SUMMARY OF 2016 ATLANTIC TROPICAL CYCLONE ACTIVITY AND VERIFICATION OF AUTHOR'S SEASONAL AND TWO-WEEK FORECASTS

The 2016 Atlantic hurricane season had slightly more activity in the aggregate sense than predicted in the seasonal outlooks, primarily due to the very long-lived intense Hurricane Matthew. Predicted numbers of named storms and hurricanes were close to observed values. Vertical shear averaged somewhat below-normal, but dry mid-levels likely were the primary suppressant preventing a more active season.

By Philip J. Klotzbach[1]

In Memory of William M. Gray[2]

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

Anne Ju Manning, Colorado State University Media Representative, (970-491-7099) is available to answer various questions about this verification.

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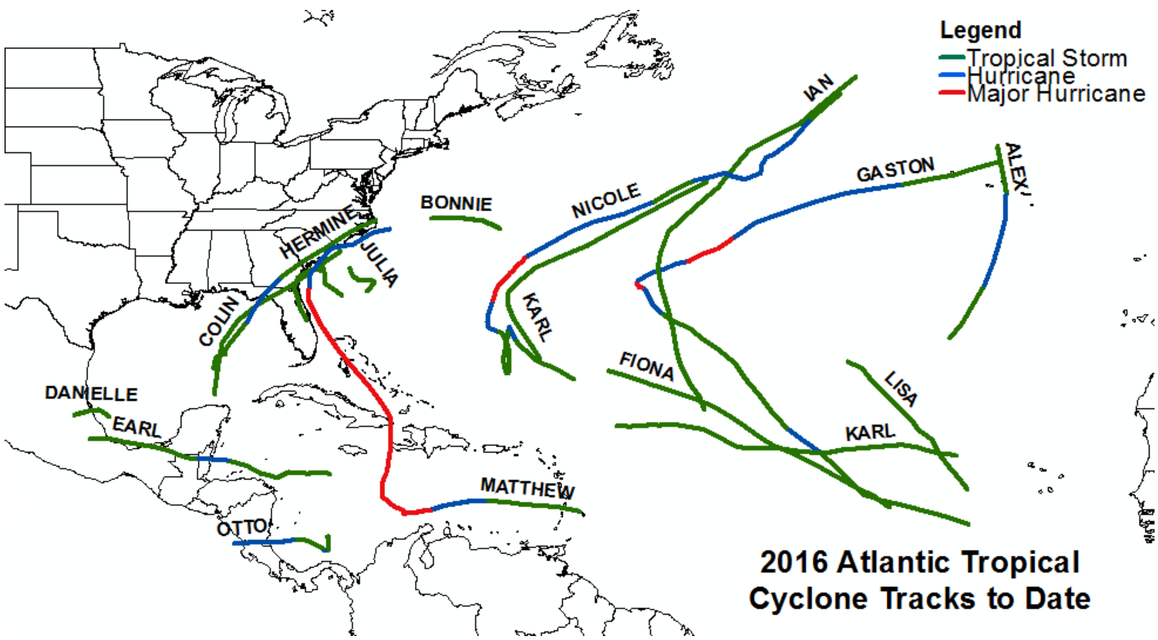
ATLANTIC BASIN SEASONAL HURRICANE FORECASTS FOR 2016

Forecast Parameter and 1981-2010 Median (in parentheses)	Issue Date 14 April 2016	Issue Date 1 June 2016	Issue Date 1 July 2016	Issue Date 4 August 2016	**Observed 2016 Activity**	% of 1981-2010 Median
Named Storms (NS) (12.0)	13	14	15	15	**15**	117%
Named Storm Days (NSD) (60.1)	52	53	55	55	**78.25**	124%
Hurricanes (H) (6.5)	6	6	6	6	**7**	92%
Hurricane Days (HD) (21.3)	21	21	21	22	**26.25**	117%
Major Hurricanes (MH) (2.0)	2	2	2	2	**3**	150%
Major Hurricane Days (MHD) (3.9)	4	4	4	5	**9.75**	250%
Accumulated Cyclone Energy (ACE) (92)	93	94	95	100	**134**	139%
Net Tropical Cyclone Activity (NTC) (103%)	101	103	105	110	**145**	134%



Atlantic basin tropical cyclone tracks in 2016. Fifteen named storms, 7 hurricanes and 3 major hurricanes occurred.

ABSTRACT

This report summarizes tropical cyclone (TC) activity which occurred in the Atlantic basin during 2016 and verifies the author's 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 2016 was issued on 14 April with updates following on 1 June, 1 July and 4 August. These seasonal forecasts also contained estimates of the probability of U.S. and Caribbean hurricane landfall during 2016.

The 2016 hurricane season ended up somewhat above average. The season was characterized by somewhat above-average named storms and major hurricanes, with slightly above-average hurricane numbers. This year's seasonal forecast under-estimated Accumulated Cyclone Energy (ACE) and Net Tropical Cyclone (NTC) activity levels due primarily to long-lasting, intense Major Hurricane Matthew. Over 40% of this season's ACE was generated by just one storm (Matthew).

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.

Integrated measures such as Net Tropical Cyclone (NTC) activity and Accumulated Cyclone Energy (ACE) were at above-average levels. Vertical wind shear was considerably reduced from what occurred the past two hurricane seasons. Dry mid-level conditions predominated throughout most of the hurricane season, likely suppressing hurricane activity until the latter part of the season.

Cool neutral ENSO to weak La Niña conditions were anticipated in the seasonal forecasts issued this year, and cool neutral ENSO conditions prevailed during the peak of the Atlantic hurricane season. Tropical Atlantic sea surface temperatures (SSTs) were slightly above-normal throughout the hurricane season.

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 20-70°N, 40-10°W and sea level pressure from 15-50°N, 60-10°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 earlier this year. 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 and Macquarie Group 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 also thank Professors Paul Mielke and Ken Berry of Colorado State University for statistical analysis and guidance over many years. We thank Bill Thorson for technical advice and assistance.

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 nearly 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 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 2016

Figure 1 and Table 1 summarize Atlantic basin TC activity which occurred in 2016. Overall, the season was characterized by somewhat above-average activity. Online entries from Wikipedia (http://www.wikipedia.org) are available for in-depth discussions of each TC that occurred in 2016.

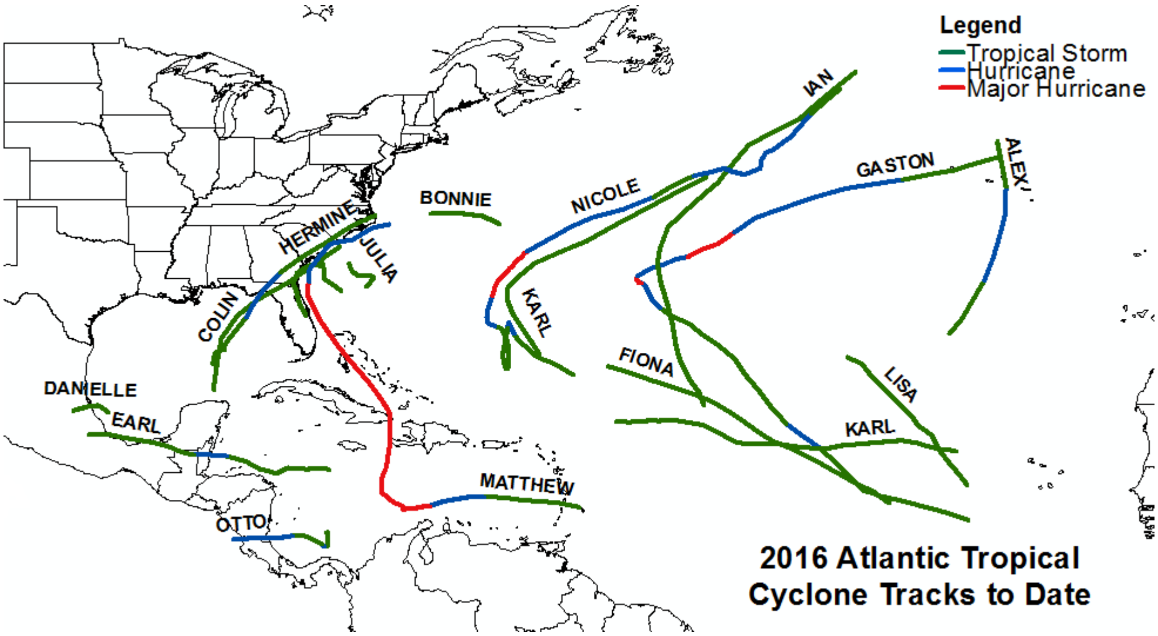


Figure 1: Atlantic tropical cyclone tracks in 2016. Fifteen named storms, seven hurricanes and three major hurricanes occurred.

