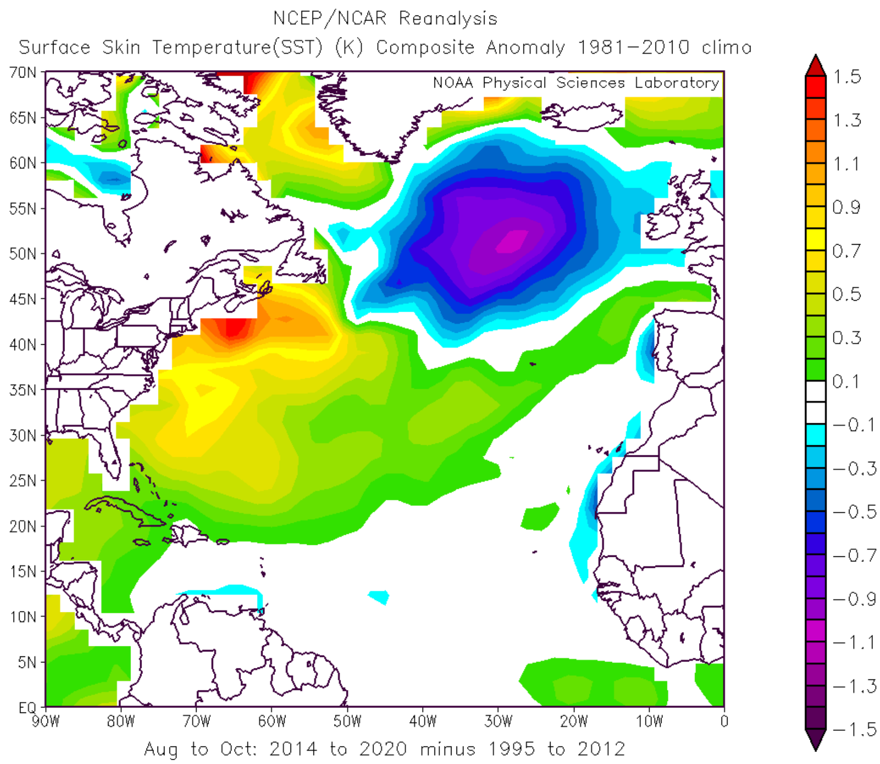

Figure 7: August-October-averaged SSTs from 2014-2020 minus 1995-2012.

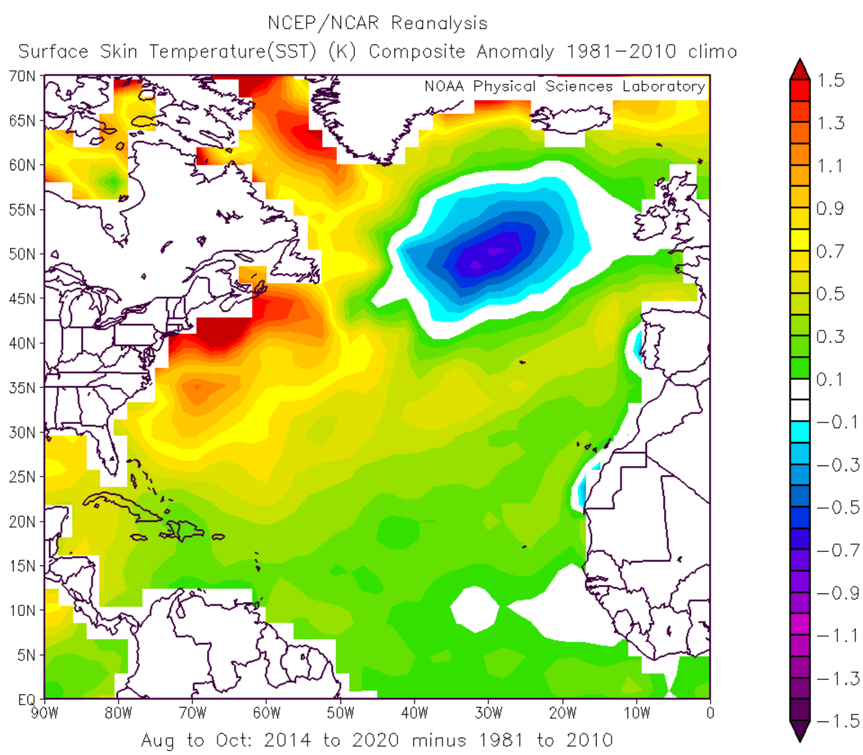

Figure 8: August-October-averaged SSTs from 2014-2020 minus 1981-2010.

