SUMMARY OF 2019 ATLANTIC TROPICAL CYCLONE ACTIVITY AND VERIFICATION OF AUTHORS' SEASONAL AND TWO-WEEK FORECASTS

The 2019 Atlantic hurricane season was slightly above average and had a little more activity than what was predicted by our June-August updates. The climatological peak months of the hurricane season were characterized by a below-average August, a very active September, and above-average named storm activity but below-average hurricane activity in October. Hurricane Dorian was the most impactful hurricane of 2019, devastating the northwestern Bahamas before bringing significant impacts to the southeastern United States and the Atlantic Provinces of Canada. Tropical Storm Imelda also brought significant flooding to southeast Texas.

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

Anne Manning, Colorado State University media representative, is coordinating media inquiries into this verification. She can be reached at 970-491-7099 or anne.manning@colostate.edu.

Department of Atmospheric Science
Colorado State University
Fort Collins, CO 80523
Email: philk@atmos.colostate.edu

As of 27 November 2019

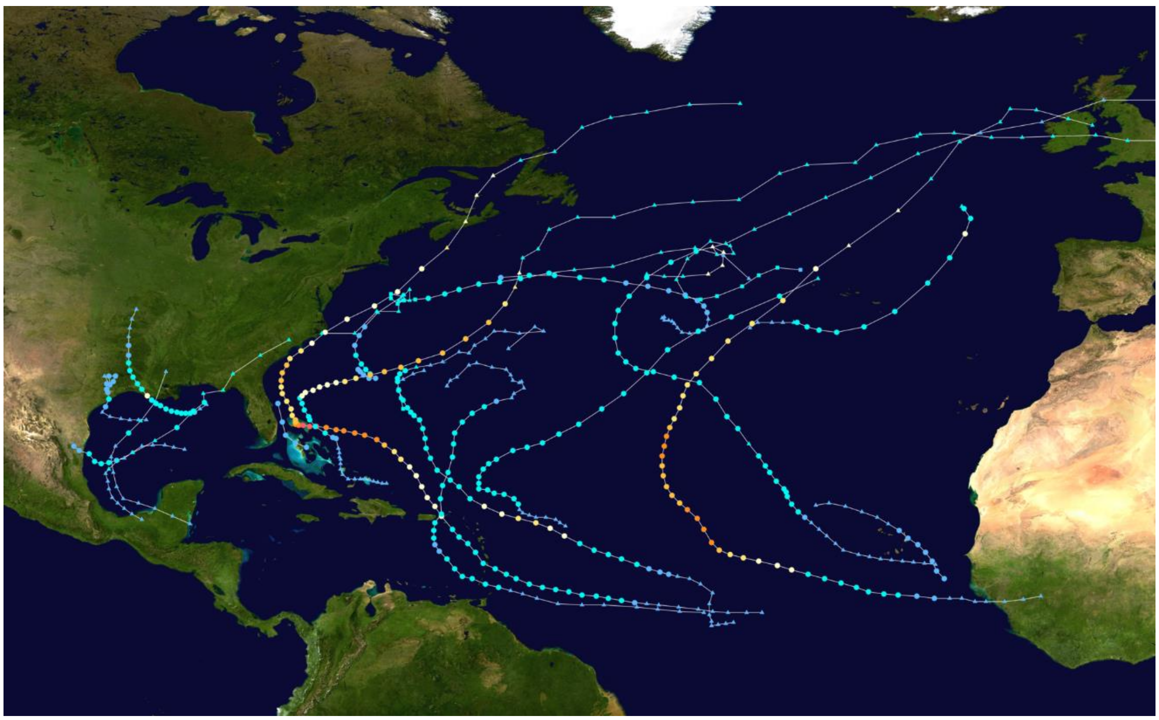
Project Sponsors:

Interstate
IRONSHORE
INSURANCE INFORMATION INSTITUTE
WEATHERBOY.COM

[1] Research Scientist
[2] Associate Professor
[3] Graduate Research Assistant
[4] Professor Emeritus

ATLANTIC BASIN SEASONAL HURRICANE FORECASTS FOR 2019

Forecast Parameter and 1981-2010 Average (in parentheses)	Issue Date 4 April 2019	Issue Date 4 June 2019	Issue Date 9 July 2019	Issue Date 5 August 2019	**Observed 2019 Activity Thru 11/27**	% of 1981-2010 Average
Named Storms (NS) (12.1)	13	14	14	14	**18**	149%
Named Storm Days (NSD) (59.4)	50	55	55	55	**68.5**	107%
Hurricanes (H) (6.4)	5	6	6	7	**6**	94%
Hurricane Days (HD) (24.2)	16	20	20	20	**23.25**	96%
Major Hurricanes (MH) (2.7)	2	2	2	2	**3**	111%
Major Hurricane Days (MHD) (6.2)	4	5	5	5	**10**	161%
Accumulated Cyclone Energy (ACE) (106)	80	100	100	105	**130**	123%
Net Tropical Cyclone Activity (NTC) (116%)	90	105	105	110	**142**	122%



2019 Atlantic basin tropical cyclone tracks through November 27. 18 named storms, 6 hurricanes and 3 major hurricanes occurred. Figure courtesy of Wikipedia.

ABSTRACT

This report summarizes tropical cyclone (TC) activity which occurred in the Atlantic basin during 2019 and verifies the authors' seasonal Atlantic basin forecasts. Also verified are six two-week Atlantic basin forecasts issued during the peak months of the hurricane season that were based on a combination of current activity, model forecasts and the phase of the Madden-Julian Oscillation (MJO).

The first quantitative seasonal forecast for 2019 was issued on 4 April with updates following on 4 June, 9 July and 5 August. These seasonal forecasts also contained estimates of the probability of US and Caribbean hurricane landfall during 2019.

The 2019 hurricane season overall was slightly above average. The season was characterized by an above-average number of named storms and a near-average number of hurricanes and major hurricanes. Our initial seasonal forecast issued in April somewhat underestimated activity, while seasonal updates issued in June, July and August, respectively, slightly underestimated overall activity. The primary reason for the underestimate was due to a more rapid abatement of weak El Niño conditions than was originally anticipated. August was a relatively quiet month for Atlantic TC activity, while September was well above-average. While October had an above-average number of named storm formations, overall Accumulated Cyclone Energy was slightly below normal.

Six consecutive two-week forecasts were issued during the peak months of the Atlantic hurricane season from August-October. These forecasts were based on current hurricane activity, predicted activity by global forecast models and the phase of the Madden-Julian Oscillation (MJO). These two-week forecasts predicted the correct tercile in 3 out of the 6 outlooks that were issued.

Integrated measures such as Net Tropical Cyclone (NTC) activity and Accumulated Cyclone Energy (ACE) were slightly above average. Tropical Atlantic sea surface temperatures were somewhat warmer than normal during the peak of the 2019 hurricane season. Vertical wind shear was generally below-average throughout the peak of the season.

The 2019 Atlantic hurricane season will primarily be remembered for Hurricane Dorian, which devastated the northwestern Bahamas at Category 5 intensity before making landfall near Cape Hatteras, North Carolina as a Category 1 hurricane. Dorian also caused significant damage in the Atlantic Provinces of Canada. Tropical Storm Imelda also deluged southeast Texas with tremendous amounts of rainfall, causing considerable damage in the process.

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 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 North Atlantic (TNA) index – A measure of sea surface temperatures in the area from 5.5-23.5°N, 15-57.5°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

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.

1 Preliminary Discussion

1a. Introduction

The year-to-year variability of Atlantic basin hurricane activity is the largest of any of the globe's tropical cyclone (TC) basins. There has always been and will continue to be much interest in knowing if the coming Atlantic hurricane season is going to be unusually active, very quiet or near average. There was never a way of objectively determining how active the coming Atlantic hurricane season was going to be until the early to mid-1980s when global data sets became more accessible.

Analyzing the available data in the 1980s, it was found that the coming Atlantic seasonal hurricane season did indeed have various precursor signals that extended backward in time from zero to 6-8 months before the start of the season. These precursor signals involved El Niño – Southern Oscillation (ENSO), Atlantic sea surface temperatures (SSTs) and sea level pressures, West African rainfall, the Quasi-Biennial Oscillation (QBO) and a number of other global parameters. Much effort has since been expended by our project's current and former members (along with other research groups) to try to quantitatively maximize the best combination of hurricane precursor signals to give the highest amount of reliable seasonal hindcast skill. We have experimented with a large number of various combinations of precursor variables and now find that our most reliable statistical forecasts utilize a combination of three or four variables.

A cardinal rule that has always been followed is to issue no forecast for which we do not have substantial hindcast skill extending back in time for at least 30 years. The NCEP/NCAR reanalysis data sets now used are available back to 1948 providing over 70 years of hindcast information. We also utilize newer reanalyses that have been developed on the past ~35 years of data (e.g., the ERA-Interim and CFSR Reanalyses). We also have been exploring longer-term reanalysis products such as the 20^{th} Century Reanalysis from the Earth System Research Laboratory. The ERA5 reanalysis dataset is now available and will be used as the historical dataset underpinning all of the CSU statistical hurricane forecast models beginning in 2020.

Beginning with the April 2019 forecast, CSU also began issuing statistical-dynamical model forecasts. These predictions use the current ECMWF climate model (SEAS5) to predict the large-scale conditions in July that underpin the early August statistical seasonal hurricane forecast model. These statistical-dynamical forecasts have shown skill at predicting Accumulated Cyclone Energy (ACE) based on hindcast data since 1981 and successfully called for a near- to slightly above-average Atlantic hurricane season in 2019.

The explorative process to skillful prediction should continue to develop as more data becomes available and as more robust relationships are found. There is no one best forecast scheme that can always be confidently applied. We have learned that precursor relations can change with time and that one must be alert to these changing relationships.

For instance, earlier seasonal forecasts relied heavily on the stratospheric QBO and West African rainfall. These precursor signals have not worked in recent years. Because of this, other precursor signals have been substituted in their place. As new data and new insights are gathered in the coming years, it is to be expected that our forecast schemes will in future years also need revision. Keeping up with the changing global climate system, using new data signals, and exploring new physical relationships is a full-time job. Success can never be measured by the success of a few real-time forecasts but only by long-period hindcast relationships and sustained demonstration of real-time forecast skill over a decade or more.

1b. Seasonal Forecast Theory

A variety of atmosphere-ocean conditions interact with each other to cause year-to-year and month-to-month hurricane variability. The interactive physical linkages between these precursor physical parameters and hurricane variability are complicated and cannot be well elucidated to the satisfaction of the typical forecaster making short range (1-5 days) predictions where changes in the current momentum and pressure fields are the crucial factors. Seasonal forecasts, unfortunately, must deal with the much more complicated interaction of the energy-moisture fields along with the momentum fields.

