SUMMARY OF 2018 ATLANTIC TROPICAL CYCLONE ACTIVITY AND VERIFICATION OF AUTHORS' SEASONAL AND TWO-WEEK FORECASTS

The 2018 Atlantic hurricane season was slightly above average and had more activity than what was predicted by our later updates. The climatological peak months of the hurricane season were characterized by an extremely quiet August, a very active early September, near-average hurricane activity for the second half of September and an active October. Two hurricanes brought death and devastation to the United States. Hurricane Florence's primary impacts were heavy rainfall, while Hurricane Michael was a powerful Category 4 hurricane that brought incredible levels of damage to portions of the Florida Panhandle.

By Philip J. Klotzbach[1] and Michael M. Bell[2]

In Memory of William M. Gray[3]

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 28 November 2018

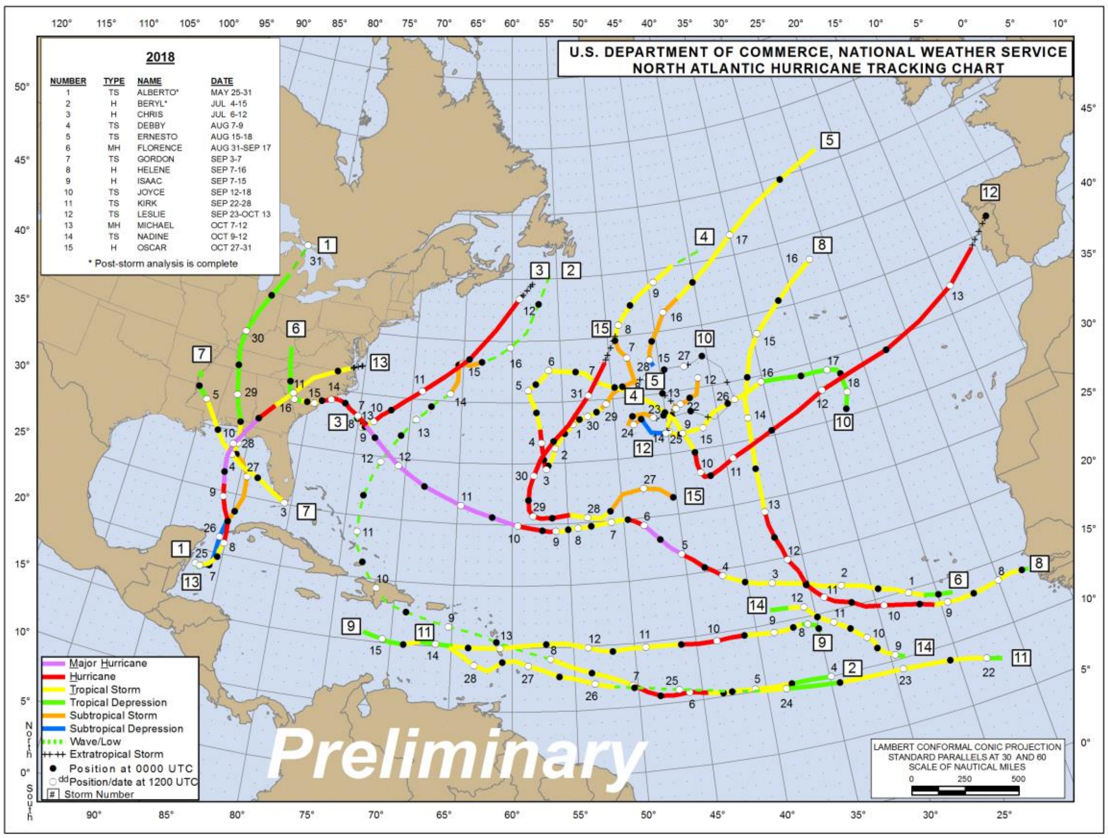
Project Sponsors:

Interstate
IRONSHORE
Insurance Information Institute
WEATHERBOY.COM

[1] Research Scientist
[2] Associate Professor
[3] Professor Emeritus of Atmospheric Science

ATLANTIC BASIN SEASONAL HURRICANE FORECASTS FOR 2018

Forecast Parameter and 1981-2010 Median (in parentheses)	Issue Date 5 April 2018	Issue Date 31 May 2018	Issue Date 2 July 2018	Issue Date 2 August 2018	**Observed 2018 Activity**	% of 1981-2010 Median
Named Storms (NS) (12.0)	14	14	11	12	**15**	125%
Named Storm Days (NSD) (60.1)	70	55	45	53	**87.25**	145%
Hurricanes (H) (6.5)	7	6	4	5	**8**	123%
Hurricane Days (HD) (21.3)	30	20	15	15	**26.75**	125%
Major Hurricanes (MH) (2.0)	3	2	1	1	**2**	100%
Major Hurricane Days (MHD) (3.9)	7	4	2	2	**5.00**	128%
Accumulated Cyclone Energy (ACE) (92)	130	90	60	64	**129**	140%
Net Tropical Cyclone Activity (NTC) (103%)	135	100	70	78	**128**	124%



Atlantic basin tropical cyclone tracks in 2018. 15 named storms, 8 hurricanes and 2 major hurricanes occurred. Figure courtesy of the National Hurricane Center.

ABSTRACT

This report summarizes tropical cyclone (TC) activity which occurred in the Atlantic basin during 2018 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 2018 was issued on 5 April with updates following on 31 May, 2 July and 2 August. These seasonal forecasts also contained estimates of the probability of US and Caribbean hurricane landfall during 2018.

The 2018 hurricane season overall was slightly above average. The season was characterized by above-average numbers of named storms and hurricanes and near-average numbers of major hurricanes. Our initial seasonal forecast issued in April correctly predicted a slightly above-average season, while later seasonal forecasts underestimated Atlantic hurricane activity. These downward adjustments were primarily due to anomalous tropical Atlantic SST cooling. Despite a relatively cold tropical Atlantic, early September 2018 was extremely active and was the primary driver of the slightly above-average season that occurred. In addition, six of the fifteen named storms that formed in 2018 were initially classified as subtropical, and these types of systems that form in the subtropics do not respond to large-scale tropical climate drivers in the same way that TCs forming in the tropics do.

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 generally verified well, although the extremely active early September was underestimated by the two-week forecasts.

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 cooler than normal during the peak of the 2018 hurricane season. Caribbean shear was very strong, which likely was responsible for the lack of activity observed in this region. However, shear was slightly below normal in the eastern part of the Atlantic, favoring TC formations in the eastern and central tropical Atlantic.

The 2018 Atlantic hurricane season will primarily be known for two hurricanes that brought significant damage and loss of life to the continental United States. Hurricane Florence made landfall as a Category 1 hurricane, but like Harvey last year, the storm then slowed considerably, bringing record flooding to portions of North and South Carolina. Hurricane Michael made landfall as a Category 4 hurricane in the Florida Panhandle, bringing devastating wind and storm surge damage..

DEFINITIONS AND ACRONYMS

Accumulated Cyclone Energy (ACE) - A measure of a named storm's potential for wind and storm surge destruction defined as the sum of the square of a named storm's maximum wind speed (in 10^4 knots^2) for each 6-hour period of its existence. The 1950-2000 average value of this parameter is 96 for the Atlantic basin.

Atlantic Multi-Decadal Oscillation (AMO) – A mode of natural variability that occurs in the North Atlantic Ocean and evidencing itself in fluctuations in sea surface temperature and sea level pressure fields. The AMO is likely related to fluctuations in the strength of the oceanic thermohaline circulation. Although several definitions of the AMO are currently used in the literature, we define the AMO based on North Atlantic sea surface temperatures from 50-60°N, 50-10°W and sea level pressure from 0-50°N, 70-10°W.

Atlantic Basin – The area including the entire North Atlantic Ocean, the Caribbean Sea, and the Gulf of Mexico.

El Niño – A 12-18 month period during which anomalously warm sea surface temperatures occur in the eastern half of the equatorial Pacific. Moderate or strong El Niño events occur irregularly, about once every 3-7 years on average.

Hurricane (H) - A tropical cyclone with sustained low-level winds of 74 miles per hour (33 ms^{-1} or 64 knots) or greater.

Hurricane Day (HD) - A measure of hurricane activity, one unit of which occurs as four 6-hour periods during which a tropical cyclone is observed or is estimated to have hurricane-force winds.

Indian Ocean Dipole (IOD) - An irregular oscillation of sea surface temperatures between the western and eastern tropical Indian Ocean. A positive phase of the IOD occurs when the western Indian Ocean is anomalously warm compared with the eastern Indian Ocean.

Madden Julian Oscillation (MJO) – A globally propagating mode of tropical atmospheric intra-seasonal variability. The wave tends to propagate eastward at approximately 5 ms^{-1}, circling the globe in roughly 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, the Insurance Information Institute, Weatherboy and Ironshore Insurance that partially support the release of these predictions. We thank the GeoGraphics Laboratory at Bridgewater State University (MA) for their assistance in developing the United States Landfalling Hurricane Probability Webpage.

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, Brian McNoldy, Paul Roundy, Jason Dunion, Mike Ventrice, 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 just 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 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 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 20th Century Reanalysis from the Earth System Research Laboratory. The ERA5 reanalysis dataset will be available in a couple of months and will provide a ~70-year reanalysis that will be at a much higher resolution with a more robust data assimilation scheme then was available when the NCEP/NCAR reanalysis was run ~20 years ago.

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 were 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 relatively little 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 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 result.

2 Tropical Cyclone Activity for 2018

Figure 1 and Table 1 summarize Atlantic basin TC activity which occurred in 2018. 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

2018. The National Hurricane Center is also currently in the process of writing up extensive reports on all 2018 TCs.

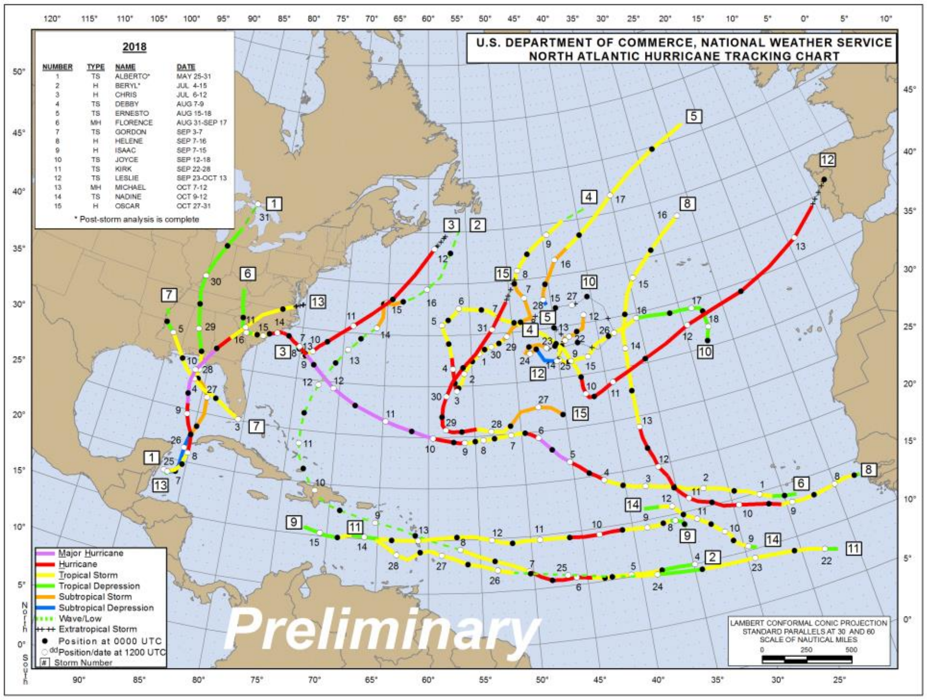


Figure 1: Atlantic basin TC tracks in 2018. 15 named storms, 8 hurricanes and 2 major hurricanes occurred. Figure courtesy of the National Hurricane Center.