Year	Storm#	Name	Dates TC Active	Max Wind (kts)	MSLP (mb)	Named Storm Days	Hurricane Days	Major Hurricane Days	Accumulated Cyclone Energy
2016	1	ALEX	1/13-1/15	75	981	2.00	1.00	0.00	3.2
2016	2	BONNIE	5/28-6/4	40	1006	2.00	0.00	0.00	1.0
2016	3	COLIN	6/5-6/7	45	1001	1.75	0.00	0.00	1.2
2016	4	DANIELLE	6/20-6/21	40	1007	0.75	0.00	0.00	0.4
2016	5	EARL	8/2-8/6	70	979	4.00	0.50	0.00	4.1
2016	6	FIONA	8/17-8/22	45	1004	4.75	0.00	0.00	2.7
2016	7	GASTON	8/23-9/3	105	956	11.25	6.00	1.75	24.6
2016	8	HERMINE	8/31-9/3	70	982	3.25	0.75	0.00	3.5
2016	9	IAN	9/12-9/16	50	994	4.00	0.00	0.00	2.9
2016	10	JULIA	9/13-9/16	35	1007	3.00	0.00	0.00	1.5
2016	11	KARL	9/15-9/25	60	986	8.50	0.00	0.00	6.3
2016	12	LISA	9/20-9/24	45	999	4.25	0.00	0.00	2.7
2016	13	MATTHEW	9/28-10/9	140	934	11.00	9.75	7.25	48.5
2016	14	NICOLE	10/4-10/18	115	950	14.00	7.00	0.75	25.6
2016	15	OTTO	11/21-11/24	95	975	3.75	1.25	0.00	6.2

Table 1: Observed 2016 Atlantic basin tropical cyclone activity.

3 Special Characteristics of the 2016 Hurricane Season

The 2016 hurricane season had the following special characteristics:

- A total of 78.25 named storm days and 26.25 hurricane days occurred in 2016. Both are the most in an individual Atlantic hurricane season since 2012.

- Seven hurricanes formed in 2016. This is the first year with above-median hurricane frequency since 2012.

- Three major hurricanes formed in 2016. This is the first year with at least three major hurricanes since 2011.

- The 9.75 major hurricane days that occurred in 2016 are the most in a single Atlantic hurricane season since 2010.

- Alex was the 2nd strongest hurricane on record in January in the Atlantic at 75 knots – trailing only Alice (1955) at 80 knots.

- Hermine made landfall in the Big Bend of Florida on September 2 – ending Florida's record-long hurricane drought at 3966 days.

- Matthew became the first Category 5 hurricane in the Atlantic basin since Felix (2007). Matthew had many other meteorological achievements which are documented here.

- Otto was the latest calendar year Atlantic hurricane on record to make landfall. It did so as a Category 2 in southern Nicaragua.

- September ACE was only 25. Four-year (2013-2016) summed September ACE for the Atlantic was only 70, the lowest since 1911-1914 when only 42 ACE were recorded during September.

- October ACE was 69 which is the highest value since 1963 when 69 ACE units were also accrued during October. This is also the first year since 1963 when October generated more ACE than August and September combined.

- No major hurricanes made United States landfall in 2016, although Hurricane Matthew came within about 50 miles of breaking this streak. The last major hurricane to make U.S. landfall was Wilma (2005), so the U.S. has now gone eleven years without a major hurricane landfall. The U.S. has never had another eleven-year period without a major hurricane landfall since records began in 1851. This eclipses the previous record of eight years set from 1861-1868.

4 Verification of Individual 2016 Lead Time Forecasts

Table 2 is a comparison of our forecasts for 2016 for four different lead times along with this year's observations. The 2016 Atlantic hurricane season was characterized by somewhat above-average levels of overall basinwide activity.

Table 2: Verification of our 2016 seasonal hurricane predictions.

Forecast Parameter and 1981-2010 Median (in parentheses)	Issue Date 14 April 2016	Issue Date 1 June 2016	Issue Date 1 July 2016	Issue Date 4 August 2016	**Observed 2016 Activity**	% of 1981-2010 Median
Named Storms (NS) (12.0)	13	14	15	15	**15**	125%
Named Storm Days (NSD) (60.1)	52	53	55	55	**78.25**	130%
Hurricanes (H) (6.5)	6	6	6	6	**7**	108%
Hurricane Days (HD) (21.3)	21	21	21	22	**26.25**	123%
Major Hurricanes (MH) (2.0)	2	2	2	2	**3**	150%
Major Hurricane Days (MHD) (3.9)	4	4	4	5	**9.75**	250%
Accumulated Cyclone Energy (ACE) (92)	93	94	95	100	**134**	146%
Net Tropical Cyclone Activity (NTC) (103%)	101	103	105	110	**145**	141%

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 three 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 seasonal forecasts were generally within one standard deviation of absolute errors.

Table 3: Verification of CSU's 2016 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. 19 out of 32 (59%) of seasonal forecast parameters were within one standard deviation of observations for the 2016 seasonal forecast. Our largest forecast bust was for major hurricane days, which was primarily due to the very long-lived intense Hurricane Matthew. Error bars for storms are rounded to the nearest storm. For example, the hurricane prediction in early April would be 0.9-5.1, which with rounding would be 1-5.

Forecast Parameter and 1981-2010 Median (in parentheses)	14 April 2016	Update 1 June 2016	Update 1 July 2016	Update 4 August 2016	Observed 2016 Total
Named Storms (NS) (12.0)	**13** (±3.5)	**14** (±2.9)	**15** (±2.6)	**15** (±2.2)	15
Named Storm Days (NSD) (60.1)	**52** ±(20.7)	**53** (±19.9)	**55** (±18.1)	**55** (±16.3)	78.25
Hurricanes (H) (6.5)	**6** (±2.1)	**6** (±2.0)	**6** (±1.8)	**6** (±1.7)	7
Hurricane Days (HD) (21.3)	**21** (±11.1)	**21** (±10.7)	**21** (±10.1)	**22** (±9.5)	26.25
Major Hurricanes (MH) (2.0)	**2** (±1.3)	**2** (±1.4)	**2** (±1.2)	**2** (±0.9)	3
Major Hurricane Days (MHD) (3.9)	**4** (±4.0)	**4** (±3.7)	**4** (±3.9)	**5** (±4.1)	9.75
Accumulated Cyclone Energy (ACE) (92)	**93** (±42)	**94** (±40)	**95** (±36)	**100** (±31)	134
Net Tropical Cyclone Activity (NTC) (103%)	**101** (±42)	**103** (±40)	**105** (±36)	**110** (±31)	145

4.1 Preface: Aggregate Verification of our Last Eighteen 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 eighteen 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).

Table 4: The number of years that our tropical cyclone forecasts issued at various lead times have correctly predicted above- or below-median activity for each predictand over the past eighteen years (1999-2016).

Tropical Cyclone Parameter	Early April	Early June	Early August
NS	15/18	16/18	15/18
NSD	13/18	13/18	13/18
H	13/18	13/18	13/18
HD	11/18	12/18	14/18
MH	13/18	14/18	14/18
MHD	12/18	13/18	14/18
NTC	11/18	13/18	15/18
Total	**88/126 (70%)**	**94/126 (75%)**	**98/126 (78%)**

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 1984-2015. These tables will be updated with 2016'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 eighth year that we have issued intraseasonal (e.g. two-week) forecasts of tropical cyclone 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. We issued forecasts for ACE using three categories as defined in Table 5.

Table 5: ACE forecast definition for two-week forecasts.

Parameter	Definition
Above-Average	Greater than 130% of Average ACE for the Two-Week Period
Average	70% - 130% of Average ACE for the Two-Week Period
Below-Average	Less than 70% of Average ACE for the Two-Week Period

Table 6 displays the six two-week forecasts that were issued during the 2016 hurricane season and shows their verification. We correctly predicted four of the six two-week periods, with somewhat of an under-forecast in the second two-week period due to an underestimation in the intensity and longevity of Hurricane Gaston. An over-forecast occurred in the third two-week period due to anticipation that Hurricane Hermine would last longer than it did.

Table 6: Two-week Atlantic ACE forecast verification for 2016. 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
8/4 – 8/17	**Below-Average (4 or Fewer)**	**3**
8/18 – 8/31	**Below-Average (13 or Fewer)**	**23**
9/1 – 9/14	**Average (19 - 34)**	**9**
9/15 – 9/28	**Below-Average (16 or Fewer)**	**11**
9/29 – 10/12	**Above-Average (13 or More)**	**60**
10/13 – 10/26	**Above-Average (9 or More)**	**13**

The MJO was fairly weak and disorganized during the early part of the peak Atlantic hurricane season with some amplification over the Maritime Continent during the middle part of September. In general, MJO Phases 4 and 5 are not particularly conducive for Atlantic hurricane formation, and the middle part of September was quite quiet in the Atlantic, with no hurricanes in the Atlantic from September 3 – 28. The MJO, as measured by the Wheeler-Hendon classification scheme, has been quite weak during most of October.