We find that there is a rather high (50-60 percent) degree of year-to-year hurricane forecast potential if one combines 3-4 semi-independent atmospheric-oceanic parameters together. The best predictors (out of a group of 3-4) do not necessarily have the best individual correlations with hurricane activity. The best forecast parameters are those that explain a portion of the variance of seasonal hurricane activity that is not associated with the other variables. It is possible for an important hurricane forecast parameter to show only a marginally significant correlation with the predictand by itself but to have an important influence when included with a set of 3-4 other predictors.

In a four-predictor empirical forecast model, the contribution of each predictor to the net forecast skill can only be determined by the separate elimination of each parameter from the full four-predictor model while noting the hindcast skill degradation. When taken from the full set of predictors, one parameter may degrade the forecast skill by 25-30 percent, while another degrades the forecast skill by only 10-15 percent. An individual parameter that, through elimination from the forecast, degrades a forecast by as much as 25-30 percent may, in fact, by itself, show less direct correlation with the predictand. 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 fully understand how all these processes interact with each other. Despite the complicated relationships that are involved, all of our statistical models show considerable hindcast skill. We are confident that in applying these skillful hindcasts to future forecasts that appreciable real-time skill will continue to result.

2 Tropical Cyclone Activity for 2019

Figure 1 and Table 1 summarize Atlantic basin TC activity which occurred in 2019. Overall, the season was characterized by slightly above-average activity. Online entries from Wikipedia are available for in-depth discussions of each TC that occurred in 2019. The National Hurricane Center is also currently in the process of writing up extensive reports on all 2019 TCs.

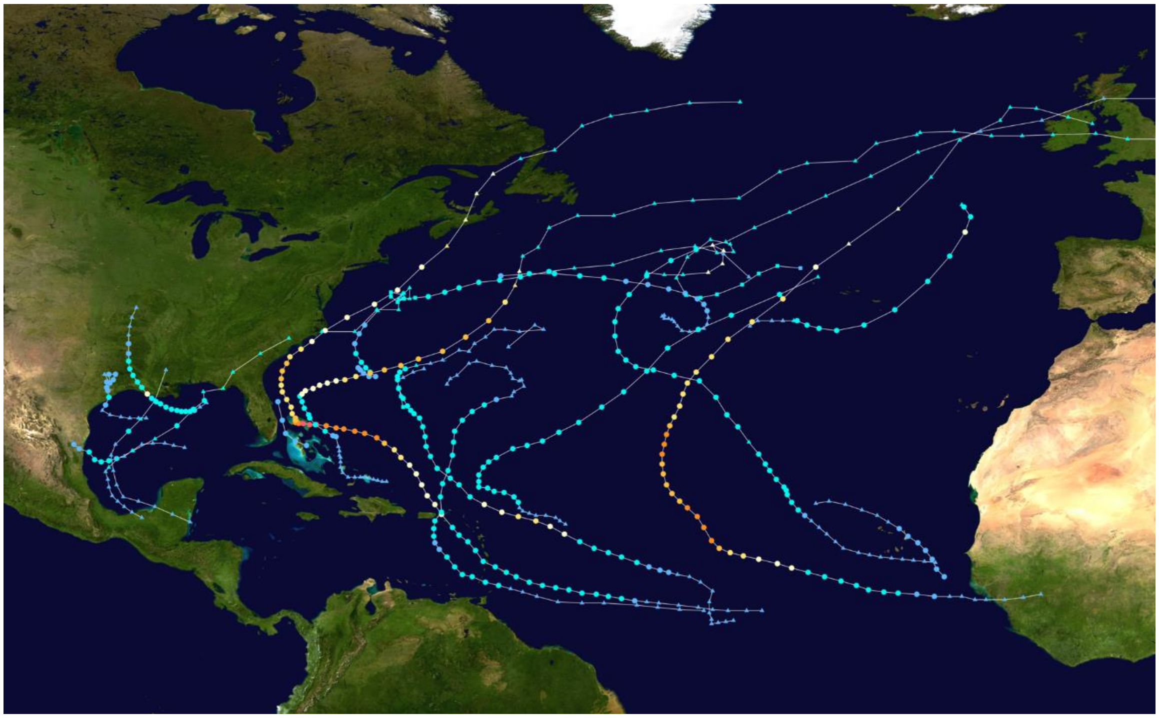


Figure 1: 2019 Atlantic basin TC tracks through November 27. 18 named storms, 6 hurricanes and 3 major hurricanes occurred. Figure courtesy of Wikipedia.

Table 1: Observed 2019 Atlantic basin TC activity through November 27.

Real-Time North Atlantic Ocean Statistics by Storm for 2019

Year	Storm#	Name	Dates TC Active	Max Wind (kts)	MSLP (mb)	Named Storm Days	Hurricane Days	Major Hurricane Days	Accumulated Cyclone Energy
2019	1	ANDREA	5/20-5/21	35	1006	0.75	0.00	0.00	0.4
2019	2	BARRY	7/11-7/14	65	993	3.50	0.25	0.00	3.3
2019	3	CHANTAL	8/21-8/21	35	1009	1.00	0.00	0.00	0.5
2019	4	DORIAN	8/24-9/7	160	910	14.00	10.00	4.75	47.6
2019	5	ERIN	8/28-8/28	35	1005	0.75	0.00	0.00	0.4
2019	6	FERNAND	9/3-9/4	45	1000	1.00	0.00	0.00	0.7
2019	7	GABRIELLE	9/4-9/10	55	995	6.25	0.00	0.00	5.2
2019	8	HUMBERTO	9/14-9/19	105	951	5.75	4.00	1.75	14.6
2019	9	JERRY	9/18-9/25	90	979	7.25	1.50	0.00	10.0
2019	10	IMELDA	9/17-9/17	35	1006	0.25	0.00	0.00	0.1
2019	11	KAREN	9/22-9/27	40	1003	4.75	0.00	0.00	2.6
2019	12	LORENZO	9/23-10/2	140	925	9.00	7.25	3.50	31.7
2019	13	MELISSA	10/11-10/14	55	995	3.00	0.00	0.00	2.3
2019	14	NESTOR	10/18-10/19	50	996	0.75	0.00	0.00	0.7
2019	15	OLGA	10/25-10/25	35	1002	0.25	0.00	0.00	0.1
2019	16	PABLO	10/25-10/28	70	977	2.75	0.25	0.00	3.0
2019	17	REBEKAH	10/30-11/1	40	982	1.75	0.00	0.00	1.1
2019	18	SEBASTIEN	11/19-11/24	55	994	5.75	0.00	0.00	5.6

3 Special Characteristics of the 2019 Hurricane Season

The 2019 hurricane season ended up slightly above average. While the season was slightly above-average for overall basin activity, it was characterized by a very quiet early season followed by a very active September and slightly below-average activity in October.

Below is a selection of some of the records that were set during the season:

- 18 named storms occurred in the Atlantic in 2019. This is the 9th Atlantic hurricane season on record (since 1851) with 18+ Atlantic named storms.

- No Atlantic named storms formed between July 12 – August 20. This is the first time that this had occurred since 1982.

- 10 named storm formations occurred in the Atlantic between August 21 – September 23. This ties 2019 with 1949 and 2010 for the most Atlantic named storm formation between August 21 and September 23 on record.

- 7 out of the 18 Atlantic named storms in 2019 lasted 24 hours or less as a named storm – the most on record. The prior record was 6 named storms lasting <=24 hours set in 2005.

- 33% of Atlantic named storms (6 out of 18) became hurricanes in 2019. This is the lowest percentage of Atlantic named storms becoming hurricanes since 2013, when only 2 out of 14 named storms (14%) reached hurricane strength.

- 93 Accumulated Cyclone Energy units were generated in the Atlantic in September. This is the 11th most Atlantic ACE during September on record.

- Hurricane Barry was the 4th hurricane on record to make landfall in Louisiana in July. The other three July landfalling Louisiana hurricanes were Bob (1979), Danny (1997) and Cindy (2005).

- Hurricane Dorian's maximum lifetime intensity of 160 knots was the strongest for any Atlantic hurricane outside of the tropics (>23.5°N) on record.

- Hurricane Dorian was the strongest hurricane to make landfall in the Bahamas on record.

- Hurricane Dorian was the strongest hurricane and the 2nd Category 5 hurricane on record to make landfall on Great Abaco Island. The other Category 5 hurricane to make landfall on Great Abaco Island was the Abaco Hurricane of 1932.

- Hurricane Dorian was the first Category 5 hurricane on record to make landfall on Grand Bahama Island.

- Hurricane Dorian's landfalling North Carolina MSLP of 956 hPa was tied for the 6th lowest MSLP for a North Carolina landfalling hurricane since 1950.

- Hurricane Lorenzo was the farthest east Atlantic Category 5 hurricane formation on record (at 45°W) – shattering the old record of Hurricane Hugo at 54.6°W.

- Hurricane Lorenzo generated the most major hurricane days at or east of 45°W on record. Lorenzo generated 3.5 major hurricane days at or east 45°W – breaking the old record set by Hurricane Carrie in 1957 of 1.75 major hurricane days.

4 Verification of Individual 2019 Lead Time Forecasts

Table 2 is a comparison of our forecasts for 2019 for four different lead times along with this year's observations. The 2019 Atlantic hurricane season was slightly above average.

Table 2: Verification of our 2019 seasonal hurricane predictions.

Forecast Parameter and 1981-2010 Average (in parentheses)	Issue Date 4 April 2019	Issue Date 4 June 2019	Issue Date 9 July 2019	Issue Date 5 August 2019	**Observed 2019 Activity Thru 11/27**
Named Storms (NS) (12.1)	13	14	14	14	**18**
Named Storm Days (NSD) (59.4)	50	55	55	55	**68.5**
Hurricanes (H) (6.4)	5	6	6	7	**6**
Hurricane Days (HD) (24.2)	16	20	20	20	**23.25**
Major Hurricanes (MH) (2.7)	2	2	2	2	**3**
Major Hurricane Days (MHD) (6.2)	4	5	5	5	**10**
Accumulated Cyclone Energy (ACE) (106)	80	100	100	105	**130**
Net Tropical Cyclone Activity (NTC) (116%)	90	105	105	110	**142**

Table 3 provides the same forecasts, with error bars (based on one standard deviation of absolute errors) as calculated from real-time forecasts from 1995-2014. We typically expect to see two-thirds of our forecasts verify within one standard deviation of observed values, with 95% of forecasts verifying within two standard deviations of observed values. Since July forecasts have only been issued in real-time for the past few years, we estimate that the July forecast should have errors halfway in between the errors of the June and August forecasts. Since we have only issued ACE forecasts for the past few years, we estimate ACE errors to be the same as NTC errors. This year's early April forecast somewhat under-forecast the season, while the updates issued in early June, July and August just slightly under-predicted overall activity.

Table 3: Verification of CSU's 2019 seasonal hurricane predictions with error bars (one standard deviation). Predictions that lie within one standard deviation of observations are highlighted in red bold font, while predictions that lie within two standard deviations are highlighted in green bold font. Predictions that are outside of two standard deviations are highlighted in black bold font. 21 out of 32 (66%) of seasonal forecast parameters were within one standard deviation of observations for the 2019 seasonal forecast, and all seasonal forecast parameters were within two standard deviations of observations. Error bars for storms are rounded to the nearest storm. For example, the hurricane prediction in early April would be 2.9-7.1, which with rounding would be 5-9.