3 ENSO

The tropical Pacific is currently characterized by La Niña conditions (Figure 9). SST anomalies are generally between 0.5-1°C below average for most of the eastern and central tropical Pacific. One of the important questions for every hurricane season is what the ENSO state will look like during the peak of the hurricane season. In general, most ENSO forecast models call for the current La Niña to weaken and that neutral ENSO conditions will prevail next summer (Figure 10). The European Center for Medium-Range Weather Forecasts (ECMWF) model ensemble spread calls for La Niña through the boreal winter, with most ensemble members calling for a trend towards neutral ENSO conditions by next June (Figure 11).

The September-October-November-averaged (SON) Oceanic Nino Index (ONI), defined as the three-month average of SSTs in the Nino 3.4 region, is currently -1.2°C. Table 1 displays SON ONI values for all moderate or strong La Niña events (<=-1°C) since 1950 along with the following year's August-September-October-averaged (ASO) ASO ONI values. Of the ten previous moderate to strong La Niña events, only one transitioned to El Niño (>=0.5°C), five were neutral ENSO while the remaining four were La Niña (<=-0.5°C). There is considerable uncertainty at this point what ENSO will look like by the peak of next hurricane season from August-October, but at this point given model forecasts as well as statistical analyses, it appears extremely unlikely that El Niño would develop before next summer.

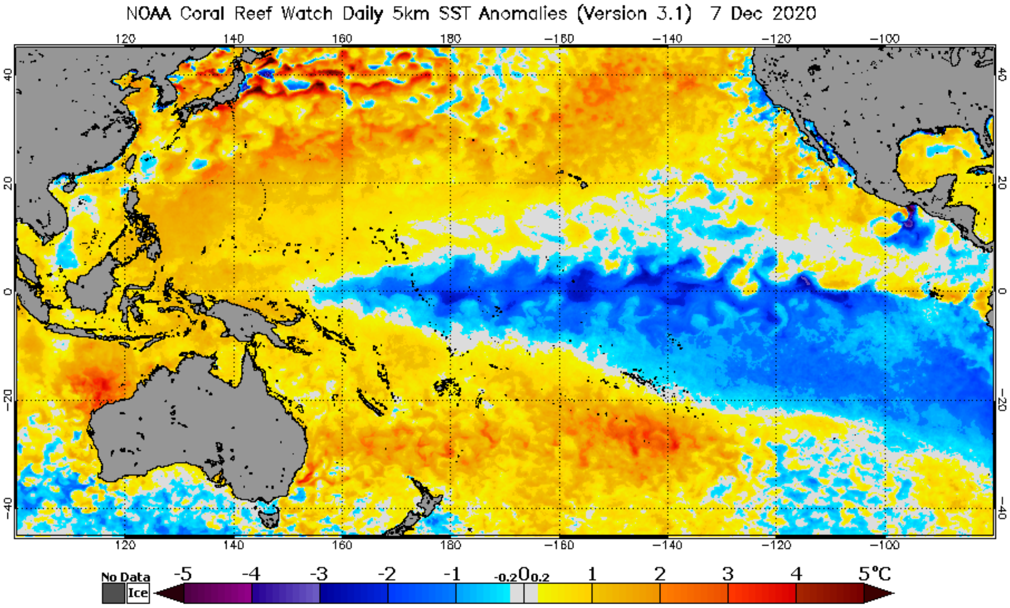

Figure 9: Early December 2020 SST anomalies across the Pacific Ocean. Cold SSTs prevail across the eastern and central equatorial tropical Pacific.