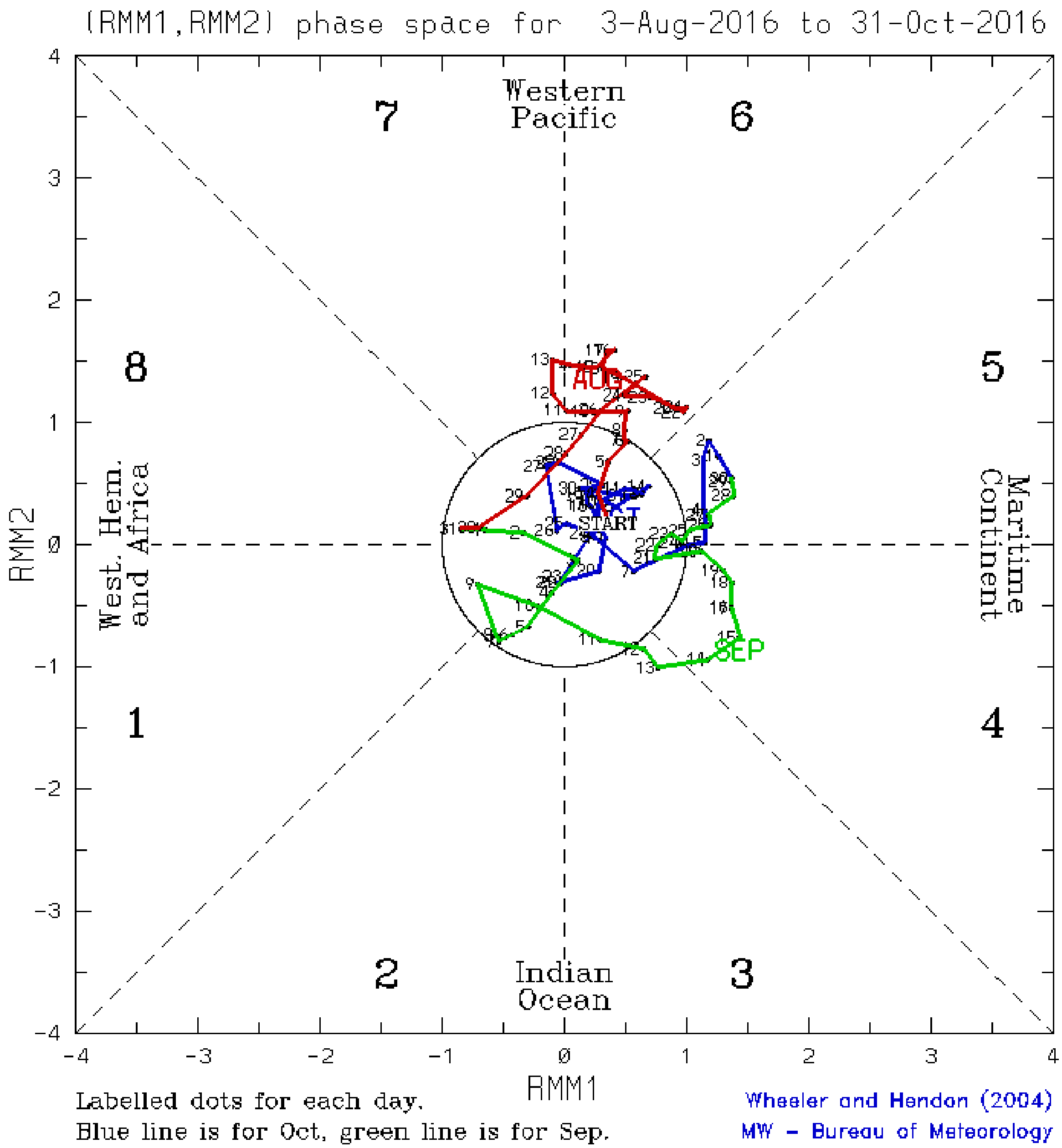


Figure 2: Propagation of the Madden-Julian Oscillation (MJO) based on the Wheeler-Hendon classification scheme over the period from August 3 to October 31. The MJO was generally weak during the early and late part of the peak of the Atlantic hurricane season, with some amplification over the Maritime Continent in middle to late September. The Maritime Continent refers to Indonesia and the surrounding islands. RMM stands for Real-Time Multivariate MJO. The dark red line represents August values, the green line represents September values, and the blue line represents October values.

5 Landfall Probabilities

Every hurricane season, we issue forecasts of the seasonal probability of hurricane landfall along the U.S. 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, U.S. probabilities have been calculated through a statistical analysis of all U.S. hurricane and named storm landfalls during a 100-year period (1900-1999). Specific landfall probabilities can be given for all tropical cyclone intensity classes for a set of distinct U.S. coastal regions. Net landfall probability is statistically related to overall Atlantic basin Net Tropical Cyclone (NTC) activity. Table 7 gives verifications of our landfall probability estimates for the United States and for the Caribbean in 2016.

Landfall probabilities for the 2016 hurricane season were estimated to be near their long-period averages for all predictions due to the forecasts of a near-average hurricane season. The 2016 hurricane season was near-normal from a U.S. landfall perspective, with two tropical storms (Colin and Julia) and two hurricanes (Hermine and Matthew) making U.S. landfall this year. Average U.S. landfalling statistics since 1900 are that 3.5 named storms, 1.8 hurricanes and 0.7 major hurricanes make U.S. landfall per year.

Three tropical cyclones passed through the Caribbean (10-20°N, 60-88°W) during 2016. Earl reached hurricane strength in the western Caribbean, while Matthew reached Category 5 status as it tore a destructive path through the eastern and central Caribbean. Hurricane Otto made landfall as a Category 2 hurricane in Nicaragua in late November.

Landfall probabilities include specific forecasts of the probability of U.S. landfalling tropical storms (TS) and hurricanes of category 1-2 and 3-4-5 intensity for each of 11 units of the U.S. coastline (Figure 3). 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.

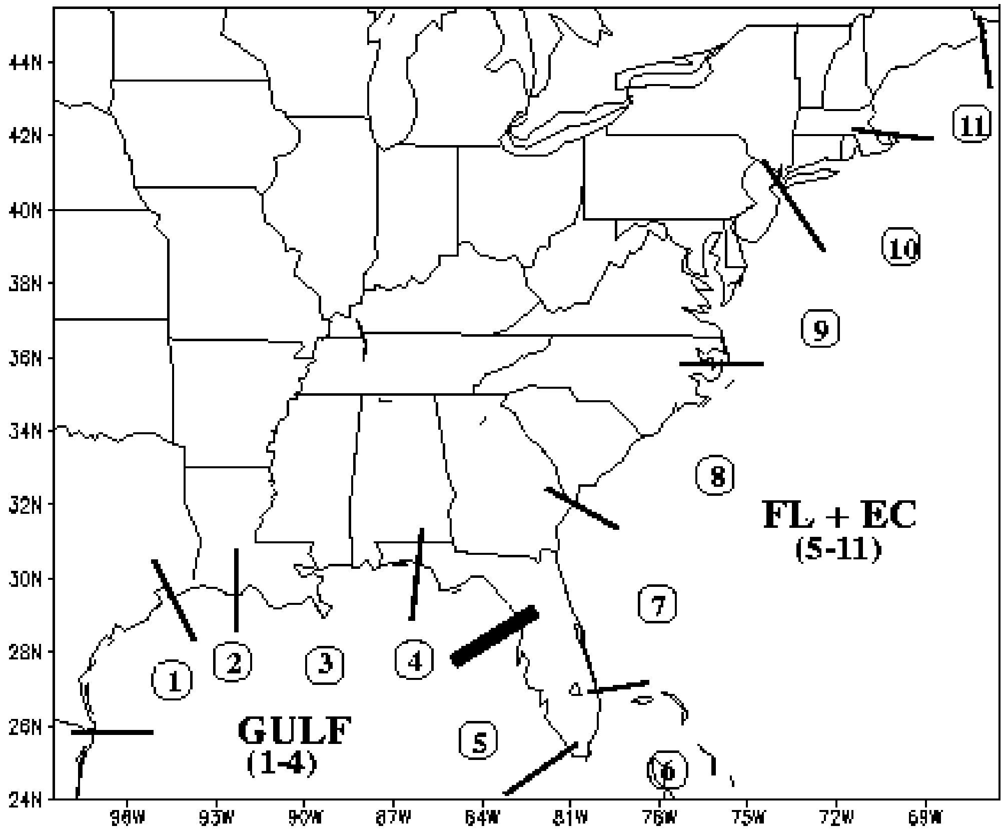


Figure 3: Location of the 11 coastal regions for which separate hurricane landfall probability estimates are made. These subdivisions were determined by the historical frequency of landfalling major hurricanes.