Forecast Parameter and 1981-2010 Average (in parentheses)	4 April 2019	Update 4 June 2019	Update 9 July 2019	Update 5 August 2019	Observed 2019 Total Thru 11/27
Named Storms (NS) (12.1)	**13** (±3.5)	**14** (±2.9)	**14** (±2.6)	**14** (±2.2)	18
Named Storm Days (NSD) (59.4)	**50** (±20.7)	**55** (±19.9)	**55** (±18.1)	**55** (±16.3)	68.5
Hurricanes (H) (6.4)	**5** (±2.1)	**6** (±2.0)	**6** (±1.8)	**7** (±1.7)	6
Hurricane Days (HD) (24.2)	**16** (±11.1)	**20** (±10.7)	**20** (±10.1)	**20** (±9.5)	23.25
Major Hurricanes (MH) (2.7)	**2** (±1.3)	**2** (±1.4)	**2** (±1.2)	**2** (±0.9)	3
Major Hurricane Days (MHD) (6.2)	**4** (±4.0)	**5** (±3.7)	**5** (±3.9)	**5** (±4.1)	10
Accumulated Cyclone Energy (ACE) (106)	**80** (±42)	**100** (±40)	**100** (±36)	**105** (±31)	130
Net Tropical Cyclone Activity (NTC) (116%)	**90** (±42)	**105** (±40)	**105** (±36)	**110** (±31)	142

4.1 Verification of Statistical-Dynamical Model Forecasts

The 2019 Atlantic hurricane season was the first time that we issued a statistical-dynamical hybrid model forecast. 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. Table 4 displays the statistical-dynamical model input to our seasonal hurricane forecast scheme in early April, early June and early July. The statistical-dynamical model predicted a somewhat above-average season in early April and a near-average season in early June and July.

Table 4: Statistical-dynamical model forecast input for the early April, early June and early July Atlantic basin seasonal hurricane forecasts for 2019.

Forecast Parameter and 1981-2010 Average (in parentheses)	Issue Date 4 April 2019	Issue Date 4 June 2019	Issue Date 9 July 2019	**Observed 2019 Activity**
Named Storms (NS) (12.1)	12.3	11.2	12.2	**18**
Named Storm Days (NSD) (59.4)	64.3	56.5	57.3	**68.5**
Hurricanes (H) (6.4)	7.3	6.5	5.9	**6**
Hurricane Days (HD) (24.2)	30.5	25.9	21.0	**23.25**
Major Hurricanes (MH) (2.7)	3.4	2.8	2.3	**3**
Major Hurricane Days (MHD) (6.2)	8.5	6.8	4.9	**10**
Accumulated Cyclone Energy (ACE) (106)	127	108	94	**130**
Net Tropical Cyclone Activity (NTC) (116%)	135	117	105	**142**

4.2 Verification of Two-Week Forecasts

This is the eleventh year that we have issued intraseasonal (e.g. two-week) forecasts of TC activity starting in early August. These two-week forecasts are based on a combination of observational and modeling tools. The primary tools that are used for these forecasts are: 1) current storm activity, 2) National Hurricane Center Tropical Weather Outlooks, 3) forecast output from global models, 4) the current and projected state of the Madden-Julian Oscillation (MJO) and 5) the current seasonal forecast.

The metric that we tried to predict with these two-week forecasts is the Accumulated Cyclone Energy (ACE) index, which is defined to be the square of a named storm's maximum wind speed (in 10^4 $knots^2$) for each 6-hour period of its existence over the two-week forecast period. These forecasts are too short in length to show significant skill for individual event parameters such as named storms and hurricanes.

Our ACE forecasts are defined by ranking observed activity in the satellite era from 1966-2016 and defining above-normal, normal and below-normal two-week periods based on terciles. Since there were 51 years from 1966-2016, each tercile is composed of 17 years. The 17 years with the most active ACE for a two-week period are classified as the upper tercile, the 17 years with the least active ACE for a two-week period are classified as the lower tercile, while the remaining 17 years are classified as the middle tercile.

Table 5 displays the six two-week forecasts that were issued during the 2019 hurricane season and shows their verification. We correctly predicted three of the six two-week periods. We did not anticipate the rapid development of Hurricane Dorian in late August. The MJO was fairly weak and disorganized during August, but it briefly amplified in phase 1 in late September, which likely aided in the development of Hurricane Lorenzo. However, this amplification of the MJO index was also likely driven by the strong positive Indian Ocean Dipole that developed around that time. The MJO became much more coherent by mid-October.

Table 5: Two-week Atlantic ACE forecast verification for 2019. Forecasts that verified in the correct category are highlighted in blue, forecasts that missed by one category are highlighted in green, while forecasts that missed by two categories are highlighted in red.

Forecast Period	Predicted ACE	Observed ACE
8/5 – 8/18	**Below-Normal (<2)**	**0**
8/19 – 9/1	**Below-Normal (<6)**	**24**
9/3 – 9/16	**Above-Normal (>35)**	**26**
9/17 – 9/30	**Above-Normal (>22)**	**51**
10/1 – 10/14	**Above-Normal (>7)**	**7**
10/15 – 10/28	**Near-Normal (1-6)**	**4**

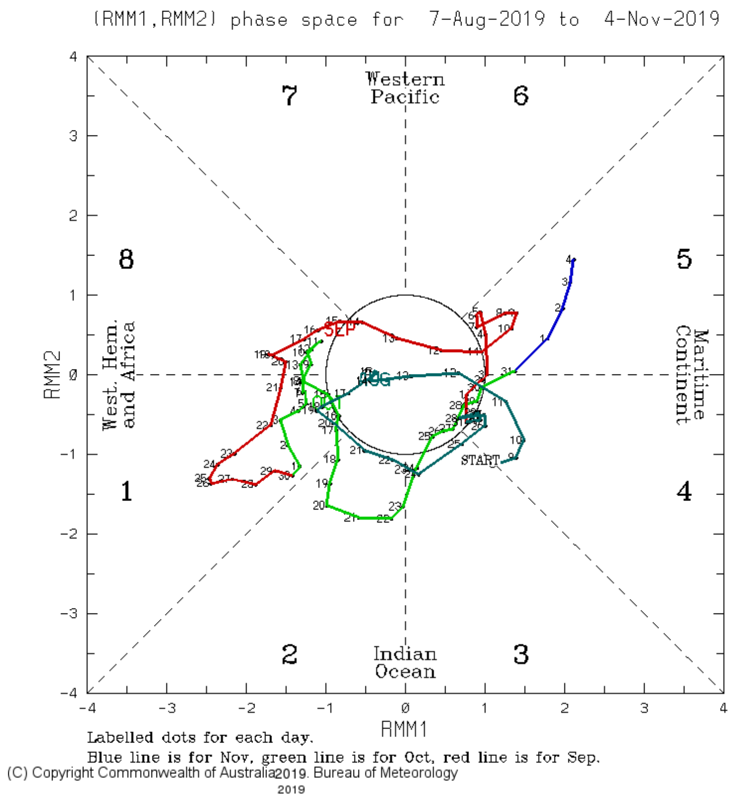


Figure 2: Propagation of the Madden-Julian Oscillation (MJO) based on the Wheeler-Hendon classification scheme over the period from August 7 to November 4. The MJO was generally weak during the peak of the Atlantic hurricane season, with lack of coherent eastward propagation until mid-October. The Maritime Continent refers to Indonesia and the surrounding islands. RMM stands for Real-Time Multivariate MJO. Figure courtesy of Bureau of Meteorology.

5 Landfall Probabilities

Every hurricane season, we issue forecasts of the seasonal probability of hurricane landfall along the US coastline as well as the Caribbean. Whereas individual hurricane landfall events cannot be accurately forecast, the net seasonal probability of landfall can be issued using past climatology and this year's forecast in combination. Our landfall probabilities have statistical skill, especially over several-year periods. With the premise that landfall is a function of varying climate conditions, US probabilities have been calculated through a statistical analysis of all US hurricane and named storm landfalls during a 100-year period (1900-1999). Specific landfall probabilities can be given for all TC intensity classes for a set of distinct US coastal regions. Net landfall probability is statistically related to overall Atlantic basin Net Tropical Cyclone (NTC) activity. Table 6 gives verifications of our landfall probability estimates for the United States and for the Caribbean in 2019.

Landfall probabilities for the 2019 hurricane season were estimated to be slightly below-average for the forecast issued in early April and were near average for the forecasts issued in early June, July and August. The 2019 Atlantic hurricane season was near average from a landfall perspective with 2 Category 1 hurricanes (Barry and Dorian) and no major hurricane hitting the continental United States. Tropical Storm Imelda also made landfall near Freeport, Texas. Average continental US landfalling statistics from 1900-1999 are that 3.5 named storms, 1.8 hurricanes and 0.7 major hurricanes make US landfall per year.

Three named storms passed through the Caribbean (10-20°N, 88-60°W) during 2019. Hurricane Dorian reached Category 1 strength before tracking north of the Caribbean. Jerry was also a Category 1 hurricane in the Caribbean. Karen was a weak tropical storm in the Caribbean.

Landfall probabilities include specific forecasts of the probability of US landfalling tropical storms (TS) and hurricanes of category 1-2 and 3-4-5 intensity for each of 11 units of the US coastline (Figure 4). These 11 units are further subdivided into 205 coastal and near-coastal counties. The climatological and current-year probabilities are available online via the Landfalling Hurricane Probability Webpage.