Real-Time North Atlantic Ocean Statistics by Storm for 2018

Year	Storm#	Name	Dates TC Active	Max Wind (kts)	MSLP (mb)	Named Storm Days	Hurricane Days	Major Hurricane Days	Accumulated Cyclone Energy
2018	1	ALBERTO	5/25-5/28	55	990	3.50	0.00	0.00	2.4
2018	2	BERYL	7/5-7/15	70	994	5.25	1.25	0.00	4.9
2018	3	CHRIS	7/8-7/12	90	970	4.25	2.00	0.00	7.1
2018	4	DEBBY	8/7-8/9	45	1000	2.50	0.00	0.00	1.5
2018	5	ERNESTO	8/15-8/18	40	999	2.75	0.00	0.00	1.6
2018	6	FLORENCE	9/1-9/16	120	941	15.00	8.00	3.75	37.5
2018	7	GORDON	9/3-9/5	60	999	2.00	0.00	0.00	2.1
2018	8	HELENE	9/8-9/16	95	966	8.50	3.75	0.00	15.5
2018	9	ISAAC	9/8-9/14	65	993	5.75	1.00	0.00	6.4
2018	10	JOYCE	9/12-9/16	45	997	4.00	0.00	0.00	2.4
2018	11	KIRK	9/22-9/28	50	998	4.50	0.00	0.00	3.0
2018	12	LESLIE	9/23-10/13	80	969	16.50	5.00	0.00	20.9
2018	13	MICHAEL	10/7-10/12	135	919	4.75	2.75	1.25	12.4
2018	14	NADINE	10/9-10/12	55	997	3.25	0.00	0.00	2.7
2018	15	OSCAR	10/27-10/31	90	970	4.75	3.00	0.00	8.6

Table 1: Observed 2018 Atlantic basin TC activity.

3 Special Characteristics of the 2018 Hurricane Season

The 2018 hurricane season ended up slightly above average. While the season was slightly above-average for overall basin activity, it was characterized by an extremely quiet August followed by an extremely active first half of September. Hurricanes Florence and Michael also were notable continental US hurricane landfalls that set several records.

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

- 87.25 named storm days occurred in the Atlantic basin in 2018. The Atlantic has had 80+ named storm days for three years in a row (2016-2018). The last time that the Atlantic had 80+ named storm days in three consecutive years was 2003-2005.

- 7 of the Atlantic named storms that formed in 2018 were classified as subtropical at some point during their lifetime. The prior record for subtropical storms in a single season was 5 set in 1969.

- 0 Atlantic named storm formations in August 2018 south of 30°N. This is the first time that this has occurred since 1997.

- 5 Atlantic named storms developed between September 1-12 – tied with 1988 for the most Atlantic named storms on record to form between September 1-12.

- 63 Accumulated Cyclone Energy units were generated in the Atlantic between September 1-15. This is the 5th most ACE during the first half of September in the satellite era (since 1966) – trailing (in order from highest to 4th highest): 2017, 2004, 2003, and 1995.

- 3 Category 4 hurricanes have made continental US landfall in the past two years: Harvey, Irma, and Michael. This is the most continental US Category 4+ hurricane landfalls in a two-year span on record.

- Hurricane Beryl was first named at 10.1°N, 38°W on July 5 – the furthest southeast that an Atlantic named storm has formed that early in the season on record.

- The Atlantic had three hurricanes simultaneously on September 10: Florence, Helene and Isaac. This is the 11th year on record that the Atlantic has had three hurricanes simultaneously.

- The Atlantic generated 31 named storm days between September 1-14 – trailing only 1964 (which had 32 named storm days) for the most Atlantic named storm days during the first two weeks of September on record.

- Hurricane Florence broke statewide rainfall records from a TC for both North and South Carolina. The new record for North Carolina is 35.93" while the old record was 24.06" from Hurricane Floyd in 1999. The new record for South Carolina is 23.63" while the old record was 18.51" from Tropical Storm Jerry in 1995.

- Hurricane Michael was the first Category 4 hurricane to make landfall in the Florida Panhandle on record.

- Hurricane Michael's landfall pressure of 919 mb was the third lowest for a continental US hurricane landfall on record, trailing only the Labor Day Hurricane of 1935 (892 mb at landfall) and Hurricane Camille of 1969 (900 mb at landfall).

- Hurricane Michael's landfalling one-minute sustained wind of 135 knots was the fourth highest for a continental US landfall on record, trailing only the Labor Day Hurricane of 1935 (160 knots), Hurricane Camille (150 knots), and Hurricane Andrew (145 knots).

- Hurricane Leslie was a named storm for 16.5 days – the longest-lived named storm of the entire 2018 Northern Hemisphere hurricane season to date (through November).

4 Verification of Individual 2018 Lead Time Forecasts

Table 2 is a comparison of our forecasts for 2018 for four different lead times along with this year's observations. The 2018 Atlantic hurricane season was slightly above average.

Table 2: Verification of our 2018 seasonal hurricane predictions.

Forecast Parameter and 1981-2010 Median (in parentheses)	Issue Date 5 April 2018	Issue Date 31 May 2018	Issue Date 2 July 2018	Issue Date 2 August 2018	**Observed 2018 Activity**	% of 1981-2010 Median
Named Storms (NS) (12.0)	14	14	11	12	**15**	125%
Named Storm Days (NSD) (60.1)	70	55	45	53	**87.25**	145%
Hurricanes (H) (6.5)	7	6	4	5	**8**	123%
Hurricane Days (HD) (21.3)	30	20	15	15	**26.75**	125%
Major Hurricanes (MH) (2.0)	3	2	1	1	**2**	100%
Major Hurricane Days (MHD) (3.9)	7	4	2	2	**5.00**	128%
Accumulated Cyclone Energy (ACE) (92)	130	90	60	64	**129**	140%
Net Tropical Cyclone Activity (NTC) (103%)	135	100	70	78	**128**	124%

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 seasonal forecast correctly anticipated a slightly above-average season, while later forecasts underestimated overall activity that was observed.

Table 3: Verification of CSU's 2018 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. In general, we expect that two-thirds of our forecasts should lie within one standard deviation of observations, with 95% of our forecasts lying within two standard deviations of observations. 17 out of 32 (53%) of seasonal forecast parameters were within one standard deviation of observations for the 2018 seasonal forecast. Unlike what we typically expect for our seasonal forecasts, the April forecast was the most skillful of our predictions issued in 2018. As discussed throughout the text of this season's verification, we underestimated overall levels of hurricane activity that occurred with our later forecasts. Error bars for storms are rounded to the nearest storm. For example, the hurricane prediction in early April would be 4.9-9.1, which with rounding would be 5-9.

Forecast Parameter and 1981-2010 Median (in parentheses)	5 April 2018	Update 31 May 2018	Update 2 July 2018	Update 2 August 2018	Observed 2018 Total
Named Storms (NS) (12.0)	**14** (±3.5)	**14** (±2.9)	**11** (±2.6)	**12** (±2.2)	15
Named Storm Days (NSD) (60.1)	**70** (±20.7)	**55** (±19.9)	**45** (±18.1)	**53** (±16.3)	87.25
Hurricanes (H) (6.5)	**7** (±2.1)	**6** (±2.0)	**4** (±1.8)	**5** (±1.7)	8
Hurricane Days (HD) (21.3)	**30** (±11.1)	**20** (±10.7)	**15** (±10.1)	**15** (±9.5)	26.75
Major Hurricanes (MH) (2.0)	**3** (±1.3)	**2** (±1.4)	**1** (±1.2)	**1** (±0.9)	2
Major Hurricane Days (MHD) (3.9)	**7** (±4.0)	**4** (±3.7)	**2** (±3.9)	**2** (±4.1)	5.00
Accumulated Cyclone Energy (ACE) (92)	**130** (±42)	**90** (±40)	**60** (±36)	**64** (±31)	129
Net Tropical Cyclone Activity (NTC) (103%)	**135** (±42)	**100** (±40)	**70** (±36)	**78** (±31)	128

4.1 Preface: Aggregate Verification of our Last Twenty Yearly Forecasts

Another way to consider the skill of our forecasts is to evaluate whether the forecast for each parameter successfully forecast above- or below-average activity. Table 4 displays how frequently our forecasts have been on the right side of climatology for the past twenty years. In general, our forecasts are successful at forecasting whether the season will be more or less active than the average season by as early as April. We tend to have improving skill as we get closer in time to the peak of the hurricane season (August-October), although the April forecast issued in 2018 was the most skillful.

Table 4: The number of years that our TC forecasts issued at various lead times have correctly predicted above- or below-median activity for each predictand over the past twenty years (1999-2018).

Tropical Cyclone Parameter	Early April	Early June	Early August
NS	16/20	18/20	17/20
NSD	14/20	13/20	14/20
H	14/20	13/20	14/20
HD	12/20	13/20	15/20
MH	15/20	15/20	16/20
MHD	14/20	15/20	15/20
NTC	12/20	14/20	16/20
Total	**97/140 (69%)**	**101/140 (72%)**	**107/140 (76%)**

Of course, there are significant amounts of unexplained variance for a number of the individual parameter forecasts. Even though the skill for some of these parameter forecasts is somewhat low, there is a great curiosity in having some objective measure as to how active the coming hurricane season is likely to be. Therefore, even a forecast that is only modestly skillful is likely of some value. In addition, we have recently redesigned all of our statistical forecast methodologies using more rigorous physical and statistical tests which we believe will lead to more accurate forecasts in the future. Complete verifications of all seasonal forecasts are available. Verifications are currently available for all of our prior seasons from 1984-2017. These tables will be updated with 2018's values once the National Hurricane Center finishes its post-season analysis of all storms that formed this year.

4.2 Verification of Two-Week Forecasts

This is the tenth 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 the named storm's maximum wind speeds (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 forecast definition of above-normal, normal, and below-normal ACE periods was changed last season to better fit, in our view, the observed historical distributions. Our ACE forecasts are now 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 were classified as the upper tercile, the 17 years with the least active ACE for a two-week period were classified as the lower tercile, while the remaining 17 years were classified as the middle tercile.

Table 5 displays the six two-week forecasts that were issued during the 2018 hurricane season and shows their verification. We correctly predicted five of the six two-week periods. We underestimated the Atlantic hurricane outbreak in early September. The MJO was fairly weak and disorganized during most of the peak of the Atlantic hurricane season (Figure 2), with an amplification of the MJO in October. The early September TC outbreak likely was driven by other factors than the MJO. The early October formation of Michael and Nadine were likely aided by convectively-favorable phases of the MJO.