Table 7: 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 U.S. coastline, along the Gulf Coast (Regions 1-4), along the Florida Peninsula and the East Coast (Regions 5-11) and in the Caribbean for 2016 at various lead times. The mean annual percentage of one or more landfalling systems during the 20th century is given in parentheses in the 4 August forecast column. Table (a) is for the entire United States, Table (b) is for the U.S. 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 U.S. (Regions 1-11)
Forecast Date

	14 Apr.	1 June	1 July	4 August	Observed Number
TS	79%	80%	81%	79% (80%)	2
HUR (Cat 1-2)	68%	69%	69%	67% (68%)	2
HUR (Cat 3-4-5)	52%	53%	54%	51% (52%)	0
All HUR	85%	85%	86%	84% (84%)	2
Named Storms	97%	97%	97%	96% (97%)	4

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

	14 Apr.	1 June	1 July	4 August	Observed Number
TS	59%	60%	60%	57% (59%)	1
HUR (Cat 1-2)	43%	43%	44%	41% (42%)	1
HUR (Cat 3-4-5)	30%	31%	31%	29% (30%)	0
All HUR	60%	61%	62%	59% (60%)	1
Named Storms	84%	84%	85%	82% (83%)	2

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

	14 Apr.	1 June	1 July	4 August	Observed Number
TS	51%	51%	52%	49% (51%)	1
HUR (Cat 1-2)	44%	45%	46%	43% (45%)	1
HUR (Cat 3-4-5)	31%	32%	32%	30% (31%)	0
All HUR	62%	62%	63%	60% (61%)	1
Named Storms	81%	82%	82%	80% (81%)	2

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

	14 Apr.	1 June	1 July	4 August	Observed Number
TS	82%	82%	83%	81% (82%)	0
HUR (Cat 1-2)	57%	57%	57%	56% (57%)	2
HUR (Cat 3-4-5)	42%	42%	42%	41% (42%)	1
All HUR	75%	75%	75%	74% (75%)	3
Named Storms	96%	96%	96%	95% (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 2016 Atlantic basin hurricane season in either a favorable or unfavorable manner.

7.1 ENSO

Going into the 2016 Atlantic hurricane season, we anticipated either cool neutral ENSO or weak La Niña conditions for the peak months of the hurricane season from August-October. For most metrics, the August-October period of 2016 was classified as cool neutral ENSO. Below we excerpt a few quotes from our forecasts describing what we anticipated for the 2016 Atlantic hurricane season.

(14 April 2016) –

"By August-October, virtually all models are calling for neutral ENSO or La Niña conditions (Figure 11). The only two dynamical models calling for reemergence of El Niño conditions (LDEO and CFSv2) had significant initialization issues in the equatorial Atlantic which likely teleconnected to faulty ENSO forecasts. These initialization issues have since been corrected, and consequently most ensemble members of the CFSv2 are now calling for weak to moderate La Niña conditions (Figure 12). Based on the above information, our best estimate is that we will likely have either cool neutral ENSO conditions or weak La Niña conditions by the peak of the Atlantic hurricane season."

(1 June 2016) –

"Our confidence that El Niño will dissipate and likely transition to La Niña conditions has grown since early April. Upper-ocean heat content anomalies are now below average across the entire tropical Pacific, indicating that the strong El Niño that just occurred discharged significant heat away from the tropical Pacific (Figure 11).

(4 August 2016) –

"Most of the ensemble members of NOAA's Climate Forecast System (CFS) model are calling for cool neutral to weak La Niña conditions for August-October

(Figure 11). Based on our assessment of both current conditions as well as forecast model output, our best estimate is that we will likely have cool neutral to weak La Niña conditions for August-October. This is somewhat a question of semantics; however, as whether the Nino 3.4 region is -0.4°C (defined as cool neutral) or -0.6°C (defined to be weak La Niña) makes relatively little difference in terms of its impacts on the Atlantic hurricane season.“

El Niño conditions rapidly dissipated during the spring and were replaced by cool neutral ENSO conditions by the late summer. We currently have weak La Niña conditions across the eastern and central tropical Pacific. Table 10 displays anomalies in the various Nino regions in January, April, July and October 2016, respectively.

Table 10: 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 2016 are in parentheses.

Region	January 2016 Anomaly (ºC)	April 2016 Anomaly (ºC)	July 2016 Anomaly (ºC)	October 2016 Anomaly (ºC)
Nino 1+2	+1.4	+0.2 (-1.2)	+0.2 (-1.2)	+0.4 (-1.0)
Nino 3	+2.6	+0.8 (-1.8)	-0.5 (-3.1)	-0.4 (-3.0)
Nino 3.4	+2.6	+1.1 (-1.5)	-0.5 (-3.1)	-0.7 (-3.3)
Nino 4	+1.4	+0.9 (-0.5)	+0.3 (-1.1)	-0.4 (-1.8)

The current ENSO event has transitioned from cool neutral to weak La Niña over the past couple of months. While the El Niño rapidly transitioned to neutral ENSO conditions by June/July, upper ocean heat content anomalies have remained between -0.5 - -1°C since that time (Figure 4). These types of upper-ocean heat content anomalies are typical for cool neutral ENSO or weak La Niña conditions.

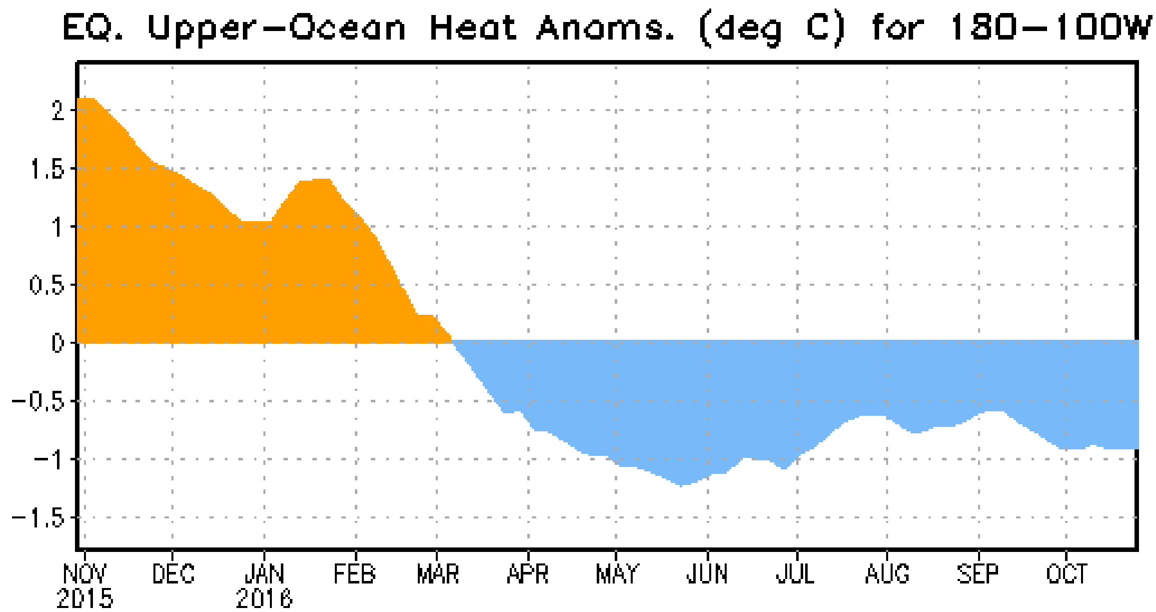


Figure 4: Upper ocean (0-300 meter) heat content anomalies in the eastern and central tropical Pacific from November 2015 – October 2016. Note the rapid cooling that occurred from late January through June, indicative of the weakening El Niño event. Upper ocean heat content anomalies have remained relatively stationary since the middle part of June.

7.2 Intra-Seasonal Variability

The MJO was fairly weak and disorganized during the early part of the peak Atlantic hurricane season with some amplification over the Maritime Continent (Phases 4-5) during the middle part of September (Figure 5). Typically Phases 1-3 are the MJO phases that are most associated with active periods for Atlantic hurricane activity (Table 11). It should be noted that the MJO spent only one day in Phase 1 (according to the Wheeler-Hendon index) during August-October. The MJO, as measured by the Wheeler-Hendon classification scheme, has been quite weak during most of October. Table 12 displays the TC formations by each phase of the MJO during the 2016 Atlantic hurricane season.