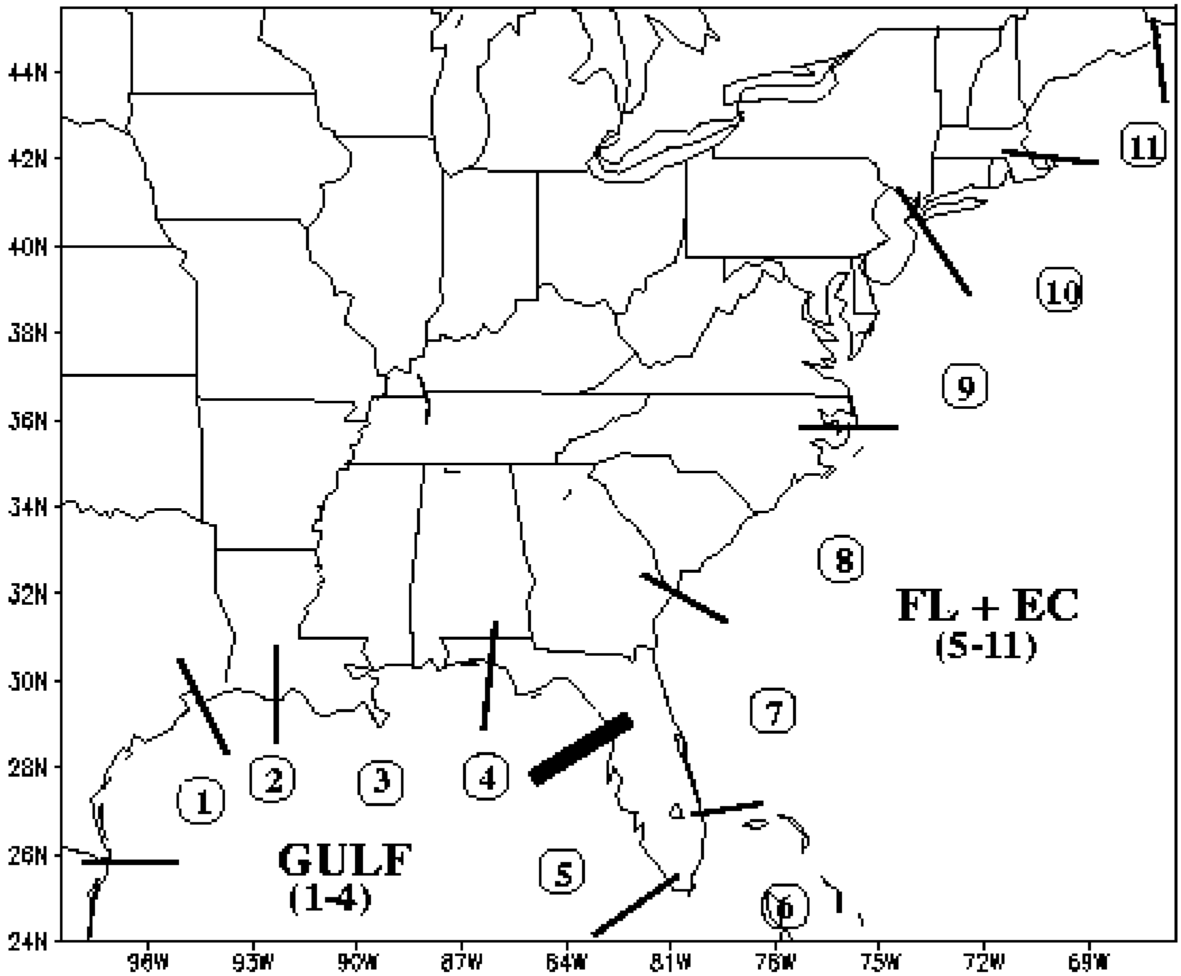


Figure 3: Location of the 11 coastal regions for which separate hurricane landfall probability estimates are made. These subdivisions were determined by the historical frequency of landfalling major hurricanes.

Table 6: Estimated forecast probability (percent) of one or more landfalling tropical storms (TS), category 1-2 hurricanes, and category 3-4-5 hurricanes, total hurricanes and named storms along the entire US coastline, along the Gulf Coast (Regions 1-4), along the Florida Peninsula and the East Coast (Regions 5-11) and in the Caribbean for 2019 at various lead times. The mean annual percentage of one or more landfalling systems during the 20th century is given in parentheses in the August forecast column. Table (a) is for the entire United States, Table (b) is for the US Gulf Coast, Table (c) is for the Florida Peninsula and the East Coast and Table (d) is for the Caribbean. Early August probabilities are calculated based on storms forming after 1 August.

(a) The entire US (Regions 1-11)

Forecast Date

	4 Apr.	5 June	5 August	Observed Number
TS	76%	81%	80% (79%)	1
HUR (Cat 1-2)	64%	69%	68% (68%)	2
HUR (Cat 3-4-5)	48%	54%	53% (52%)	0
All HUR	81%	86%	85% (84%)	2
Named Storms	95%	97%	97% (97%)	3

(b) The Gulf Coast (Regions 1-4)

Forecast Date

	4 Apr.	5 June	5 August	Observed Number
TS	55%	60%	59% (59%)	1
HUR (Cat 1-2)	39%	44%	43% (42%)	1
HUR (Cat 3-4-5)	28%	31%	31% (30%)	0
All HUR	56%	62%	60% (60%)	1
Named Storms	80%	85%	84% (83%)	2

(c) Florida Peninsula Plus the East Coast (Regions 5-11)

Forecast Date

	4 Apr.	5 June	5 August	Observed Number
TS	47%	52%	51% (50%)	0
HUR (Cat 1-2)	41%	46%	45% (44%)	1
HUR (Cat 3-4-5)	28%	32%	31% (31%)	0
All HUR	57%	63%	62% (61%)	1
Named Storms	77%	82%	81% (81%)	1

(d) Caribbean (10-20°N, 88-60°W)

Forecast Date

	4 Apr.	5 June	5 August	Observed Number
TS	79%	84%	83% (82%)	1
HUR (Cat 1-2)	53%	59%	58% (57%)	2
HUR (Cat 3-4-5)	39%	44%	43% (42%)	0
All HUR	71%	77%	76% (75%)	2
Named Storms	94%	96%	96% (96%)	3

7 Summary of Atmospheric/Oceanic Conditions

In this section, we go into detail discussing large-scale conditions that we believe significantly impacted the 2019 Atlantic basin hurricane season.

7.1 ENSO

A weak El Niño was present during the winter of 2018/2019 and with our early April and June updates, we believed that these weak El Niño conditions were likely to persist. By the time of the early August update, we believed that the odds of El Niño persisting had diminished. Overall, neutral ENSO conditions were present during the peak of the Atlantic hurricane season (August-October), although SSTs in October did reach the weak El Niño threshold in the Nino 3.4 region (e.g., >=0.5°C). Below are some quotes excerpted from our seasonal forecasts issued this year discussing our thoughts on the likely state of ENSO.

(4 April 2019) –

"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."

(5 June 2019) –

"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. 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."

(5 August 2019) –

"The official forecast from the Climate Prediction Center calls for only a ~30% chance that El Niño will persist through the peak of the Atlantic hurricane season from August-October (Figure 10). However, as noted earlier, regardless of whether the Nino 3.4 region persists in meeting the NOAA El Niño threshold of 0.5°C, we believe that the anomalous warmth in the central tropical Pacific will be a slight inhibiting factor for this year's Atlantic hurricane season."

The dynamical and statistical models initialized during the late winter/early spring generally over-predicted ENSO SSTs during the peak of the Atlantic hurricane season. Figure 4 displays the ECMWF seasonal forecast for Nino 3.4 from March, which is the forecast information that we had available for our early April seasonal forecast. The observed values was within the ensemble spread, but about 1°C below the ensemble mean. Figure 5 displays the March ENSO prediction plume from ~25 statistical and dynamical models. The observed monthly ENSO values during the Atlantic hurricane season were ~0.5°C cooler than the ensemble average during August-October.

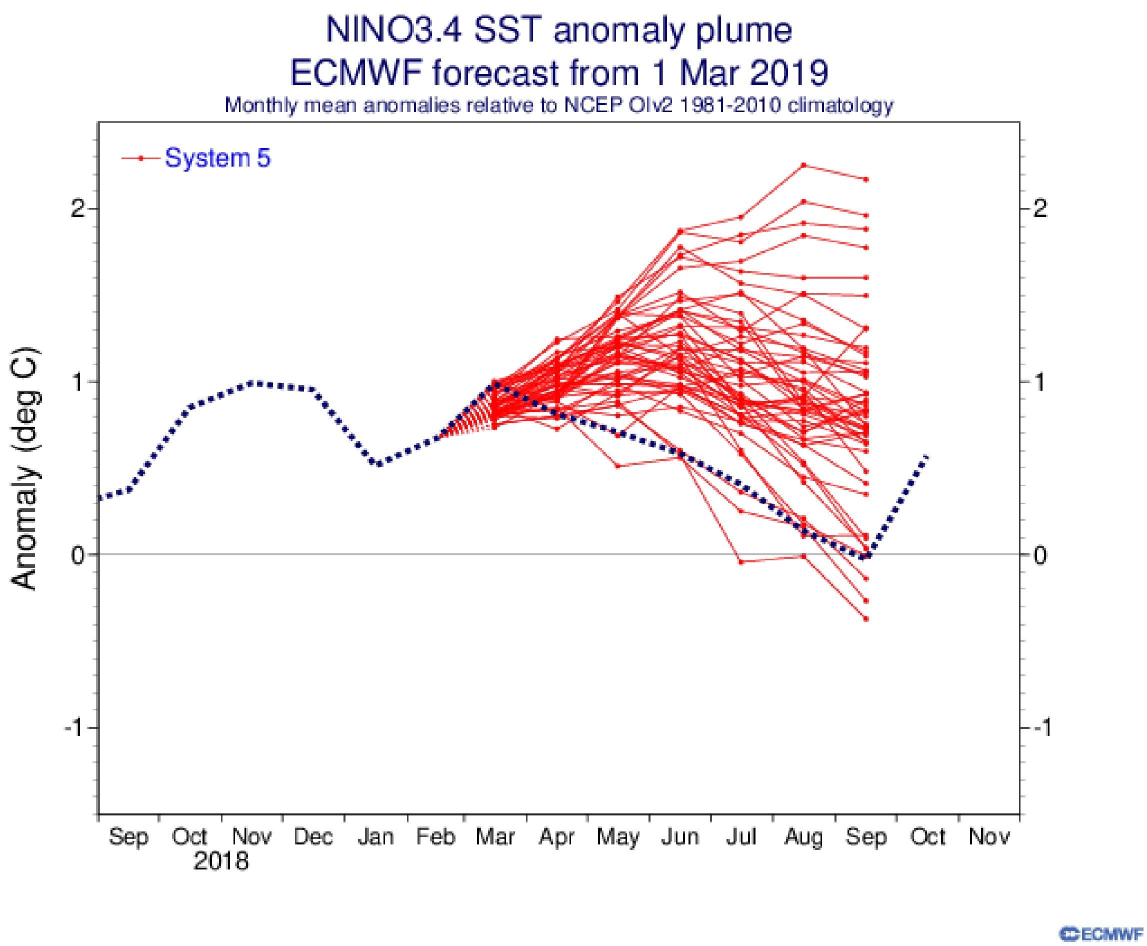


Figure 4: ECMWF ensemble prediction for Nino 3.4 from 1 March – the most recent information that we had available for our early April forecast in 2019. The blue dotted line represents the observed value.