Table 5: Two-week Atlantic ACE forecast verification for 2018. 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
8/2 – 8/15	**Below-Normal (2 or Fewer)**	**2**
8/16 – 8/29	**Below-Normal (5 or Fewer)**	**1**
8/30 – 9/12	**Near-Normal (14-25)**	**54**
9/13 – 9/26	**Near-Normal (13-26)**	**17**
9/27 – 10/10	**Above-Normal (11 or More)**	**28**
10/11 – 10/24	**Above-Normal (7 or More)**	**9**

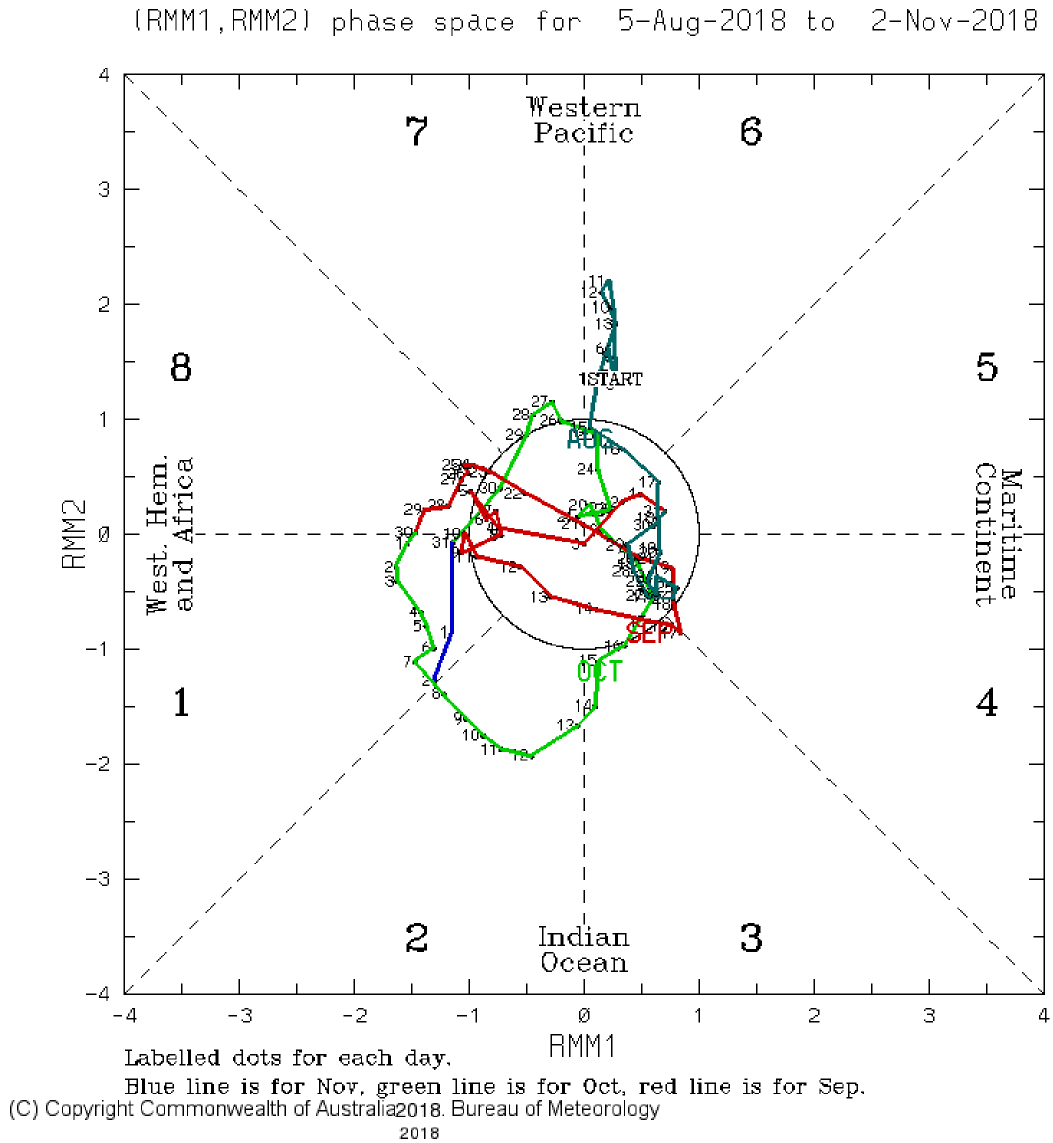


Figure 2: Propagation of the Madden-Julian Oscillation (MJO) based on the Wheeler-Hendon classification scheme over the period from August 5 to November 2. The MJO was generally weak during the peak of the Atlantic hurricane season, with amplification of the signal in October. The Maritime Continent refers to Indonesia and the surrounding islands. RMM stands for Real-Time Multivariate MJO. Figure courtesy of Bureau of Meteorology.

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 2018.

Landfall probabilities for the 2018 hurricane season were estimated to be above average for the forecast issued in early April, were near average for the forecast issued in early June and were below average for the forecast issued in early August. The 2018 Atlantic hurricane season was slightly above average from a landfall perspective with 2 hurricanes (Florence and Michael) and 1 major hurricane hitting the continental United States (Michael). In addition, 2 tropical storms also made continental US landfall (Alberto and Gordon). Average continental US landfalling statistics since 1900 are that 3.5 named storms, 1.8 hurricanes and 0.7 major hurricanes make US landfall per year.

Four named storms passed through the Caribbean (10-20°N, 60-88°W) during 2018; however, unlike 2017 when several major hurricanes tracked through the Caribbean (Irma, Jose and Maria), no hurricanes tracked through the Caribbean in 2018. Alberto, Kirk, Isaac and Michael all either formed or tracked through the Caribbean this year. Michael became very intense, but it did so once it emerged in the Gulf of Mexico. Isaac had weakened below hurricane strength before it reached 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.

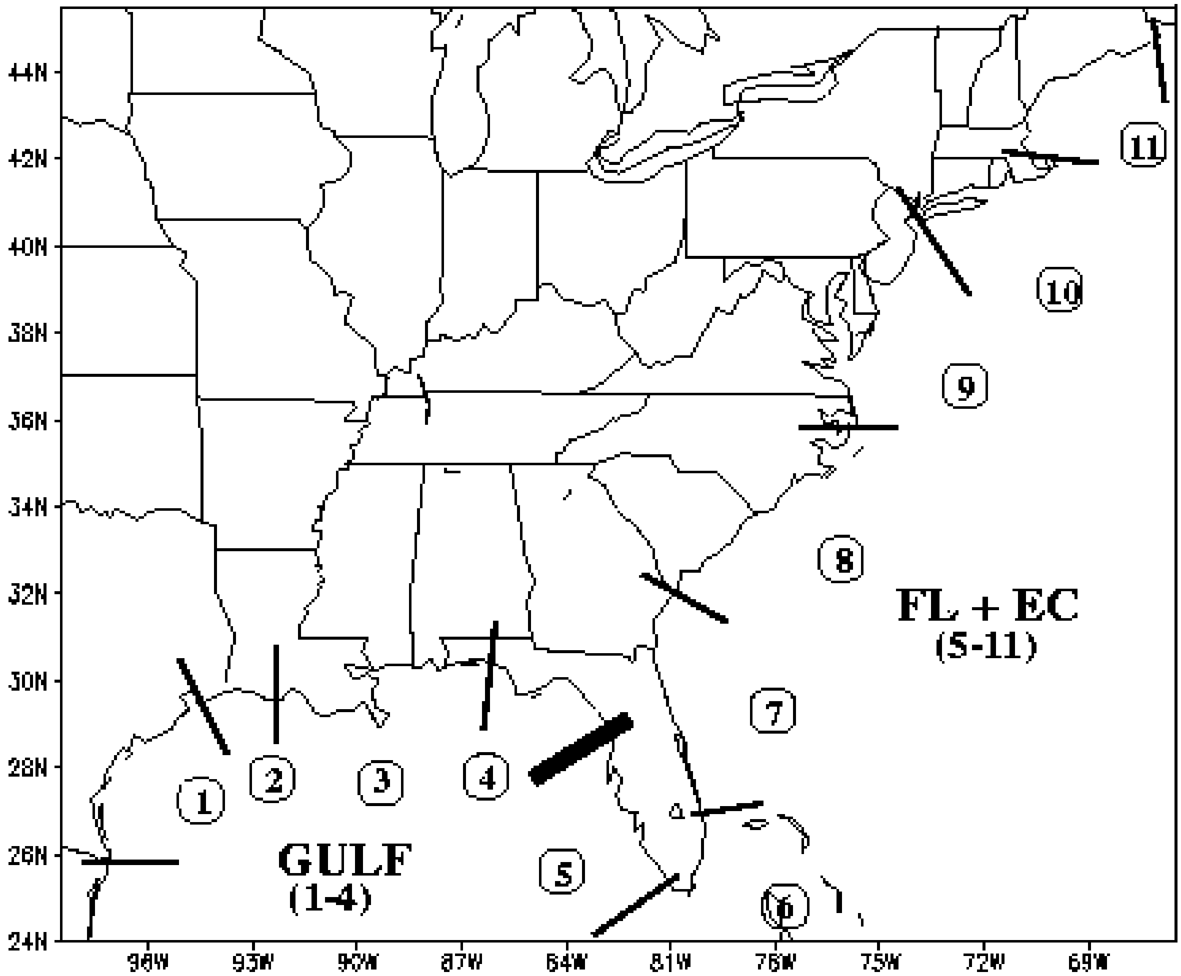


Figure 3: Location of the 11 coastal regions for which separate hurricane landfall probability estimates are made. These subdivisions were determined by the historical frequency of landfalling major hurricanes.

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 2018 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

	5 Apr.	31 May	2 August	Observed Number
TS	88%	78%	61% (79%)	2
HUR (Cat 1-2)	78%	67%	49% (68%)	1
HUR (Cat 3-4-5)	63%	51%	35% (52%)	1
All HUR	92%	84%	67% (84%)	2
Named Storms	99%	96%	87% (97%)	4

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

	5 Apr.	31 May	2 August	Observed Number
TS	70%	57%	41% (59%)	2
HUR (Cat 1-2)	52%	41%	28% (42%)	0
HUR (Cat 3-4-5)	38%	29%	19% (30%)	1
All HUR	71%	59%	42% (60%)	1
Named Storms	91%	82%	66% (83%)	3

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

	5 Apr.	31 May	2 August	Observed Number
TS	61%	49%	34% (50%)	0
HUR (Cat 1-2)	54%	43%	29% (44%)	1
HUR (Cat 3-4-5)	39%	30%	20% (31%)	0
All HUR	72%	60%	43% (61%)	1
Named Storms	89%	80%	63% (81%)	1

(d) Caribbean (10-20°N, 60-88°W)
Forecast Date

	5 Apr.	31 May	2 August	Observed Number
TS	90%	81%	64% (82%)	4
HUR (Cat 1-2)	68%	56%	40% (57%)	0
HUR (Cat 3-4-5)	52%	41%	28% (42%)	0
All HUR	85%	74%	56% (75%)	0
Named Storms	98%	95%	85% (96%)	4

7 Summary of Atmospheric/Oceanic Conditions

In this section, we go into detail discussing large-scale conditions that we believe significantly impacted the 2018 Atlantic basin hurricane season.