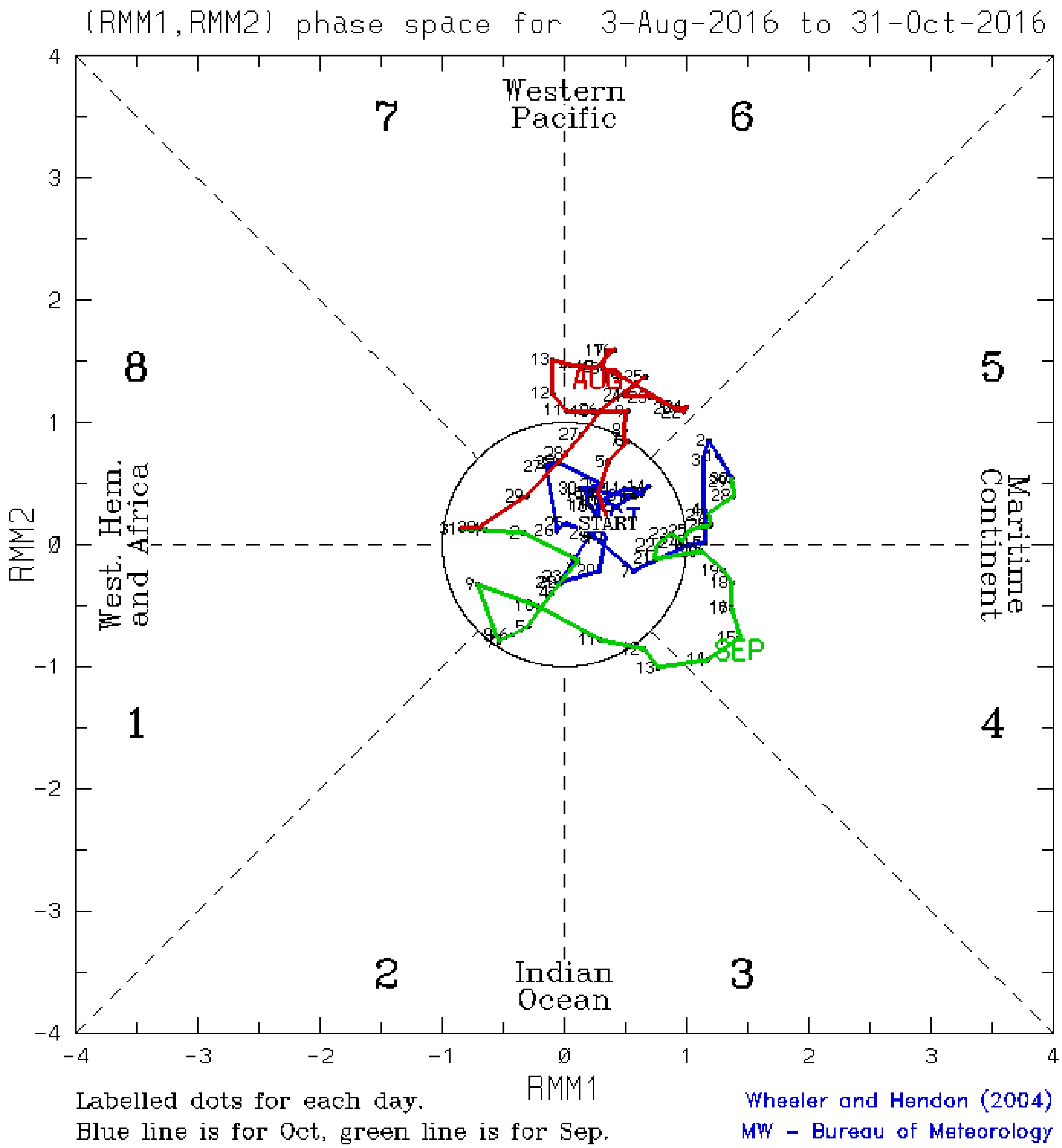


Figure 5: Propagation of the Madden-Julian Oscillation (MJO) based on the Wheeler-Hendon classification scheme over the period from August 3 to October 31. The MJO was generally weak during the early and late part of the peak of the Atlantic hurricane season, with some amplification over the Maritime Continent in middle to late September. The Maritime Continent refers to Indonesia and the surrounding islands. RMM stands for Real-Time Multivariate MJO. The dark red line represents August values, the green line represents September values, and the blue line represents October values.

Table 11: 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 tropical cyclones 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

Table 12: TC formations by MJO phase during the 2016 Atlantic hurricane season.

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

7.3 Atlantic SST

At the time of our final seasonal forecast in early August, we observed that while the tropical Atlantic was warmer than normal, the subtropical North Atlantic was somewhat cooler than normal (Figure 6). Typically a cooler than normal subtropical North Atlantic is not considered conducive for hurricane formation, due to the fact that it favors enhanced baroclinicity and potential penetration of upper-level cold lows and associated shear into the tropics. In addition, cold anomalies in the subtropics tend to propagate into the tropics due to the prevailing circulation of the ocean.

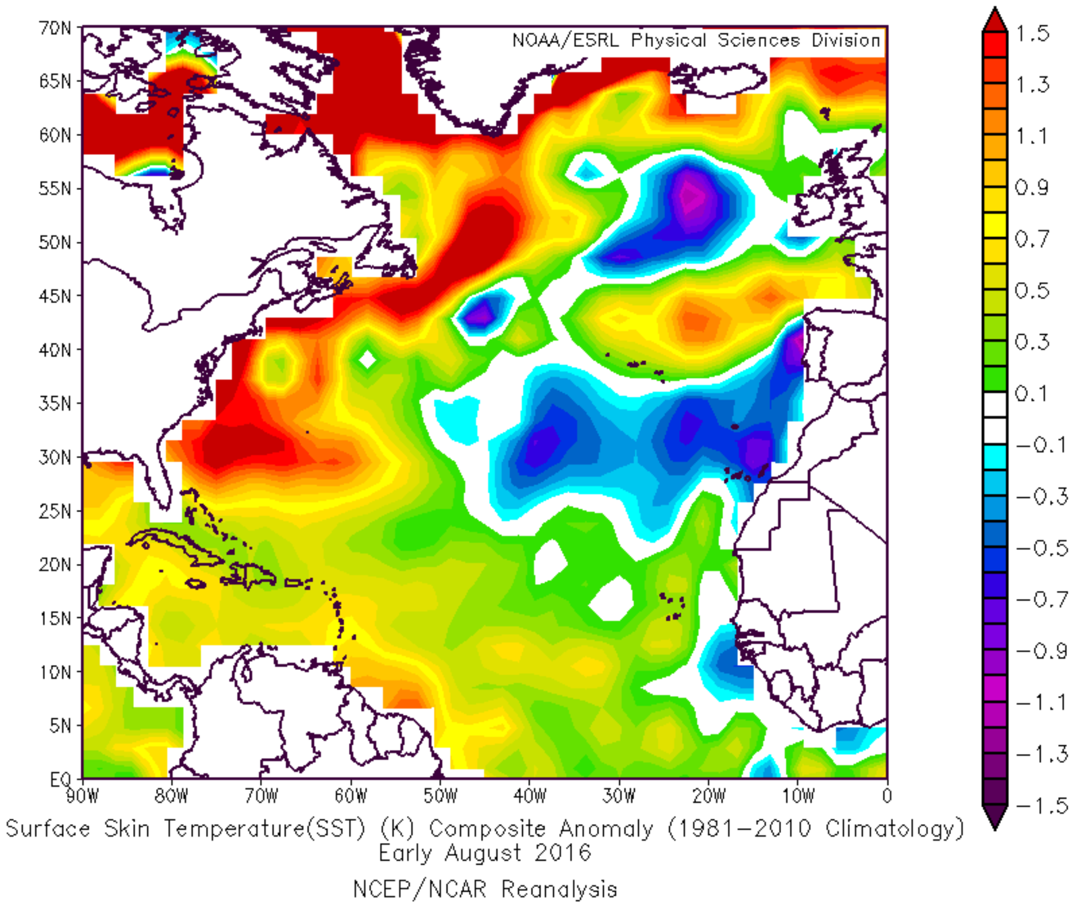


Figure 6: Early August 2016 SST anomalies across the Atlantic basin. Note the cold anomalies that pervaded the subtropical North Atlantic.

Figure 7 displays the anomalous SST pattern change that took place across the Atlantic from early August to late October. Relatively little change in SSTs took place in the tropical Atlantic, while there was considerable warming in the subtropical Atlantic and cooling in the western part of the far North Atlantic.