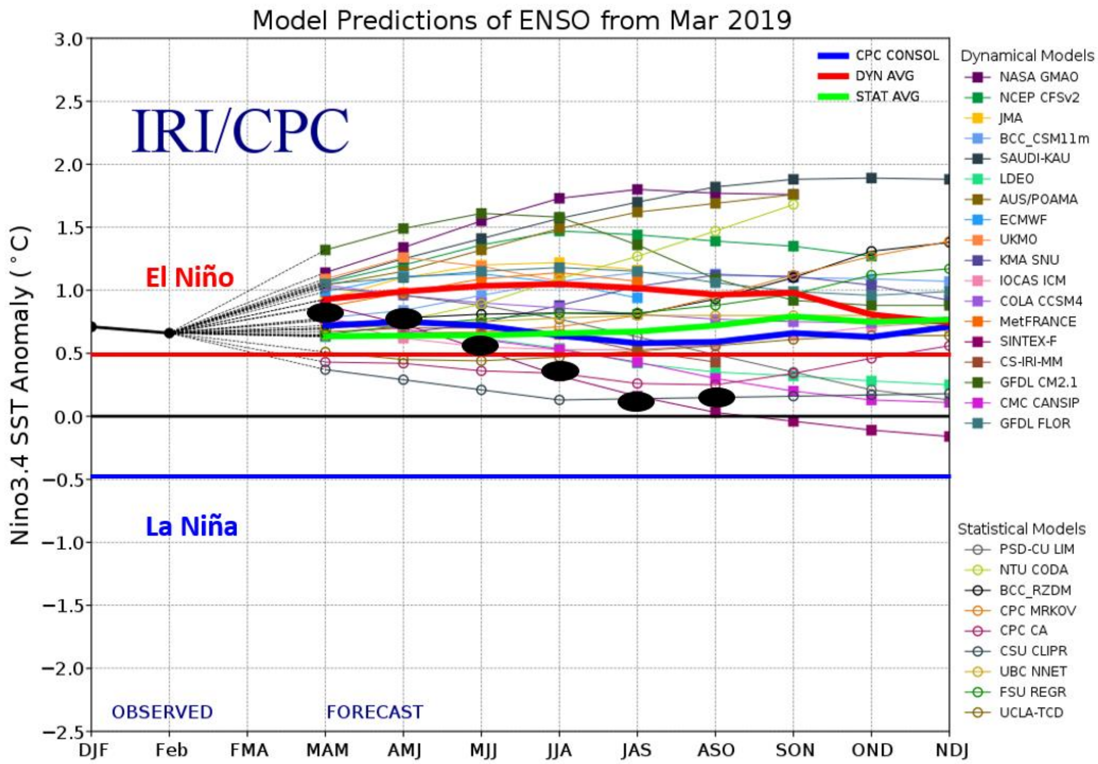


Figure 5: Ensemble prediction from ~25 statistical and dynamical models for Nino 3.4 from mid-March. Black dots represent observed values.

Weak El Niño conditions were present during the winter of 2018/2019 and the early spring of 2019 before anomalously cooling during the late spring and summer. SSTs in the central tropical Pacific have anomalously warmed in the past several weeks and have now reached the weak El Niño threshold in the Nino 3.4 region, although this anomalous warming is likely to be temporary. Table 7 displays anomalies in the various Nino regions in January, April, July and October 2019, respectively.

Table 7: January anomalies, April anomalies, July anomalies, and October anomalies for the Nino 1+2, Nino 3, Nino 3.4 and Nino 4 regions. SST anomaly differences from January 2019 are in parentheses.

Region	January 2019 Anomaly (ºC)	April 2019 Anomaly (ºC)	July 2019 Anomaly (ºC)	October 2019 Anomaly (ºC)
Nino 1+2	+0.6	+0.1 (-0.5)	-0.3 (-0.9)	-0.8 (-1.4)
Nino 3	+0.5	+0.7 (+0.2)	+0.1 (-0.4)	+0.2 (-0.3)
Nino 3.4	+0.5	+0.8 (+0.3)	+0.4 (-0.1)	+0.6 (+0.1)
Nino 4	+0.7	+0.7 (0.0)	+0.9 (+0.2)	+1.0 (+0.3)

An additional way to visualize the changes in ENSO that occurred over the past several months is to look at upper-ocean heat content anomalies in the eastern and central tropical Pacific (Figure 6). Upper-ocean heat content anomalies were well above-average in March, then dropped rapidly until mid-May. Upper ocean heat content was then quite variable but generally near-average through mid-September. Upper-ocean heat content anomalies have then increased and are now above average, although they have fallen again in the past couple of weeks.

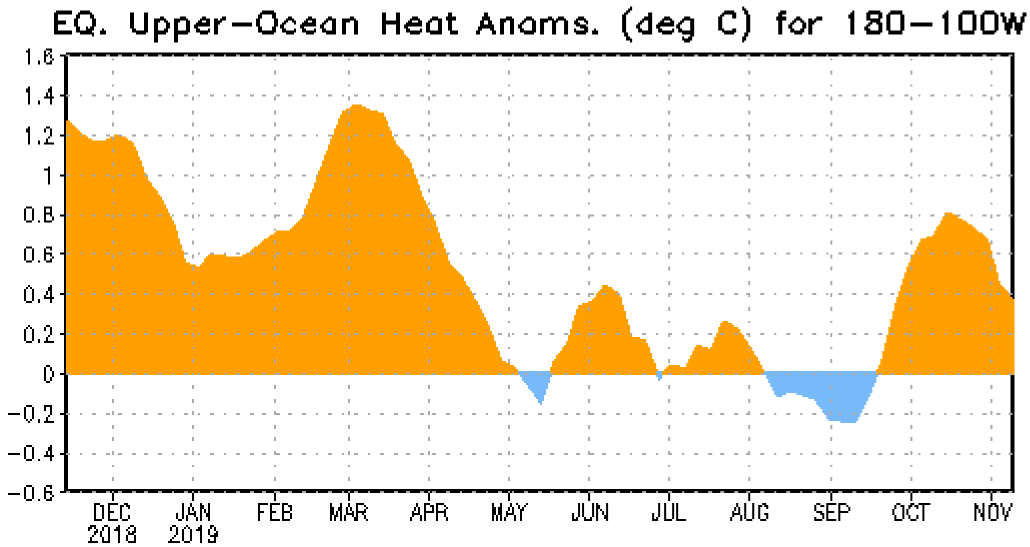


Figure 6: Upper ocean (0-300 meter) heat content anomalies in the eastern and central tropical Pacific from December 2018 – November 2019.

7.2 Intra-Seasonal Variability

The MJO was fairly weak and disorganized during August, but it did amplify in late September in phase 1 (Figure 7). This amplification likely helped fuel the development of Hurricane Lorenzo, as phase 1 is climatologically associated with more Atlantic hurricane activity (Table 8) due to decreased vertical wind shear and increased low- and mid-level moisture. The MJO has amplified in the past couple of weeks. The peak of the 2019 Atlantic hurricane season when measured by ACE was characterized by a below-average August, a well-above average September and a slightly below-average October (Figure 8).

Table 9 displays the number of storms that were first named in each phase of the MJO over the course of the 2019 Atlantic hurricane season. In general, the relationships that have previously been documented between MJO phase and Atlantic hurricane activity matched up fairly well with what was observed in 2019.

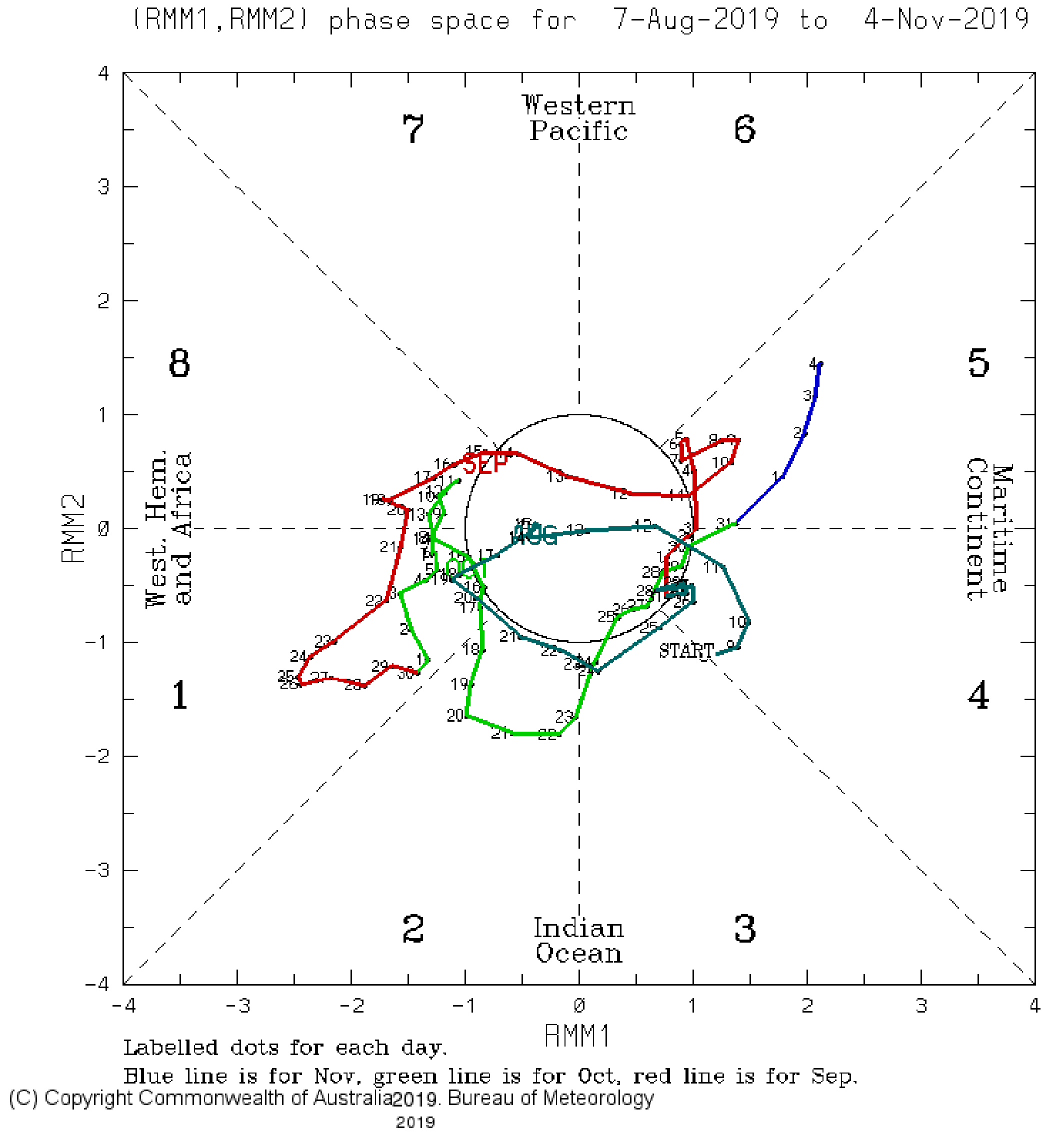


Figure 7: Propagation of the Madden-Julian Oscillation (MJO) based on the Wheeler-Hendon classification scheme over the period from August 7 to November 4. The MJO was generally weak during the peak of the Atlantic hurricane season, with amplification of the signal over the Maritime Continent and the western Pacific in October. The Maritime Continent refers to Indonesia and the surrounding islands. RMM stands for Real-Time Multivariate MJO. Figure courtesy of [Bureau of Meteorology](#).