7.1 ENSO

Going into the 2018 Atlantic hurricane season, we did not anticipate a significant El Niño event this season, based on both analysis of current conditions and statistical and dynamical forecasts. We noted that there was a chance that weak El Niño conditions could potentially develop by the peak of the Atlantic hurricane season (August-October). In general, the state of ENSO during this year's hurricane season was fairly close to what was anticipated – with warm neutral ENSO conditions characterizing the peak of the season. Below are some quotes excerpted from our seasonal forecasts issued this year discussing our thoughts on the likely state of ENSO.

(5 April 2018) –

"Based on the above information, our best estimate is that we will likely have neutral ENSO conditions by the peak of the Atlantic hurricane season. There remains a need to closely monitor ENSO conditions over the next few months. We believe we will be slightly more confident about ENSO conditions for the upcoming hurricane season by the time of our next forecast on May 31."

(31 May 2018) –

"Currently, our best estimate is that warm neutral ENSO conditions will be present during the peak of the Atlantic hurricane season from August to October."

(2 August 2018) –

"There is considerable uncertainty as to whether a weak El Niño will develop in time for peak of the Atlantic hurricane season from August-October. At this point, the transition to El Niño appears to have briefly stalled."

The dynamical and statistical models did a relatively good job predicting the ENSO state during the summer/fall. Most of the models were calling for a warm neutral ENSO to weak El Niño for the peak of the 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 close to the mean of the ensemble members throughout the forecast period. 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 close to the mean of these forecasts as well.

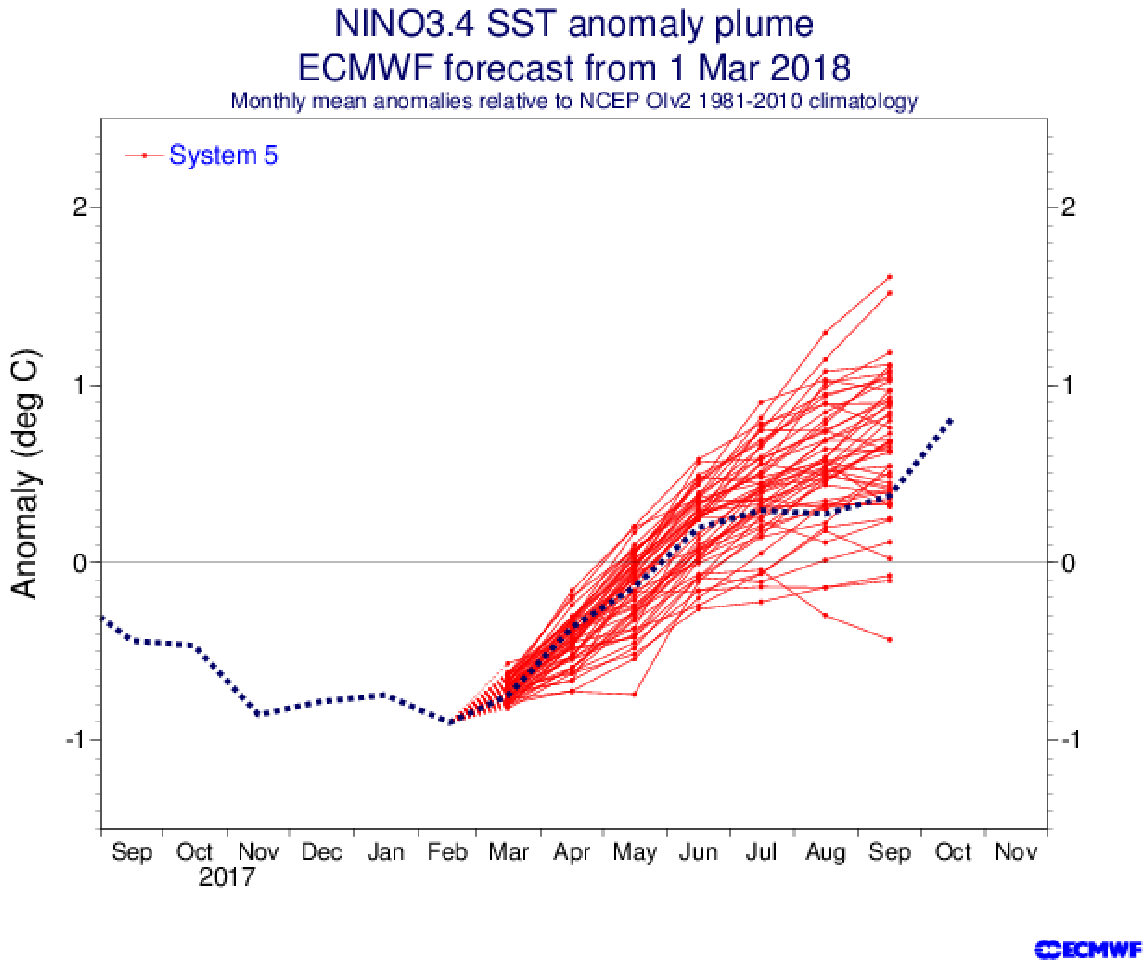


Figure 4: ECMWF ensemble prediction for Nino 3.4 from 1 March – the most recent information that we had available for our early April forecast in 2018. The blue dotted line represents the observed value.

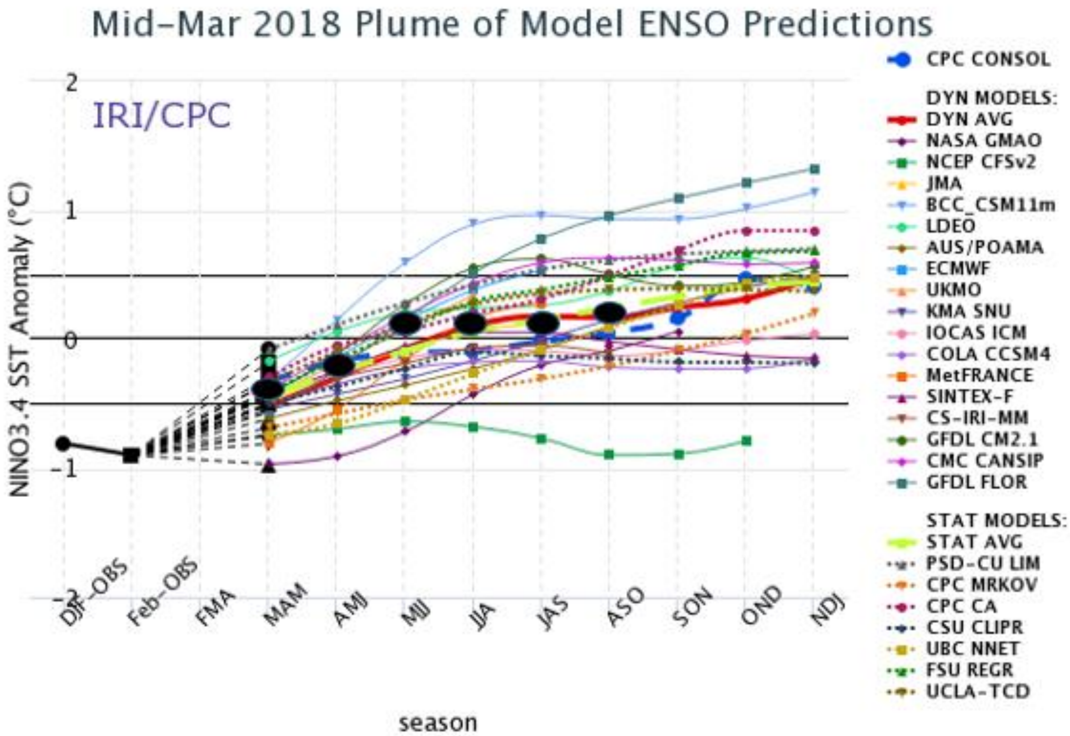


Figure 5: CFS ensemble prediction for Nino 3.4 from early April. Black dots represent the observed values.

Weak La Niña conditions briefly occurred during the winter of 2017/18, then slowly warmed to near borderline El Niño conditions by October 2018. Table 7 displays anomalies in the various Nino regions in January, April, July and October 2018, 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 2018 are in parentheses.

Region	January 2018 Anomaly (ºC)	April 2018 Anomaly (ºC)	July 2018 Anomaly (ºC)	October 2018 Anomaly (ºC)
Nino 1+2	-0.8	-1.0 (-0.2)	-0.2 (+0.6)	+0.4 (+1.2)
Nino 3	-1.1	-0.4 (+0.7)	+0.4 (+1.5)	+0.9 (+2.0)
Nino 3.4	-0.8	-0.4 (+0.4)	+0.3 (+1.1)	+0.9 (+1.7)
Nino 4	-0.3	+0.1 (+0.4)	+0.3 (+0.6)	+1.0 (+1.3)

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 slightly below average in the early part of 2018 and slowly increased until April. The anomalies then remained fairly constant through September before rising again in October then slowly falling in November.

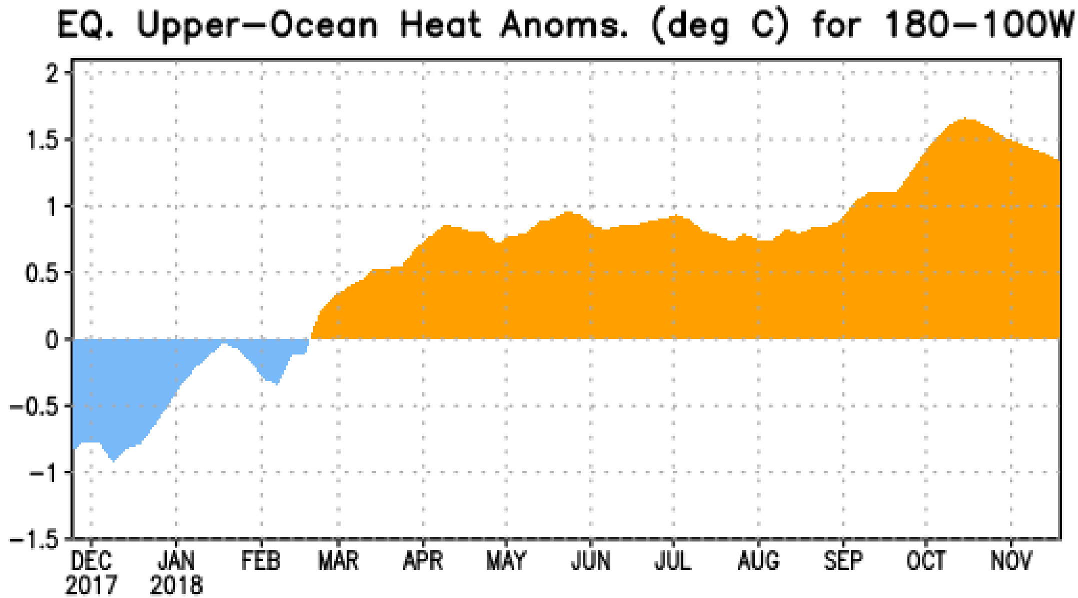


Figure 6: Upper ocean (0-300 meter) heat content anomalies in the eastern and central tropical Pacific from December 2017 – November 2018.