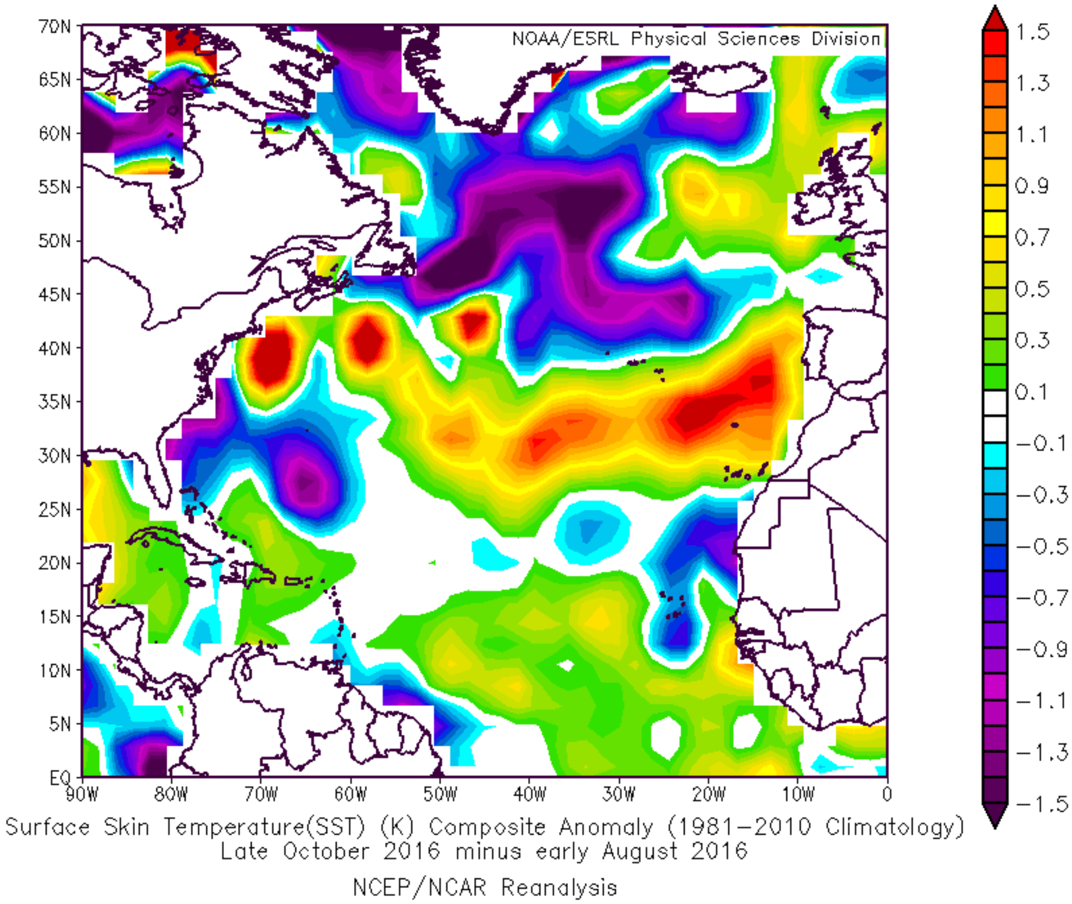


Figure 7: Late October 2016 minus early August 2016 anomalous SST change across the Atlantic basin. Little change in SST has occurred in the tropical Atlantic, while there has been considerable warming in the subtropical Atlantic and cooling in the western part of the far North Atlantic.

Figure 8 displays current SST anomalies across the Atlantic basin. In general, most of the tropical and subtropical Atlantic is warmer than normal, while the cold in the far North Atlantic remains. We expect that this cold SST anomaly may intensify over the next couple of months, as anomalously cold water that became sequestered at depth in the North Atlantic when the westerly winds weakened in the summer may become re-entrained into the mixed layer this fall and early winter.

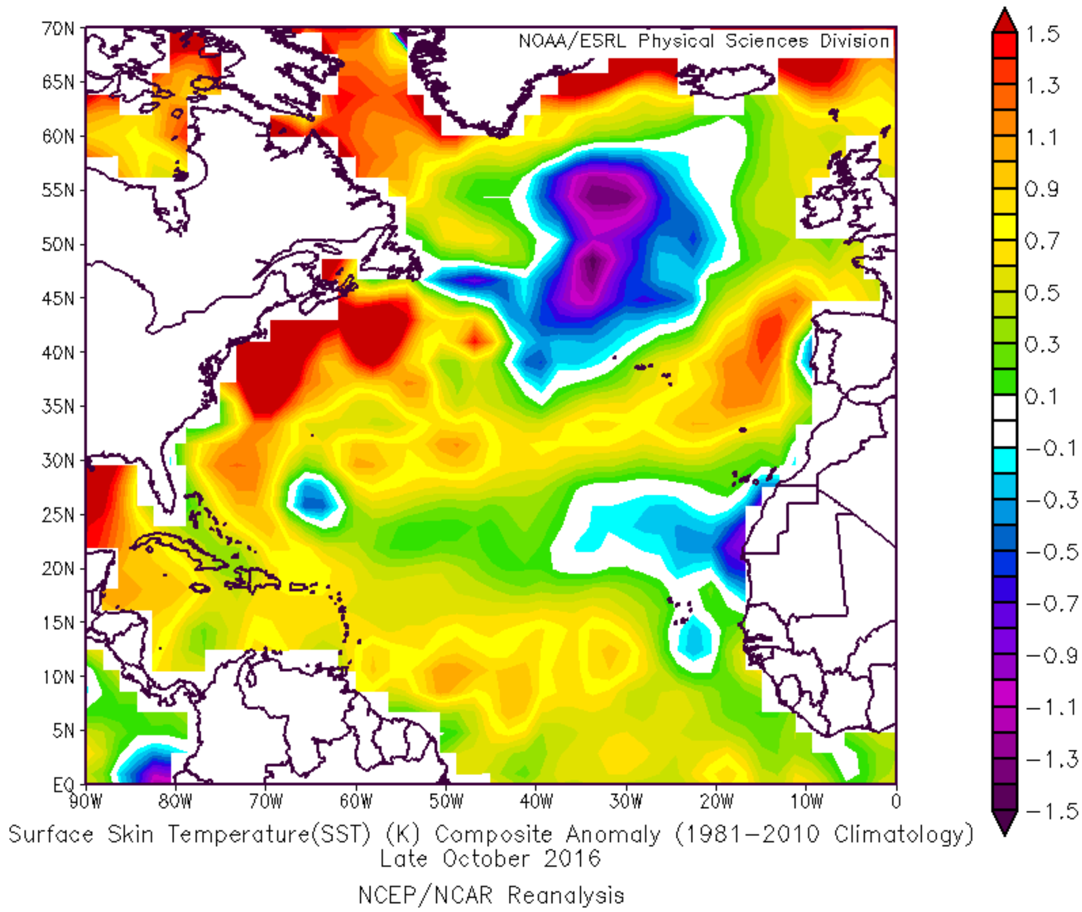


Figure 8: Late October 2016 SST anomalies.

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 2016 Atlantic hurricane season was characterized by slightly below-normal sea level pressures across the tropical Atlantic. Figure 9 displays August-October 2016 tropical and sub-tropical sea level pressure anomalies in the North Atlantic.

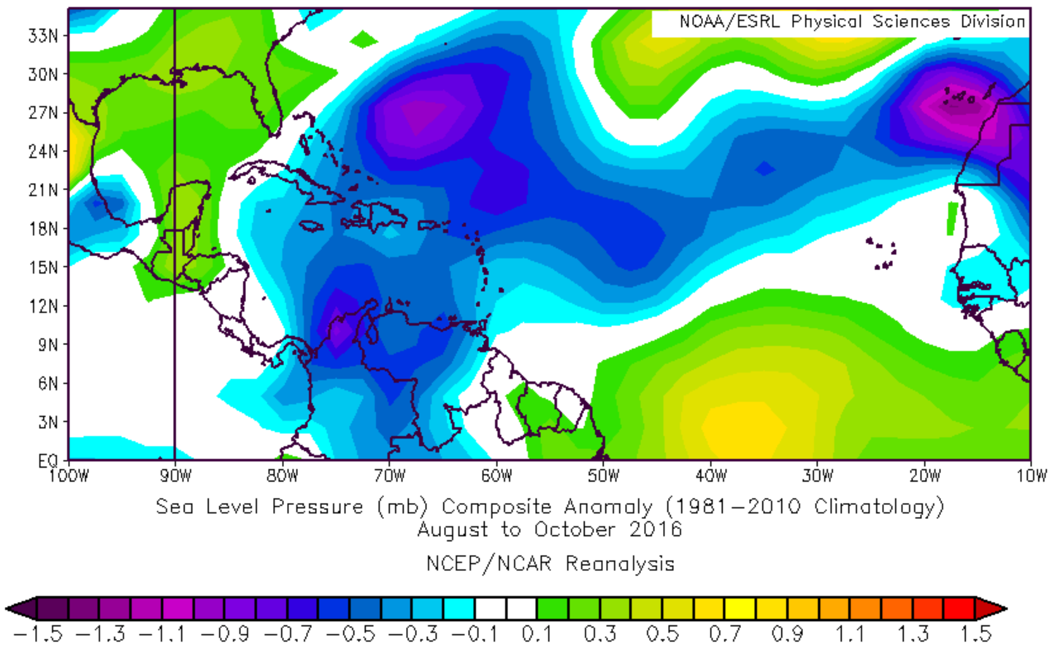


Figure 9: August-October 2016 tropical and sub-tropical North Atlantic sea level pressure anomalies.