Table 8: Normalized values of named storms (NS), named storm days (NSD), hurricanes (H), hurricane days (HD), major hurricanes (MH), major hurricane days (MHD) and Accumulated Cyclone Energy (ACE) generated by all TCs forming in each phase of the MJO over the period from 1974-2007. Normalized values are calculated by dividing storm activity by the number of days spent in each phase and then multiplying by 100. This basically provides the level of TC activity that would be expected for 100 days given a particular MJO phase.

MJO Phase	NS	NSD	H	HD	MH	MHD	ACE
Phase 1	6.4	35.9	3.7	17.9	1.8	5.3	76.2
Phase 2	7.5	43.0	5.0	18.4	2.1	4.6	76.7
Phase 3	6.3	30.8	3.0	14.7	1.4	2.8	56.0
Phase 4	5.1	25.5	3.5	12.3	1.0	2.8	49.4
Phase 5	5.1	22.6	2.9	9.5	1.2	2.1	40.0
Phase 6	5.3	24.4	3.2	7.8	0.8	1.1	35.7
Phase 7	3.6	18.1	1.8	7.2	1.1	2.0	33.2
Phase 8	6.2	27.0	3.3	10.4	0.9	2.6	46.8
Phase 1-2	7.0	39.4	4.3	18.1	1.9	4.9	76.5
Phase 6-7	4.5	21.5	2.5	7.5	1.0	1.5	34.6
Phase 1-2 / Phase 6-7	1.6	1.8	1.7	2.4	2.0	3.2	2.2

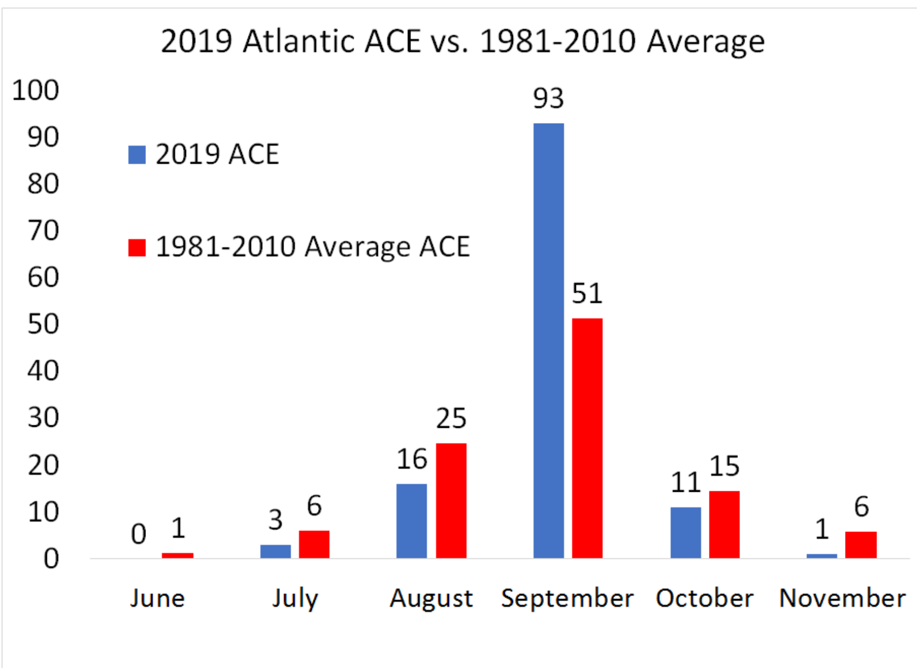


Figure 8: Atlantic Accumulated Cyclone Energy generated by month during the 2019 Atlantic hurricane season through November 19.

Table 9: TC formations by MJO phase during the 2019 Atlantic hurricane season.

MJO Phase	TC Formations
1	3
2	2
3	3
4	2
5	2
6	0
7	1
8	5

7.3 Atlantic SST

One of the reasons that the early seasonal forecasts called for slightly below-average Atlantic hurricane activity was due to slightly below- to near-average tropical Atlantic SST conditions during March (Figure 9).

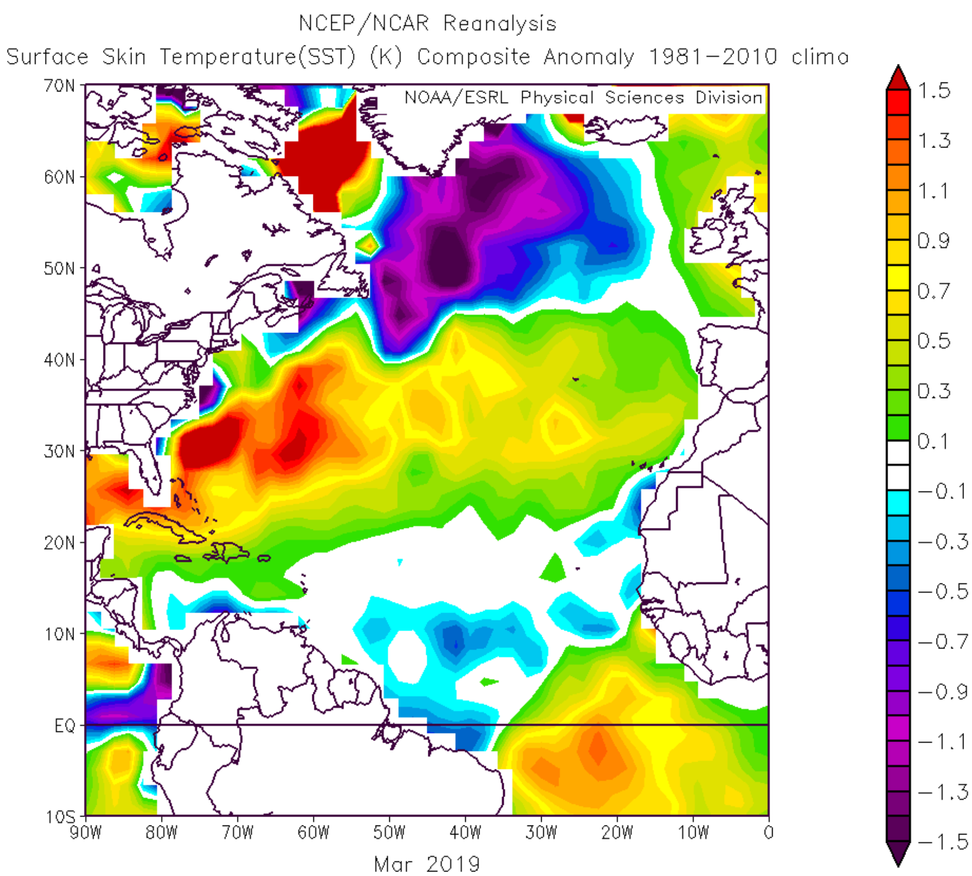


Figure 9: March 2019 SST anomaly pattern across the North Atlantic Ocean.

A similar SST anomaly pattern was evident at the time of CSU's next forecast issued in early June (Figure 10), with slightly-below to near-average SSTs present across the tropical Atlantic.

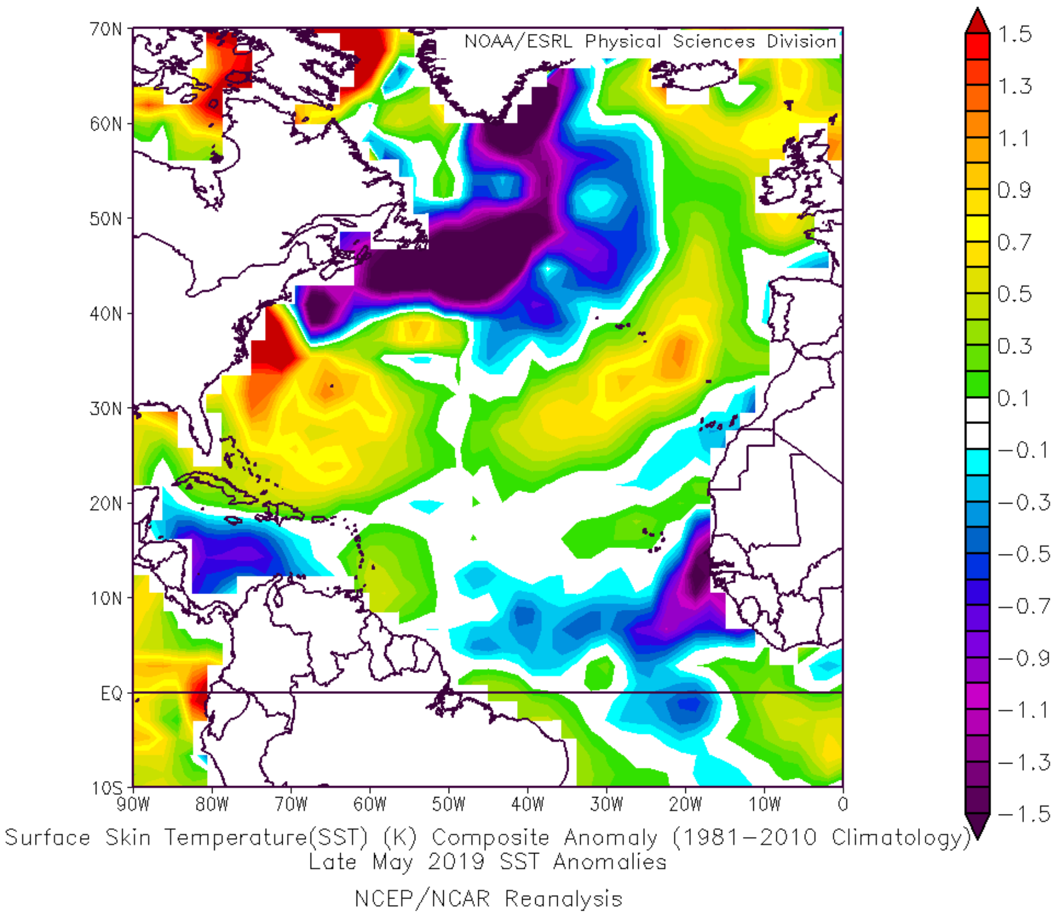


Figure 10: Late May 2019 minus late March 2019 SST anomaly change across the North Atlantic.

While cold SST anomalies persisted right off of the coast of west Africa by the end of July, considerable anomalous warming occurred elsewhere in the tropical Atlantic (Figure 11). The Main Development Region (MDR), which we define to be 10-20°N, 60-20°W, was 0.1°C above the 1981-2010 MDR average for July.