7.2 Intra-Seasonal Variability

The MJO was fairly weak and disorganized for most of the peak of the Atlantic hurricane season (Figure 7) before amplifying in October. The MJO amplification in early October in convectively-favorable phases (phases 1-2) for the Atlantic likely helped fuel the development of Michael and Nadine. These phases are climatologically associated with more Atlantic hurricane activity (Table 8) due to decreased vertical wind shear and increased low- and mid-level moisture. The 2018 Atlantic hurricane season when measured by ACE was characterized by an active July, an extremely quiet August, and an active September and October (Figure 8). The early September TC outbreak that occurred in 2018 did not appear to coincide with an MJO event. Additional research is being conducted by the TMP and colleagues to explain this TC outbreak, and a peer-reviewed journal article on this outbreak is likely forthcoming.

Table 9 displays the number of storms that were first named in each phase of the MJO over the course of the 2018 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 2018.

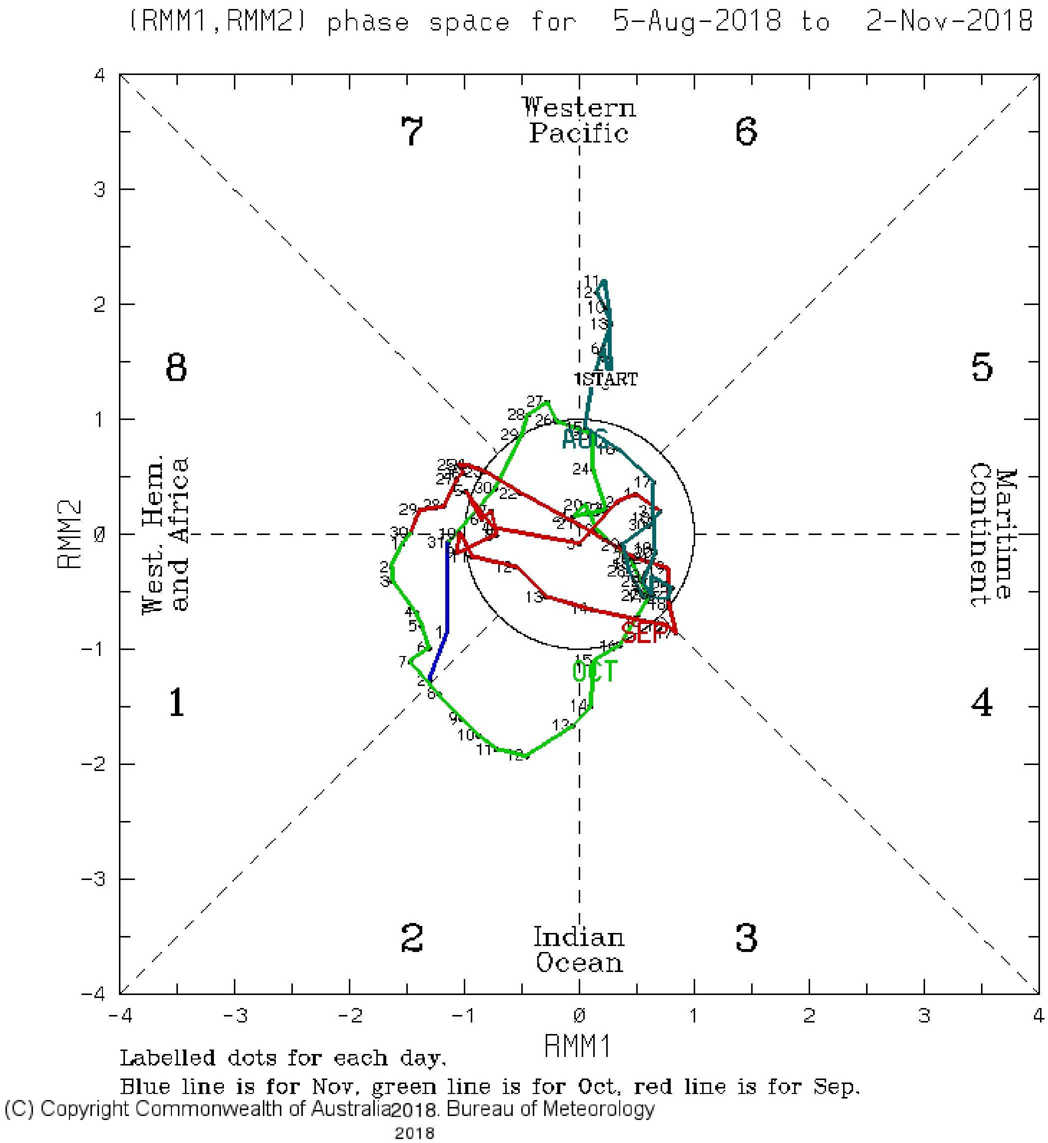


Figure 7: Propagation of the Madden-Julian Oscillation (MJO) based on the Wheeler-Hendon classification scheme over the period from August 5 to November 2. The MJO was generally weak during the peak of the Atlantic hurricane season, with amplification of the signal over the Maritime Continent and the 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

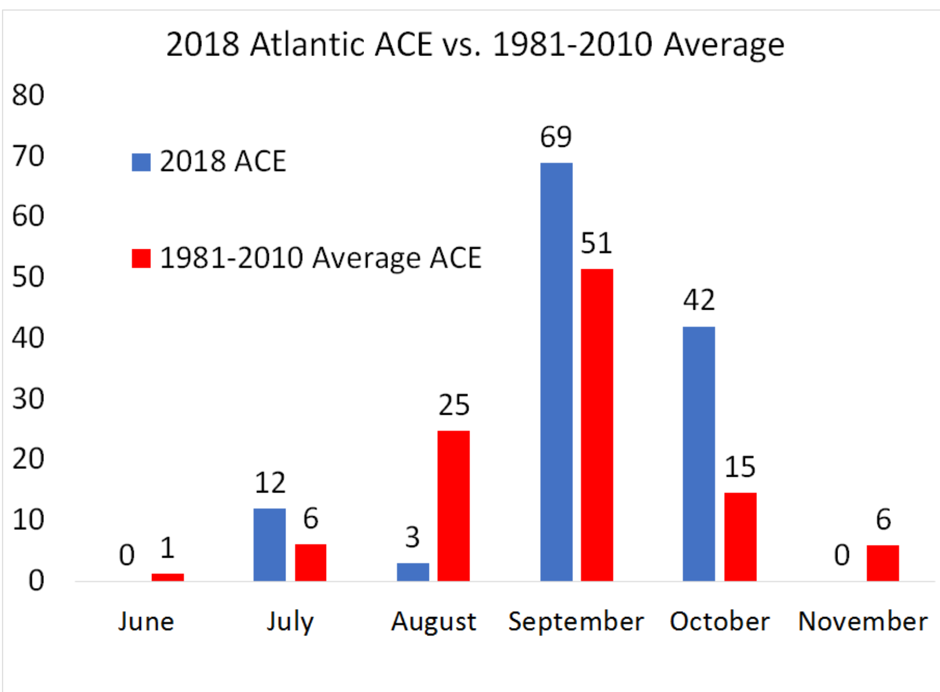


Figure 8: Atlantic Accumulated Cyclone Energy generated by month during the 2018 Atlantic hurricane season.

Table 9: TC formations by MJO phase during the 2018 Atlantic hurricane season.

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

7.3 Atlantic SST

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

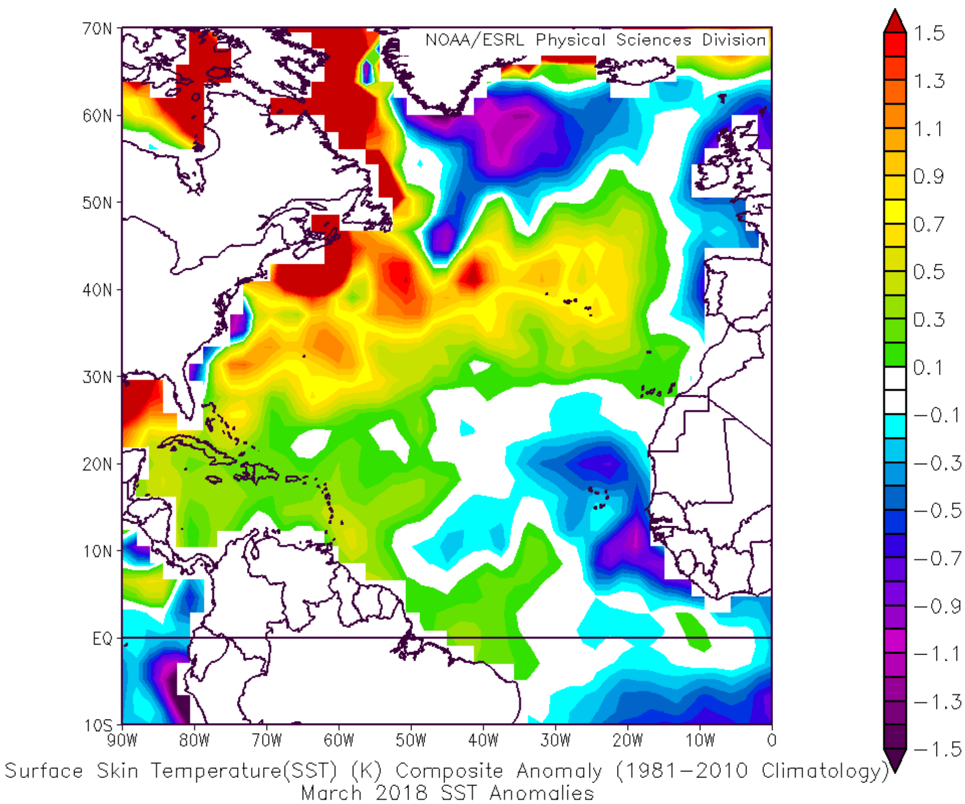


Figure 9: March 2018 SST anomaly pattern across the North Atlantic Ocean.

During April and May, the subtropical high in the North Atlantic was quite strong, driving strong trade winds that caused considerable anomalous cooling via evaporation, mixing and upwelling. Anomalous cooling took place across the tropical Atlantic as well as the far North Atlantic (Figure 10).