7.5 Tropical Atlantic Vertical Wind Shear

Caribbean vertical wind shear was considerably reduced from the levels that it has been the past two years, when record shear prevailed across most of the Caribbean. While shear averaged over August through October remained elevated across the western Caribbean, August-October-averaged shear was lower than normal across most of the central tropical Atlantic (Figure 10). Unlike the past two seasons, at least in the aggregate sense, vertical wind shear did not appear to be a primary deterrent for TC formation and intensification this year.

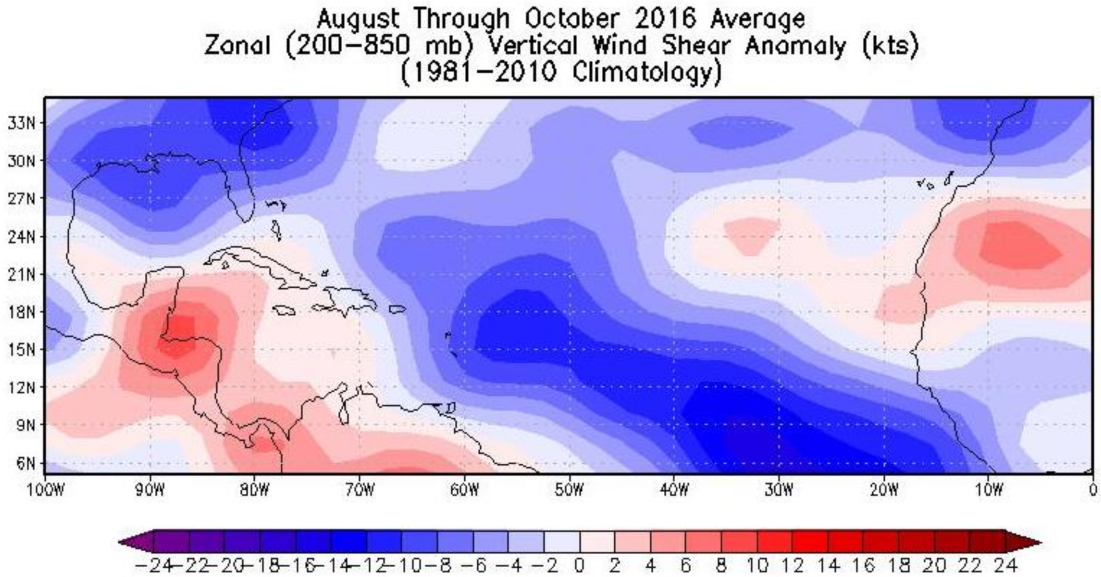


Figure 10: Anomalous vertical wind shear observed across the Atlantic from August 1 – October 31, 2016.

7.6 Tropical Atlantic Moisture

The tropical Atlantic and Caribbean was anomalously dry at mid-levels in the atmosphere in August through October, similar in magnitude to the past few hurricane seasons where the tropical Atlantic has been similarly dry (Figure 11). Dry mid-levels suppress hurricane formation and intensification by enhancing mid-level entrainment and suppressing deep convection. The dryness was especially pronounced in the southern portions of the tropical Atlantic as well as in the Caribbean.

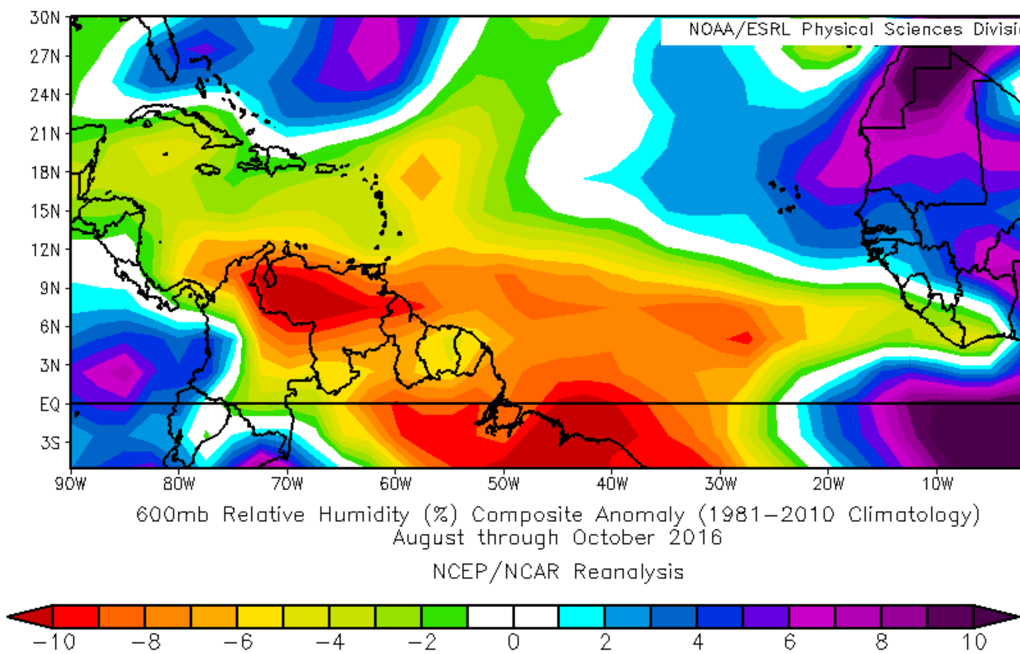


Figure 11: August-October 2016 600-mb RH anomalies. Most of the tropical Atlantic and Caribbean was anomalously dry this year.

7.7 Steering Currents

Unlike the past few years, when a trough of low pressure dominated along the United States East Coast, mid-level heights were above-average across virtually the entire North Atlantic during August-October of 2016 (Figure 12). This is what you would expect given the very warm mid-levels of the atmosphere that dominated the mid-latitudes this summer. The gradient of these anomalies in 2016, however, did not seem to favor recurvature of TCs like they have in recent years. Anomalously high heights over New England as well as the Maritime Provinces would, in general, favor anomalous easterly flow which would push TCs towards the mainland United States. While the U.S. major hurricane landfall drought streak continued for a record 11th year, it was within about 50 miles of being broken when Hurricane Matthew brushed the east coast of Florida in early October.

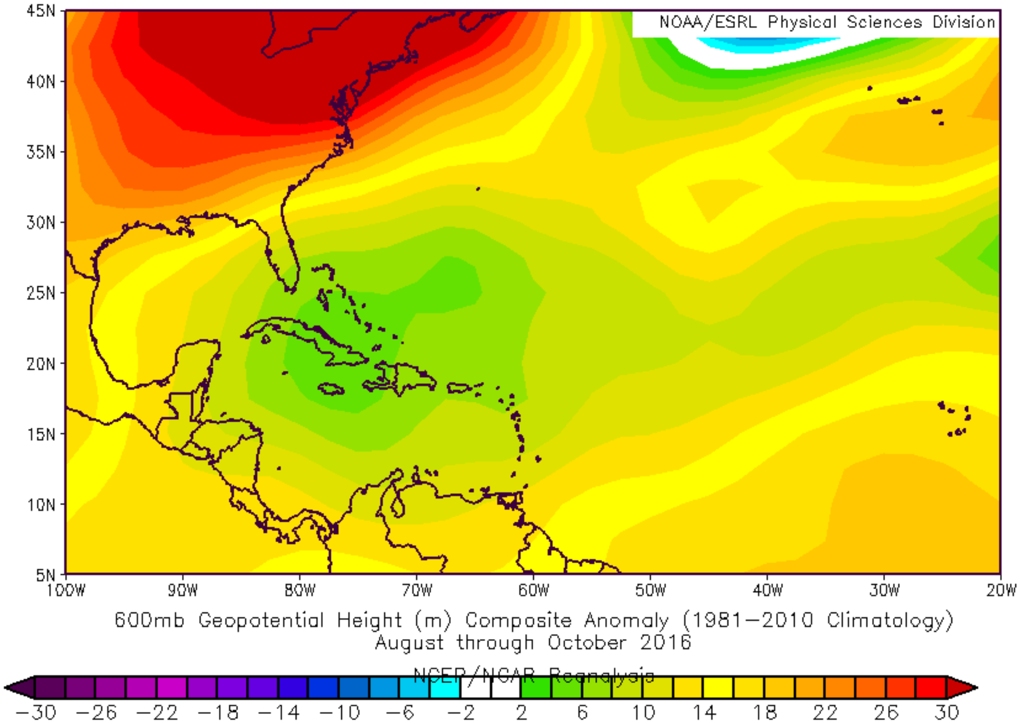


Figure 12: 600-mb height anomalies in the central and western part of the Atlantic from August through October 2016. Anomalous troughing dominated along the East Coast of the United States.