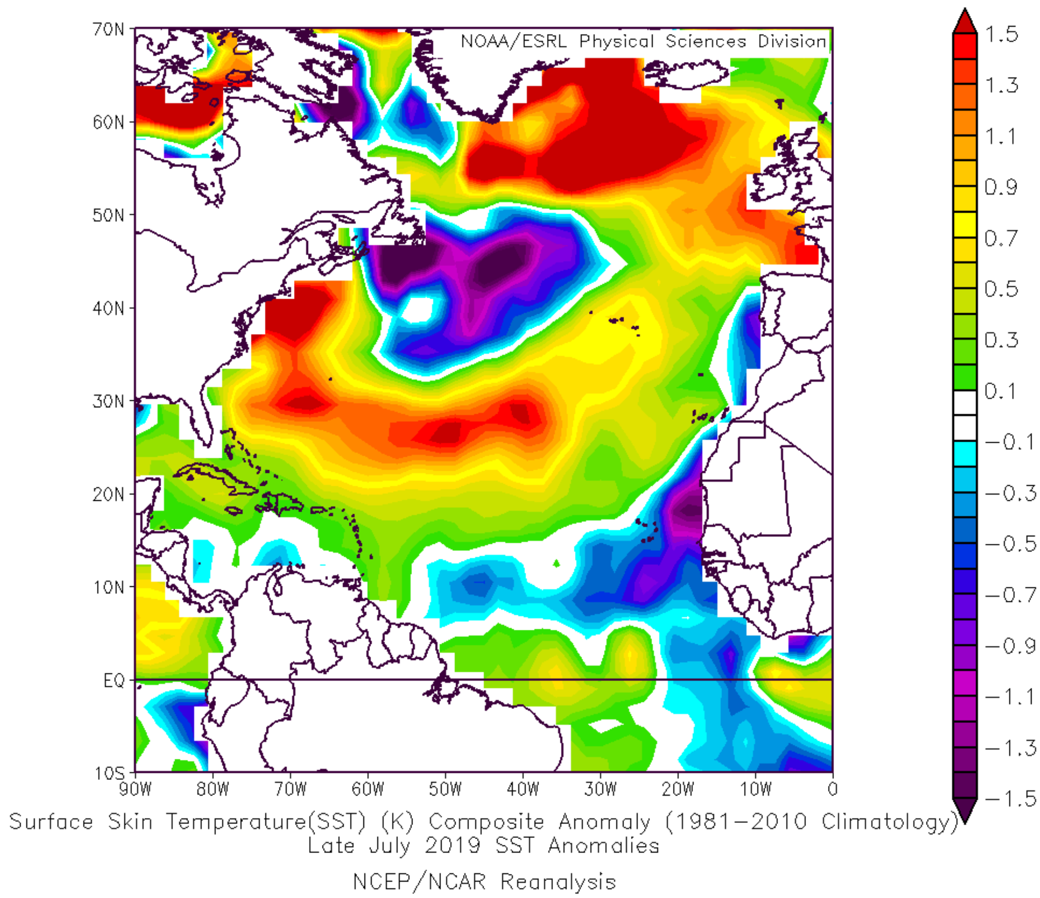


Figure 11: Late July 2019 SST anomalies.

SST anomalies continued to increase from late July through the peak of the Atlantic hurricane season. MDR-averaged SST anomalies were 0.3°C above the 1981-2010 average during September (Figure 12).

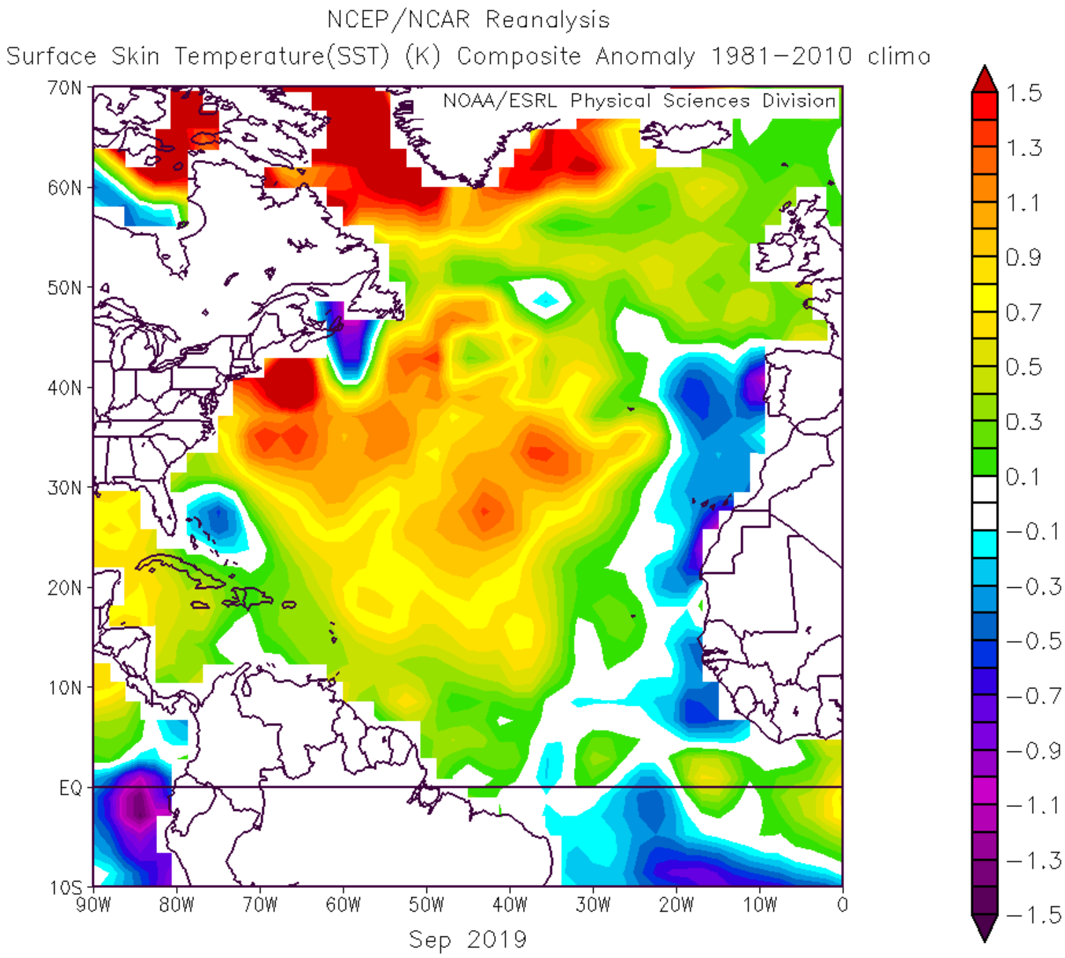


Figure 12: September 2019 SST anomalies.

7.4 Tropical Atlantic SLP

Tropical Atlantic sea level pressure values are another important parameter to consider when evaluating likely TC activity in the Atlantic basin. In general, lower sea level pressures across the tropical Atlantic imply increased instability, increased low-level moisture, and conditions that are generally favorable for TC development and intensification. The August-October portion of the 2019 Atlantic hurricane season was characterized by slightly below-normal sea level pressures across the tropical Atlantic and Caribbean (Figure 13), in line with the slightly above-average hurricane season that occurred.

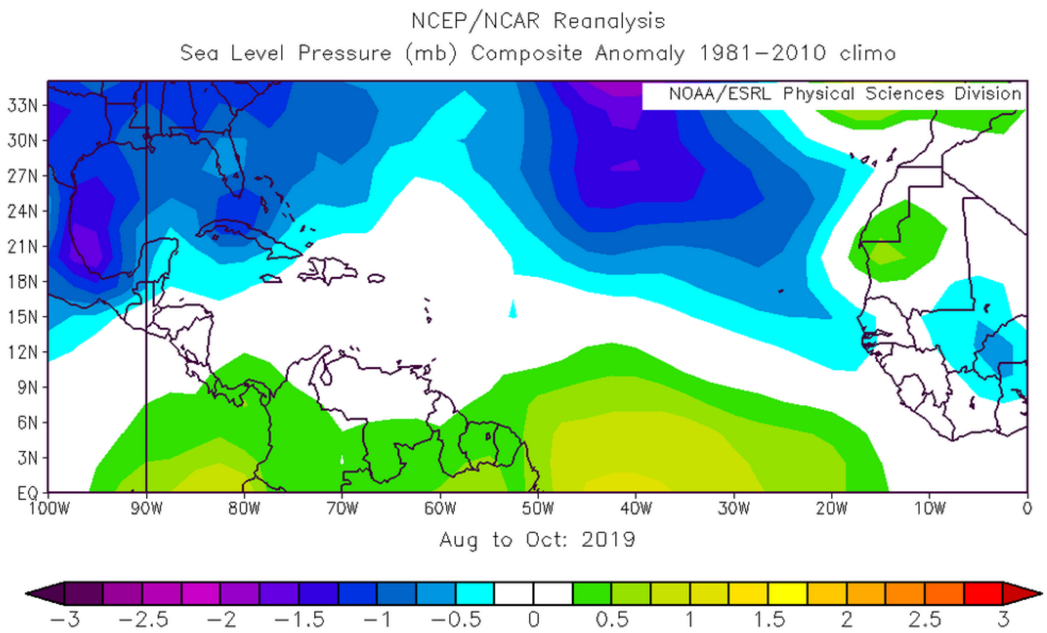


Figure 13: August-October 2019 tropical and sub-tropical North Atlantic sea level pressure anomalies.

7.5 Tropical Atlantic Vertical Wind Shear

During the two-month peak of the Atlantic season from mid-August to mid-October, wind shear anomalies were below-normal across the Caribbean and tropical Atlantic, as highlighted in the green box (Figure 14). Below-normal vertical wind shear is typically associated with above-average Atlantic hurricane seasons. These favorable wind shear conditions were likely one of the reasons why the 2019 Atlantic hurricane season was more active than normal.

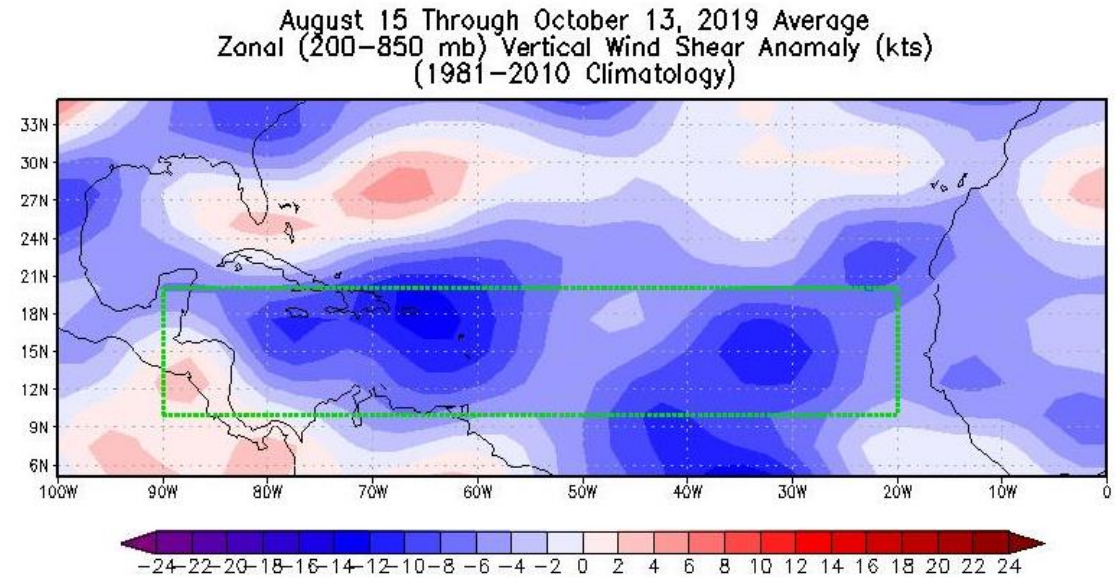


Figure 14: Anomalous vertical wind shear observed across the Atlantic from mid-August to mid-October. The green box represents the Caribbean basin.