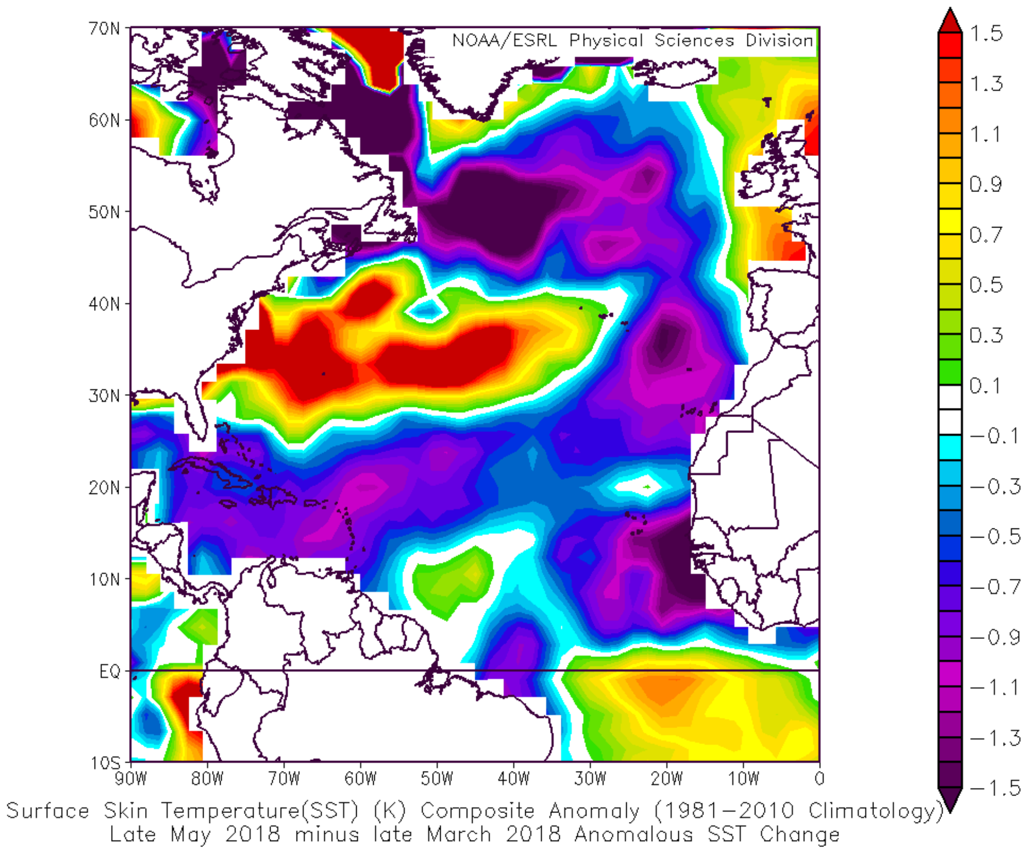


Figure 10: Late May 2018 minus late March 2018 SST anomaly change across the North Atlantic.

Anomalous cold SST anomalies were present at the time of the final CSU seasonal forecast issued in early August (Figure 11). This was one of the primary reasons why the final CSU seasonal forecast called for below-normal Atlantic hurricane activity. Typically, a colder tropical Atlantic is associated with higher pressure, a more stable atmosphere and higher levels of vertical wind shear. The Main Development Region, which we define to be 10-20°N, 60-20°W, was ~1.5°C below the 1982-2010 average in July and was the coldest on record for July since 1986.

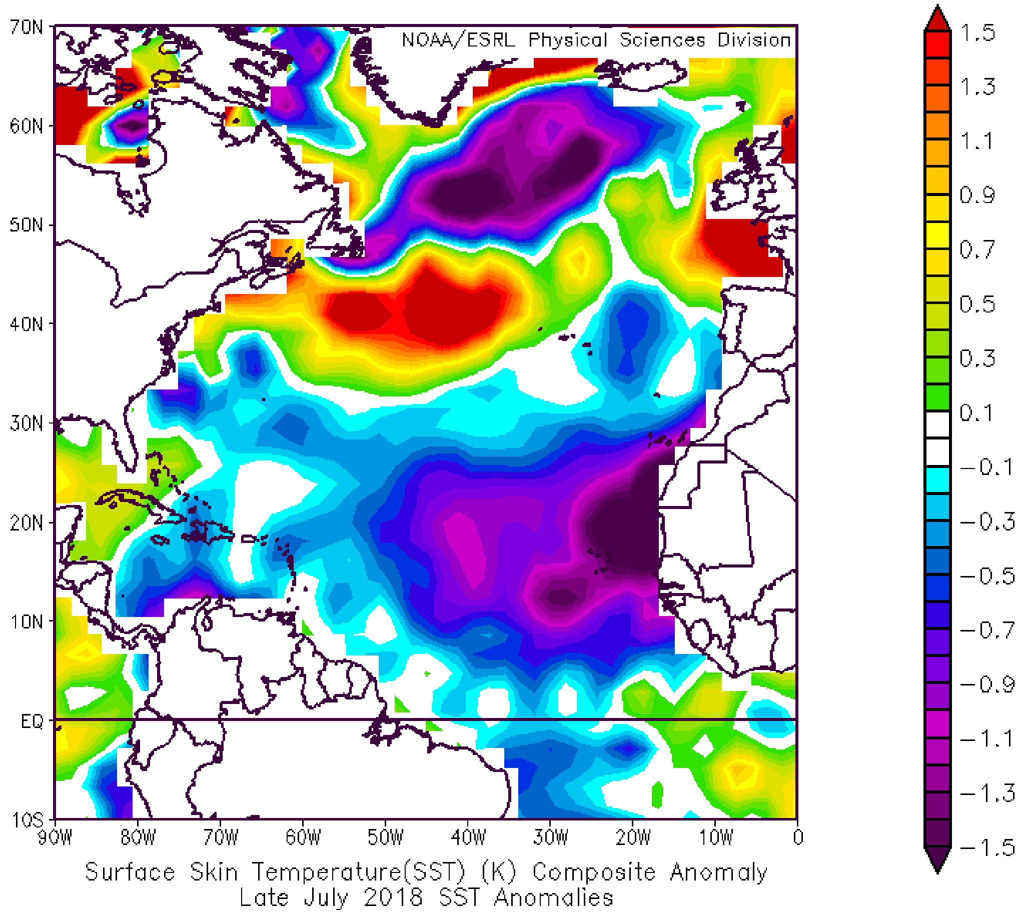


Figure 11: Late July 2018 SST anomalies.

While there was some anomalous warming of tropical Atlantic SSTs in August, SSTs in September 2018 were still below normal across most of the MDR. They averaged ~0.3°C below the 1982-2010 average and were the coldest September SST values in the MDR since 2002.

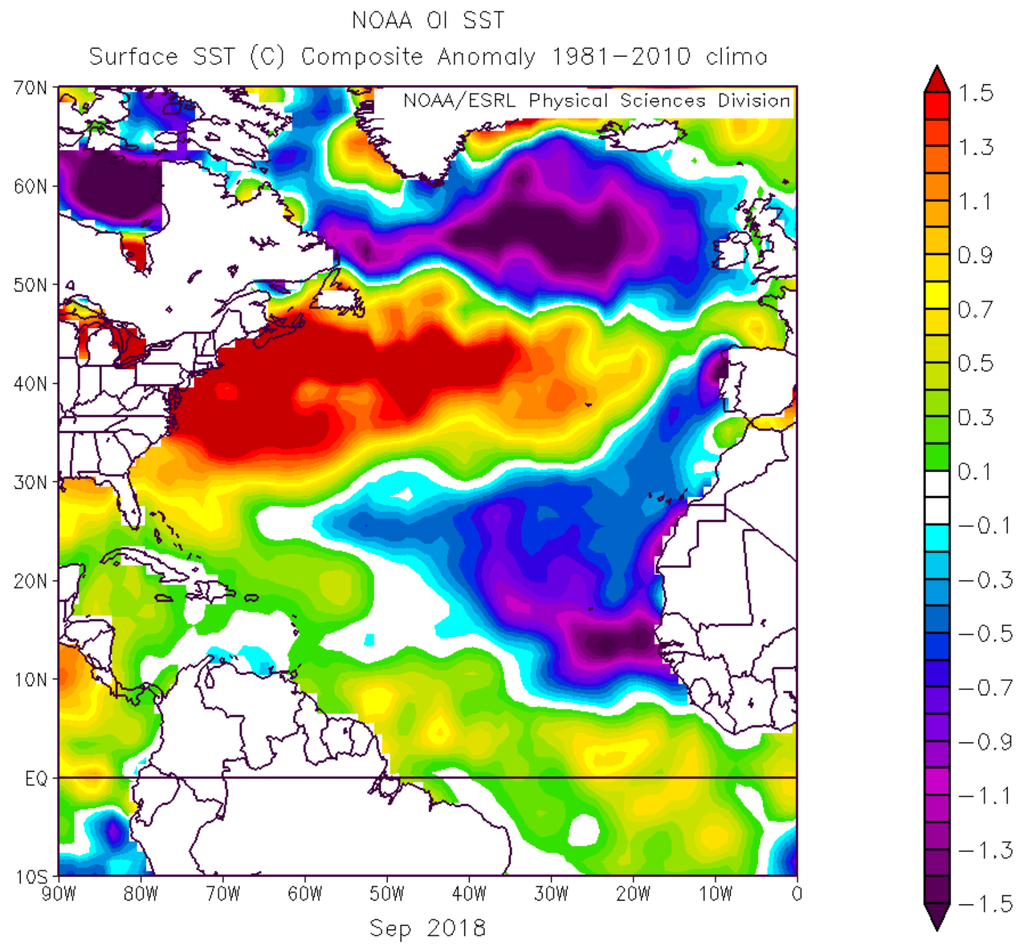


Figure 12: September 2018 SST anomalies.

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 2018 Atlantic hurricane season was characterized by above-normal sea level pressures in the Caribbean and near-normal sea level pressures in the eastern and central tropical Atlantic (Figure 13). The anomalous low pressure in the subtropical eastern and central Atlantic is likely somewhat due to Hurricane Leslie, which spent about three weeks transiting the region as both a tropical and an extra-tropical cyclone.

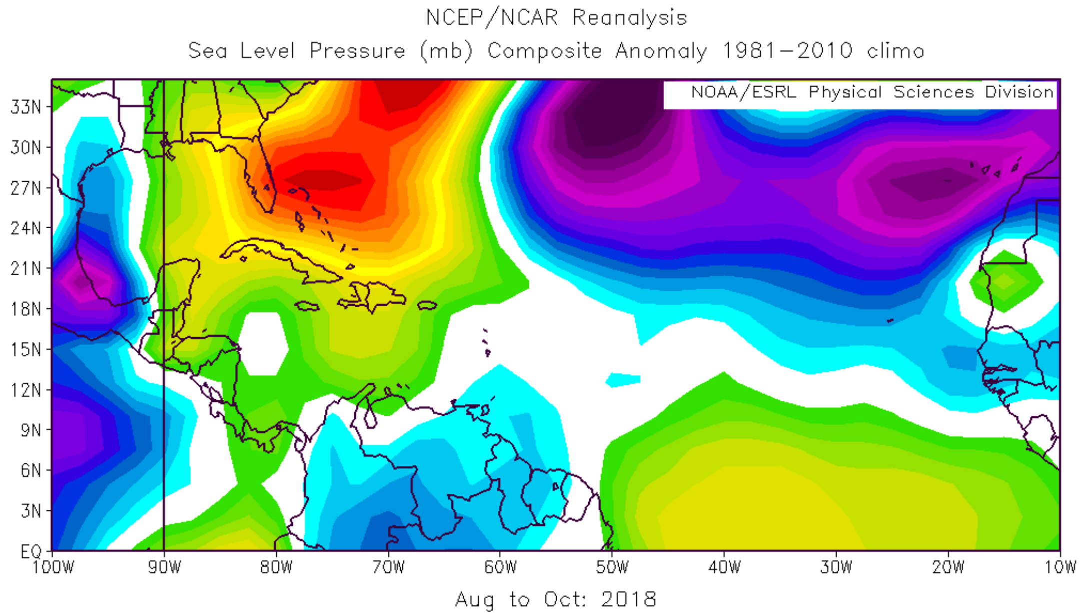


Figure 13: August-October 2018 tropical and sub-tropical North Atlantic sea level pressure anomalies.