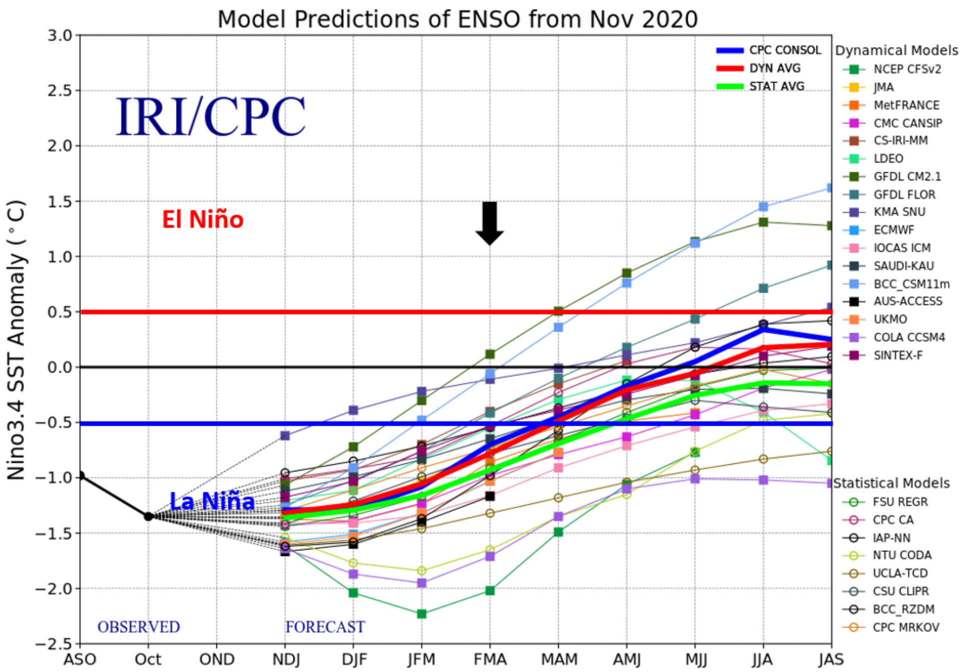

Figure 10: ENSO model prediction plume from mid-November for the next several months. Figure courtesy of the International Research Institute for Climate and Society.

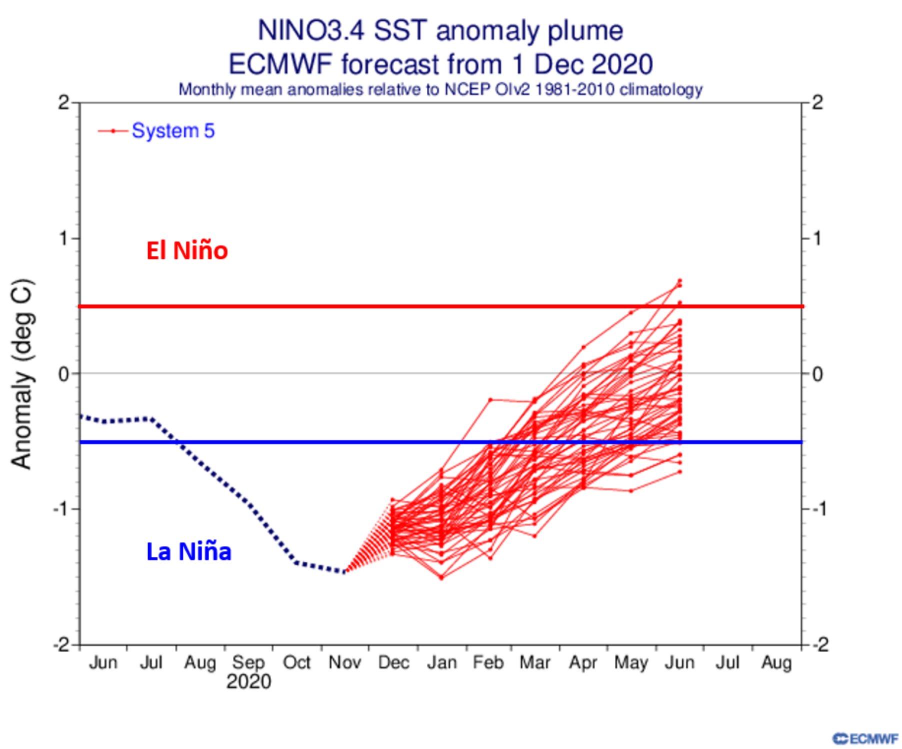

Figure 11: Ensemble ECMWF forecast plume for Nino 3.4 SSTs over the next few months. Most ECMWF ensemble members predict neutral ENSO conditions by next June.