7.6 Steering Currents

The steering currents in August-October 2019 were characterized by an anomalous mid-level high pressure zone located along the east coast of the United States (compared to the 2006-2016 period of the US major hurricane landfall drought) (Figure 15). There was an anomalous mid-level low pressure area located between 40-60°W that likely aided in recurvature of most of the named storms that formed in the tropical Atlantic prior to reaching the US mainland in 2019.

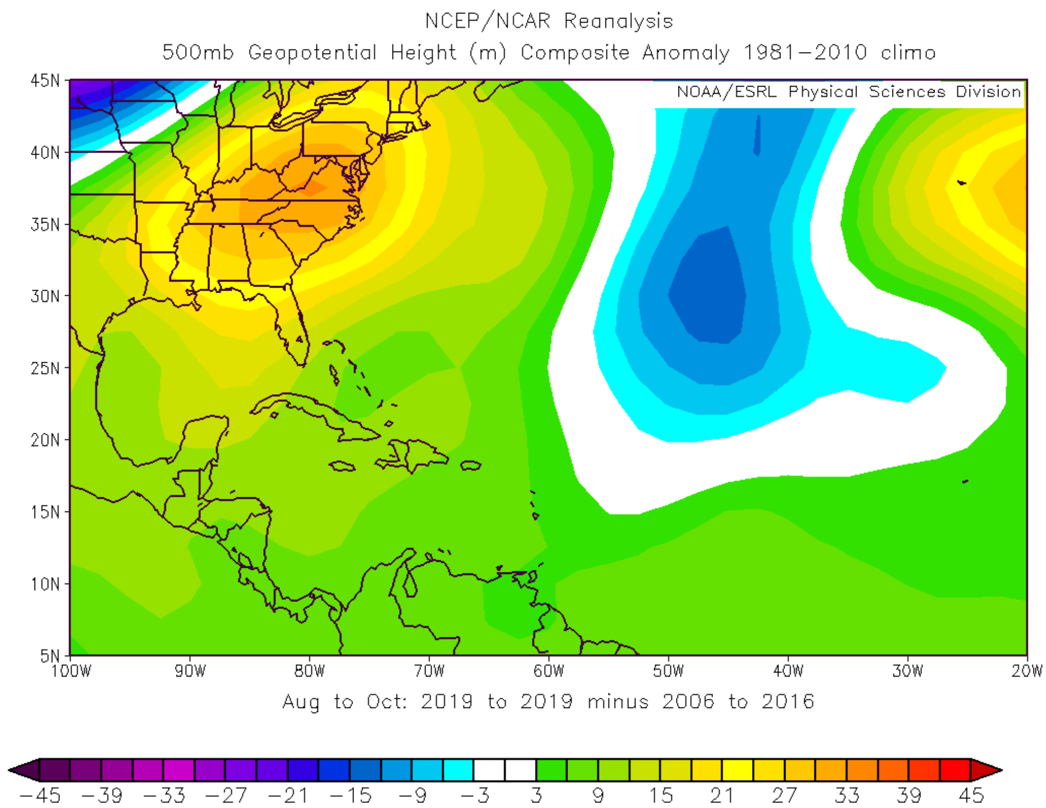


Figure 15: 500-mb height in the central and western part of the Atlantic from August to October in 2019 differenced from the August-October 2006 to 2016 period.

7.7 Atlantic Multi-Decadal Oscillation (AMO) Status

One of the big questions that has been raised in recent years has been: are we moving out of the active era? We addressed this question in an article published in *Nature Geoscience* (Klotzbach et al. 2015). Following three below-average Atlantic hurricane seasons from 2013-2015, the past four seasons (2016-2019) have all met the NOAA definition of an above-average Atlantic hurricane season, with 2017 being a hyperactive season.

We monitor the strength of the AMO in real-time through an index that combines SSTs measured from (50-60°N, 50-10°W) as well as SLPs measured from (0-50°N, 70-10°W) (Figure 16). This index was low throughout the first half of 2019 but has been above-average since June (Figure 17), due both to anomalously warm SSTs in the far North Atlantic and anomalously low sea level pressures across the tropical and subtropical Atlantic.

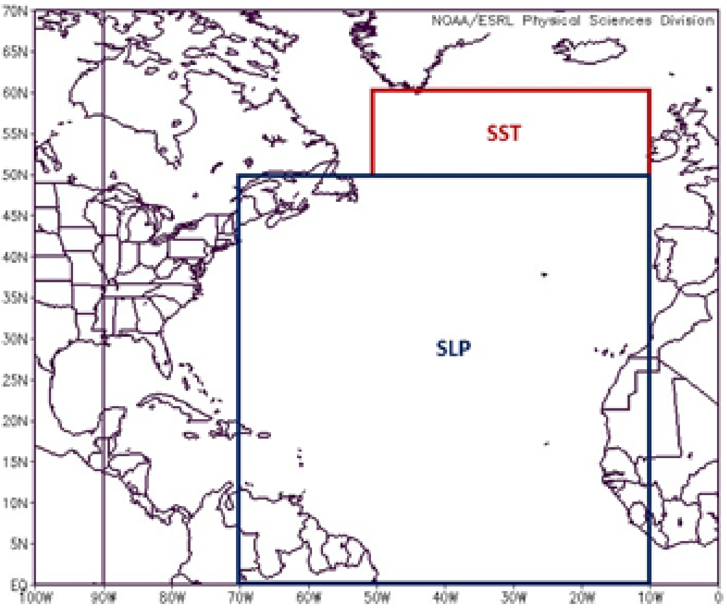


Figure 16: Regions which are utilized for the calculation of our AMO index.

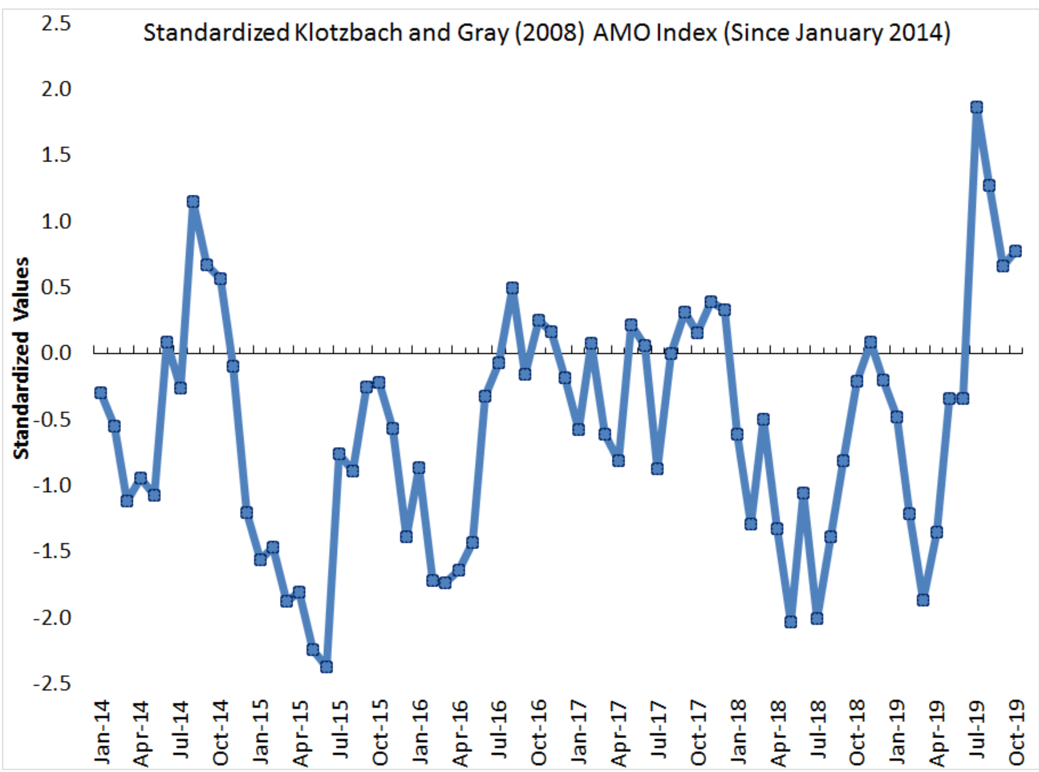


Figure 17: Standardized values of the AMO index by month since January 2014. The index was below normal for the first half of 2019 and has since been positive.

8 Forecasts of 2020 Hurricane Activity

We will be issuing our first outlook for the 2020 hurricane season on Thursday, 12 December 2019. This forecast will provide a qualitative outlook for factors likely to impact the 2020 hurricane season. This December forecast will include the dates of all of our updated 2020 forecasts. All of these forecasts will be made available online.

9 Verification of Previous Forecasts

Table 10: Verification of the authors' early August forecasts of Atlantic named storms and hurricanes between 1984-2019. Observations only include storms that formed after 1 August. Note that these early August forecasts have either exactly verified or forecasted the correct deviation from climatology in 30 of 36 years for named storms and 28 of 36 years for hurricanes. If we predict an above- or below-average season, it tends to be above or below average, even if our exact forecast numbers do not verify.

Year	Predicted NS	Observed NS	Predicted H	Observed H
1984	10	12	7	5
1985	10	9	7	6
1986	7	4	4	3
1987	7	7	4	3
1988	11	12	7	5
1989	9	8	4	7
1990	11	12	6	7
1991	7	7	3	4
1992	8	6	4	4
1993	10	7	6	4
1994	7	6	4	3
1995	16	14	9	10
1996	11	10	7	7
1997	11	3	6	1
1998	10	13	6	10
1999	14	11	9	8
2000	11	14	7	8
2001	12	14	7	9
2002	9	11	4	4
2003	14	12	8	5
2004	13	14	7	9
2005	13	20	8	12
2006	13	7	7	5
2007	13	12	8	6
2008	13	12	7	6
2009	10	9	4	3
2010	16	17	9	11
2011	12	15	9	7
2012	10	15	5	9
2013	14	9	8	2
2014	9	7	3	5
2015	5	8	2	4
2016	15	15	6	7
2017	11	12	8	10
2018	9	12	3	6
2019	12	16	6	5
Average	**10.9**	**10.9**	**6.1**	**6.1**
1984-2019 Correlation		**0.61**		**0.52**

Table 10: 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	27.50
Named Storm Days	70	55	45	53	86.75
Major Hurricanes	3	2	1	1	2
Major Hurricane Days	7	4	2	2	5.25
Accumulated Cyclone Energy	130	90	60	64	133
Net Tropical Cyclone Activity	135	100	70	78	129