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 above-normal across the Caribbean and slightly below normal in the eastern tropical Atlantic (Figure 14). Typically, above-normal shear in the Caribbean correlates with below-average Atlantic hurricane seasons. It also tends to correlate with above-normal shear further east in the basin, so to get an anomalous shear dipole across the tropical Atlantic is unusual. Atlantic hurricane activity in 2018 responded to this shear dipole, with several hurricanes forming in the eastern and central tropical Atlantic. No hurricanes reached the Caribbean, however.

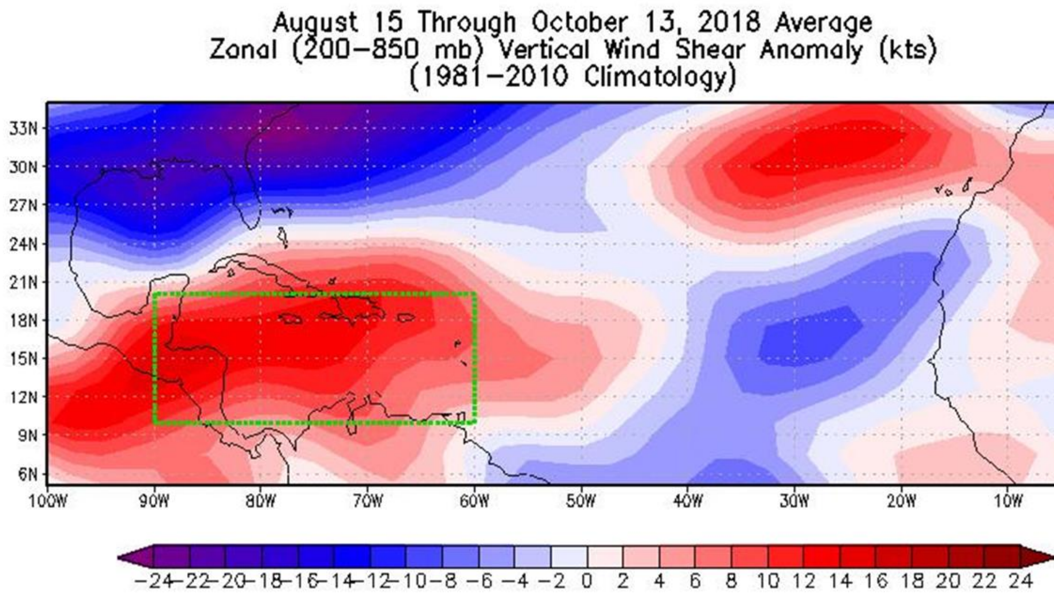


Figure 14: Anomalous vertical wind shear observed across the Atlantic from mid-August to mid-October. The green box represents the Caribbean basin.

7.6 Steering Currents

The steering currents in August-October 2018 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). The anomalous low pressure in the central subtropical Atlantic was likely due to Hurricane Leslie, which spent several weeks transiting this portion of the basin. When Hurricane Florence made its transit due west across the subtropical Atlantic, a strong high pressure zone to its north was responsible. Several of the storms forming in the MDR tracked due westward, such as Isaac and Kirk. Helene was the only MDR system to recurve east of the islands in 2018. Nadine was torn apart by strong shear by the time it reached ~40°W.

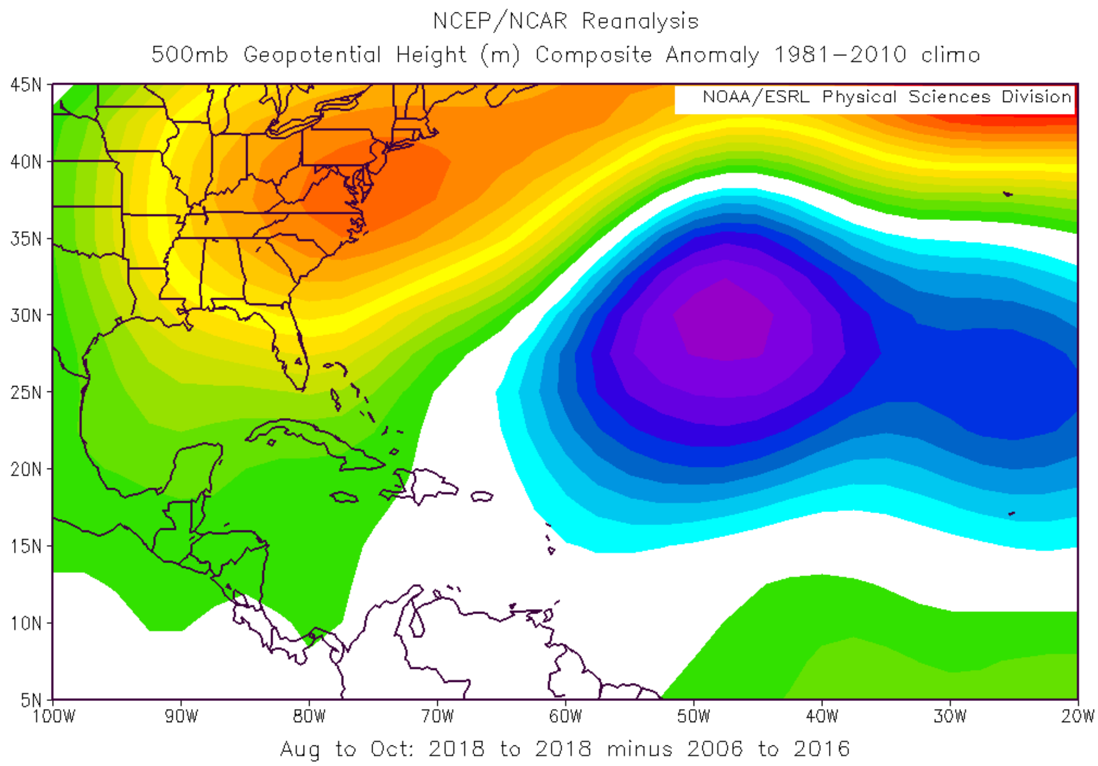


Figure 15: 500-mb height in the central and western part Atlantic from August to October in 2018 differenced from the August-October 2006 to 2016 period.

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 recently addressed this in an article published in *Nature Geoscience* (Klotzbach et al. 2015). Following three below-average Atlantic hurricane seasons from 2013-2015, the past three seasons (2016-2018) 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 generally very low throughout 2018 (associated with both colder than normal SSTs as well as higher than normal SLPs) (Figure 17), with the AMO increasing in October 2018 due to anomalous far North Atlantic SST warming and slightly-below normal SLPs.

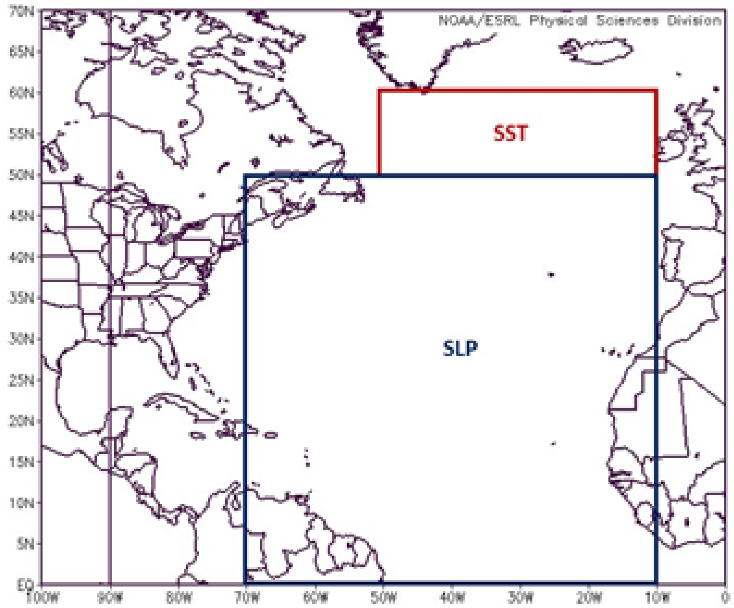


Figure 16: Regions which are utilized for the calculation of our AMO index.

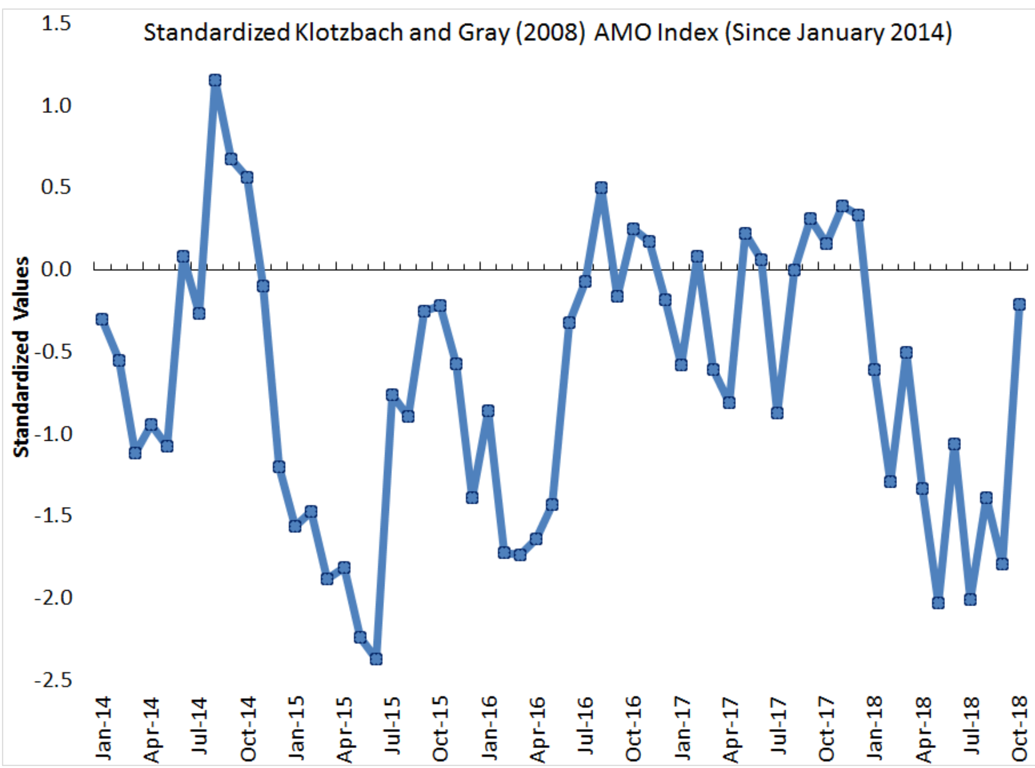


Figure 17: Standardized values of the AMO index by month since January 2014. The index was below normal throughout 2018 but has recently rebounded to near normal.

8 Forecasts of 2019 Hurricane Activity

We will be issuing our first outlook for the 2019 hurricane season on Thursday, 13 December 2018. This forecast will provide a qualitative outlook for factors likely to impact the 2019 hurricane season. This December forecast will include the dates of all of our updated 2019 forecasts. All of these forecasts will be made available online.