Table 1: Oceanic Nino Index (ONI) values in September-November of moderate to strong La Niña events (<=-1°C) along with ONI values during the following August-October. Events meeting the La Niña threshold are color-coded in blue, while events meeting the El Niño threshold are color-coded in red.

Year	SON ONI	Following Year ASO ONI
1955	**-1.4**	**-0.5**
1973	**-1.7**	-0.4
1975	**-1.4**	**0.6**
1988	**-1.5**	-0.2
1995	**-1.0**	-0.4
1998	**-1.4**	**-1.2**
1999	**-1.3**	**-0.5**
2007	**-1.4**	-0.3
2010	**-1.7**	**-0.9**
2011	**-1.1**	0.3
2020	**-1.2**	???

4 Climatological Landfall Probabilities

A significant focus of our recent research involves efforts to develop forecasts of the probability of hurricane landfall along the U.S. coastline and in the Caribbean. While we are not issuing a quantitative forecast in this early outlook, we can still provide interested readers with the climatological probabilities of landfall for various portions of the United States coastline.

Table 2 lists climatological strike probabilities for the 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.

Table 2: Climatological 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). Probabilities of a tropical storm, hurricane and major hurricane tracking into the Caribbean are also provided.

Region	TS	Category 1-2 HUR	Category 3-4-5 HUR	All HUR	Named Storms
Entire U.S. (Regions 1-11)	79%	68%	52%	84%	97%
Gulf Coast (Regions 1-4)	59%	42%	30%	60%	83%
Florida plus East Coast (Regions 5-11)	50%	44%	31%	61%	81%
Caribbean (10-20°N, 60-88°W)	82%	57%	42%	75%	96%

We have also calculated probabilities of each state being impacted by a tropical cyclone, using the impacts database available from the National Hurricane Center. Table 3 displays the climatological probabilities for each state along the United States coastline being impacted by a hurricane and major hurricane, respectively. We define a hurricane impact to be that sustained hurricane-force winds were experienced somewhere in the state.

Table 3: Climatological probability of each state along the United States coastline being impacted by a hurricane and major hurricane, respectively.

State	Hurricane	Major Hurricane
Texas	33%	12%
Louisiana	30%	12%
Mississippi	11%	4%
Alabama	16%	3%
Florida	51%	21%
Georgia	11%	1%
South Carolina	17%	4%
North Carolina	28%	8%
Virginia	6%	1%
Maryland	1%	<1%
Delaware	1%	<1%
New Jersey	1%	<1%
New York	8%	3%
Connecticut	7%	2%
Rhode Island	6%	3%
Massachusetts	7%	2%
New Hampshire	1%	<1%
Maine	4%	<1%

The Landfall Probability Website has additional probability information including county-level probabilities for 205 coastal counties from Brownsville, TX to Eastport, ME. These probabilities will be updated with the 8 April quantitative forecast.

5 Summary

We detail in this outlook two key parameters that are critical for determining levels of Atlantic hurricane activity: North Atlantic SSTs and ENSO. Currently, tropical Atlantic SSTs are slightly above normal and far North Atlantic SSTs are cooler than normal. The tropical Pacific is currently characterized by La Niña conditions. Most models predict that La Niña will transition to neutral ENSO conditions by next summer, while statistical analyses indicates the potential for continued La Niña conditions (albeit at a weaker magnitude than currently observed). We are closely monitoring these conditions and will have additional extensive discussion with our early April outlook.

6 Forthcoming Updated Forecasts of 2021 Hurricane Activity

Seasonal outlooks for the 2021 Atlantic basin hurricane season will be issued on **Thursday April 8**, **Thursday June 3, Thursday July 8, 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. These forecasts will be available on our project's website.