7.9 Atlantic Thermohaline Circulation (THC) Conditions

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). The 2016 Atlantic hurricane season has likely led to more questions than answers in this regard, as the climatologically most active portion of the season (September) was quiet for the fourth straight year. However, we had a very active October including a very intense Caribbean hurricane (Matthew).

We monitor the strength of the THC 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 13). This index reached very low levels earlier this year (associated with both colder than normal SSTs as well as higher than normal SLPs) (Figure 14). From July-September, far North Atlantic SSTs anomalously warmed. However, during October, far North Atlantic SSTs anomalously cooled again. This is consistent with cold anomalies being trapped below the thermocline in the summer months which were then re-entrained back into the mixed layer as westerly winds began to re-strengthen with the transition from the summer to fall. Despite this cooling, our AMO index in October remained near average due to slightly below-normal SLP anomalies.

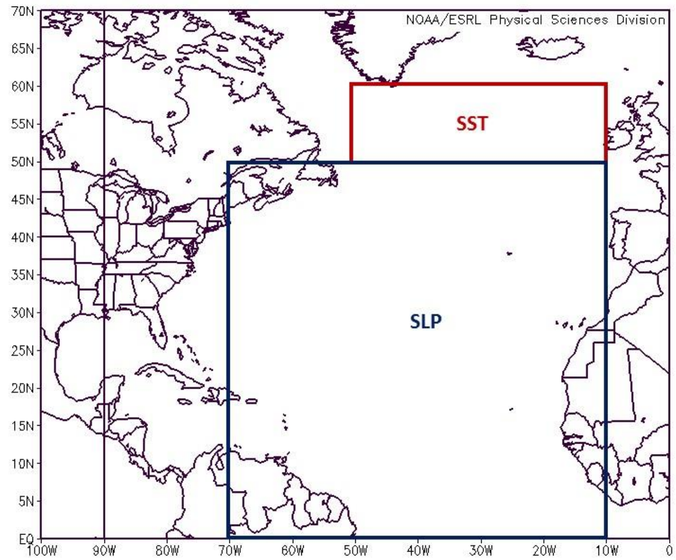


Figure 13: Regions which are utilized for the calculation of our AMO index.

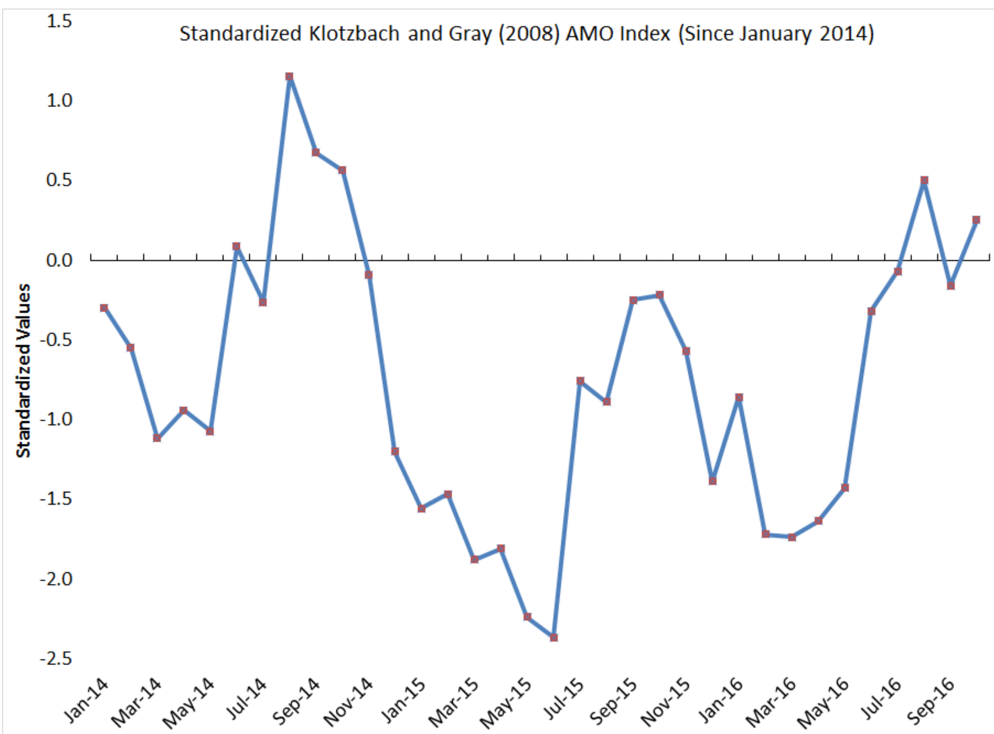


Figure 14: Standardized values of the AMO index by month since January 2014. The index was very low during the spring of 2016 but has since rebounded to near-normal levels.

8 Forecasts of 2017 Hurricane Activity

We will be issuing our first outlook for the 2017 hurricane season on Wednesday, 14 December 2016. This forecast will provide a qualitative outlook for factors likely to impact the 2017 hurricane season. This December forecast will include the dates of all of our updated 2017 forecasts. All of these forecasts will be made available online.

9 Acknowledgments

Besides the individuals named on page 5, there have been a number of other meteorologists that have furnished us with data and given valuable assessments of the current state of global atmospheric and oceanic conditions. These include Carl Schreck, Brian McNoldy, Art Douglas, Ray Zehr, Mark DeMaria, Todd Kimberlain, Paul Roundy, Jason Dunion and Amato Evan. In addition, Barbara Brumit and Amie Hedstrom have provided excellent manuscript, graphical and data analysis and assistance over a number of years. We have profited over the years from many in-depth discussions with most of the current and past NHC hurricane forecasters. We are grateful for support from Interstate Restoration, Ironshore Insurance and Macquarie Group that partially support the release of these predictions.

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11 Verification of Previous Forecasts

Table 13: Verification of the authors' early August forecasts of Atlantic named storms and hurricanes between 1984-2016. 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 28 of 33 years for named storms and 25 of 33 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
Average	**10.9**	**10.7**	**6.1**	**6.0**
1984-2016 Rank Correlation		**0.62**		**0.52**

Table 14: Summary verification of the authors' five previous years of seasonal forecasts for Atlantic TC activity between 2011-2015. Verifications of all seasonal forecasts back to 1984 are available here: http://tropical.atmos.colostate.edu/Includes/Documents/Publications/forecast_verifications.xls

2011	8 Dec. 2010	Update 6 April	Update 1 June	Update 3 August	Obs.
Hurricanes	9	9	9	9	7
Named Storms	17	16	16	16	19
Hurricane Days	40	35	35	35	26
Named Storm Days	85	80	80	80	89.75
Major Hurricanes	5	5	5	5	4
Major Hurricane Days	10	10	10	10	4.50
Accumulated Cyclone Energy	165	160	160	160	126
Net Tropical Cyclone Activity	180	175	175	175	145

2012	4 April	Update 1 June	Update 3 August	Obs.
Hurricanes	4	5	6	10
Named Storms	10	13	14	19
Hurricane Days	16	18	20	28.50
Named Storm Days	40	50	52	101.25
Major Hurricanes	2	2	2	2
Major Hurricane Days	3	4	5	0.50
Accumulated Cyclone Energy	70	80	99	133
Net Tropical Cyclone Activity	75	90	105	131

2013	10 April	Update 3 June	Update 2 August	Obs.
Hurricanes	9	9	8	2
Named Storms	18	18	18	14
Hurricane Days	40	40	35	3.75
Named Storm Days	95	95	84.25	42.25
Major Hurricanes	4	4	3	0
Major Hurricane Days	9	9	7	0
Accumulated Cyclone Energy	165	165	142	36
Net Tropical Cyclone Activity	175	175	150	47

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	12.00
Named Storm Days	30	30	30	25	43.50
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	63
Net Tropical Cyclone Activity	45	45	45	40	81