9 Citations and Additional Reading

Alexander, M. A., I. Blade, M. Newman, J. R. Lanzante, N.-C. Lau, and J. D. Scott, 2002: The atmospheric bridge: The influence of ENSO teleconnections on air-sea interaction over the global oceans. *J. Climate,* 15, 2205-2231.

Blake, E. S., 2002: Prediction of August Atlantic basin hurricane activity. Dept. of Atmos. Sci. Paper No. 719, Colo. State Univ., Ft. Collins, CO, 80 pp.

Blake, E. S. and W. M. Gray, 2004: Prediction of August Atlantic basin hurricane activity. *Wea. Forecasting,* 19, 1044-1060.

Chiang, J. C. H. and D. J. Vimont, 2004: Analogous Pacific and Atlantic meridional modes of tropical atmosphere-ocean variability. *J. Climate*, 17, 4143-4158.

DeMaria, M., J. A. Knaff and B. H. Connell, 2001: A tropical cyclone genesis parameter for the tropical Atlantic. *Wea. Forecasting*, 16, 219-233.

Elsner, J. B., G. S. Lehmiller, and T. B. Kimberlain, 1996: Objective classification of Atlantic hurricanes. *J. Climate*, 9, 2880-2889.

Evan, A. T., J. Dunion, J. A. Foley, A. K. Heidinger, and C. S. Velden, 2006: New evidence for a relationship between Atlantic tropical cyclone activity and African dust outbreaks, *Geophys. Res. Lett,* 33, doi:10.1029/2006GL026408.

Goldenberg, S. B., C. W. Landsea, A. M. Mestas-Nunez, and W. M. Gray, 2001: The recent increase in Atlantic hurricane activity: Causes and Implications. *Science*, 293, 474-479.

Goldenberg, S. B. and L. J. Shapiro, 1996: Physical mechanisms for the association of El Niño and West African rainfall with Atlantic major hurricane activity. *J. Climate*, 1169-1187.

Gray, W. M., 1984a: Atlantic seasonal hurricane frequency: Part I: El Niño and 30 mb quasi-biennial oscillation influences. *Mon. Wea. Rev.*, 112, 1649-1668.

Gray, W. M., 1984b: Atlantic seasonal hurricane frequency: Part II: Forecasting its variability. *Mon. Wea. Rev.*, 112, 1669-1683.

Gray, W. M., 1990: Strong association between West African rainfall and US landfall of intense hurricanes. *Science,* 249, 1251-1256.

Gray, W. M., 2011: Gross errors in the IPCC-AR4 report regarding past and future changes in global tropical cyclone activity. Science and Public Policy Institute, 122 pp. Available online at http://tropical.atmos.colostate.edu/Includes/Documents/Publications/gray2011.pdf.

Gray, W. M., C. W. Landsea, P. W. Mielke, Jr., and K. J. Berry, 1992: Predicting Atlantic seasonal hurricane activity 6-11 months in advance. *Wea. Forecasting,* 7, 440-455.

Gray, W. M., C. W. Landsea, P. W. Mielke, Jr., and K. J. Berry, 1993: Predicting Atlantic basin seasonal tropical cyclone activity by 1 August. *Wea. Forecasting,* 8, 73-86.

Gray, W. M., C. W. Landsea, P. W. Mielke, Jr., and K. J. Berry, 1994a: Predicting Atlantic basin seasonal tropical cyclone activity by 1 June. *Wea. Forecasting,* 9, 103-115.

Gray, W. M., J. D. Sheaffer and C. W. Landsea, 1996: Climate trends associated with multi-decadal variability of intense Atlantic hurricane activity. Chapter 2 in "Hurricanes, Climatic Change and Socioeconomic Impacts: A Current Perspective", H. F. Diaz and R. S. Pulwarty, Eds., Westview Press, 49 pp.

Gray, W. M., 1998: Atlantic ocean influences on multi-decadal variations in El Niño frequency and intensity. Ninth Conference on Interaction of the Sea and Atmosphere, 78th AMS Annual Meeting, 11-16 January, Phoenix, AZ, 5 pp.

Grossmann, I. and P. J. Klotzbach, 2009: A review of North Atlantic modes of natural variability and their driving mechanisms. *J. Geophys. Res.*, 114, D24107, doi:10.1029/2009JD012728.

Henderson-Sellers, A., H. Zhang, G. Berz, K. Emanuel, W. Gray, C. Landsea, G. Holland, J. Lighthill, S-L. Shieh, P. Webster, and K. McGuffie, 1998: Tropical cyclones and global climate change: A post-IPCC assessment. *Bull. Amer. Meteor. Soc.*, 79, 19-38.

Klotzbach, P. J., 2002: Forecasting September Atlantic basin tropical cyclone activity at zero and one-month lead times. Dept. of Atmos. Sci. Paper No. 723, Colo. State Univ., Ft. Collins, CO, 91 pp.

Klotzbach, P. J., 2006: Trends in global tropical cyclone activity over the past twenty years (1986-2005). *Geophys. Res. Lett.*, 33, doi:10.1029/2006GL025881.

Klotzbach, P. J., 2007: Revised prediction of seasonal Atlantic basin tropical cyclone activity from 1 August. *Wea. and Forecasting,* 22, 937-949.

Klotzbach, P. J. and W. M. Gray, 2003: Forecasting September Atlantic basin tropical cyclone activity. *Wea. and Forecasting*, 18, 1109-1128.

Klotzbach, P. J. and W. M. Gray, 2004: Updated 6-11 month prediction of Atlantic basin seasonal hurricane activity. *Wea. and Forecasting*, 19, 917-934.

Klotzbach, P. J. and W. M. Gray, 2006: Causes of the unusually destructive 2004 Atlantic basin hurricane season. *Bull. Amer. Meteor. Soc.,* 87, 1325-1333.

Klotzbach, P. J. and W. M. Gray, 2008: Multi-decadal variability in North Atlantic tropical cyclone activity. *J. Climate*, 21, 3929-3935.

Klotzbach, P. J., W. M. Gray, and C. T. Fogarty, 2015: Active Atlantic hurricane era at its end? *Nature Geoscience,* **8,** 737-738, doi:10.1038/ngeo2529.

Knaff, J. A., 1997: Implications of summertime sea level pressure anomalies. *J. Climate,* 10, 789-804.

Knaff, J. A., 1998: Predicting summertime Caribbean sea level pressure. *Wea. and Forecasting,* 13, 740-752.

Kossin, J. P., and D. J. Vimont, 2007: A more general framework for understanding Atlantic hurricane variability and trends. *Bull. Amer. Meteor. Soc.,* 88, 1767-1781.

Landsea, C. W., 1991: West African monsoonal rainfall and intense hurricane associations. Dept. of Atmos. Sci. Paper, Colo. State Univ., Ft. Collins, CO, 272 pp.

Landsea, C. W., 1993: A climatology of intense (or major) Atlantic hurricanes. *Mon. Wea. Rev.*, 121, 1703-1713.

Landsea, C. W., 2007: Counting Atlantic tropical cyclones back to 1900. *EOS*, 88, 197, 202.

Landsea, C. W. and W. M. Gray, 1992: The strong association between Western Sahel monsoon rainfall and intense Atlantic hurricanes. *J. Climate*, 5, 435-453.

Landsea, C. W., W. M. Gray, P. W. Mielke, Jr., and K. J. Berry, 1992: Long-term variations of Western Sahelian monsoon rainfall and intense US landfalling hurricanes. *J. Climate*, 5, 1528-1534.

Landsea, C. W., W. M. Gray, K. J. Berry and P. W. Mielke, Jr., 1996: June to September rainfall in the African Sahel: A seasonal forecast for 1996. 4 pp.

Landsea, C. W., N. Nicholls, W.M. Gray, and L.A. Avila, 1996: Downward trends in the frequency of intense Atlantic hurricanes during the past five decades. *Geo. Res. Letters*, 23, 1697-1700.

Landsea, C. W., R. A. Pielke, Jr., A. M. Mestas-Nunez, and J. A. Knaff, 1999: Atlantic basin hurricanes: Indices of climatic changes. *Climatic Changes*, 42, 89-129.

Landsea, C.W. et al., 2005: Atlantic hurricane database re-analysis project. Available online at http://www.aoml.noaa.gov/hrd/data_sub/re_anal.html

Mielke, P. W., K. J. Berry, C. W. Landsea and W. M. Gray, 1996: Artificial skill and validation in meteorological forecasting. *Wea. Forecasting*, 11, 153-169.

Mielke, P. W., K. J. Berry, C. W. Landsea and W. M. Gray, 1997: A single sample estimate of shrinkage in meteorological forecasting. *Wea. Forecasting*, 12, 847-858.

Pielke, Jr. R. A., and C. W. Landsea, 1998: Normalized Atlantic hurricane damage, 1925-1995. *Wea. Forecasting*, 13, 621-631.

Pielke, Jr. R. A., J. Gratz, C. W. Landsea, D. Collins, and R. Masulin, 2008: Normalized hurricane damage in the United States: 1900-2005. *Nat. Haz. Rev.*, 9, 29-42, doi:10.1061/(ASCE)1527-6988(2008)9:1(29).

Powell, M. D., and T. A. Reinhold, 2007: Tropical cyclone destructive potential by integrated kinetic energy. *Bull. Amer. Meteor. Soc., 88,* 513-526.

Rasmusson, E. M. and T. H. Carpenter, 1982: Variations in tropical sea-surface temperature and surface wind fields associated with the Southern Oscillation/El Niño. *Mon. Wea. Rev.*, 110, 354-384.

Seseske, S. A., 2004: Forecasting summer/fall El Niño-Southern Oscillation events at 6-11 month lead times. Dept. of Atmos. Sci. Paper No. 749, Colo. State Univ., Ft. Collins, CO, 104 pp.

Vimont, D. J., and J. P. Kossin, 2007: The Atlantic meridional mode and hurricane activity. *Geophys. Res. Lett.*, 34, L07709, doi:10.1029/2007GL029683.

Wheeler, M. C., and H. H. Hendon, 2004: An all-season real-time multivariate MJO index: Development of an index for monitoring and prediction. *Mon. Wea. Rev.*, 132, 1917-1932.

10 Verification of Previous Forecasts

Table 10: Verification of the authors' early August forecasts of Atlantic named storms and hurricanes between 1984-2018. 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 29 of 35 years for named storms and 27 of 35 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
Average	**10.9**	**10.7**	**6.1**	**6.1**
1984-2018 Correlation		**0.61**		**0.52**

Table 11: Summary verification of the authors' five previous years of seasonal forecasts for Atlantic TC activity from 2013-2017.

2013	10 April	Update 3 June	Update 2 August	Obs.
Hurricanes	9	9	8	2
Named Storms	18	18	18	13
Hurricane Days	40	40	35	3.75
Named Storm Days	95	95	84.25	38.50
Major Hurricanes	4	4	3	0
Major Hurricane Days	9	9	7	0
Accumulated Cyclone Energy	165	165	142	33
Net Tropical Cyclone Activity	175	175	150	44

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	9 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	51.75
Named Storm Days	50	60	70	70	93.00
Major Hurricanes	2	2	3	3	6
Major Hurricane Days	4	5	7	7	19.25
Accumulated Cyclone Energy	75	100	135	135	225
Net Tropical Cyclone Activity	85	110	140	140	232