SUMMARY OF 2015 ATLANTIC TROPICAL CYCLONE ACTIVITY AND VERIFICATION OF AUTHORS' SEASONAL AND TWO-WEEK FORECASTS

The 2015 Atlantic hurricane season had slightly more activity than predicted in our seasonal outlooks although we did correctly predict a somewhat below-average season. Strong vertical wind shear driven by a strong El Niño was the primary reason why below-average activity was experienced. Overall ACE activity in 2015 was approximately 65% of the 1981-2010 median.

By Philip J. Klotzbach[1] and William M. Gray[2]

This forecast as well as past forecasts and verifications are available online at http://hurricane.atmos.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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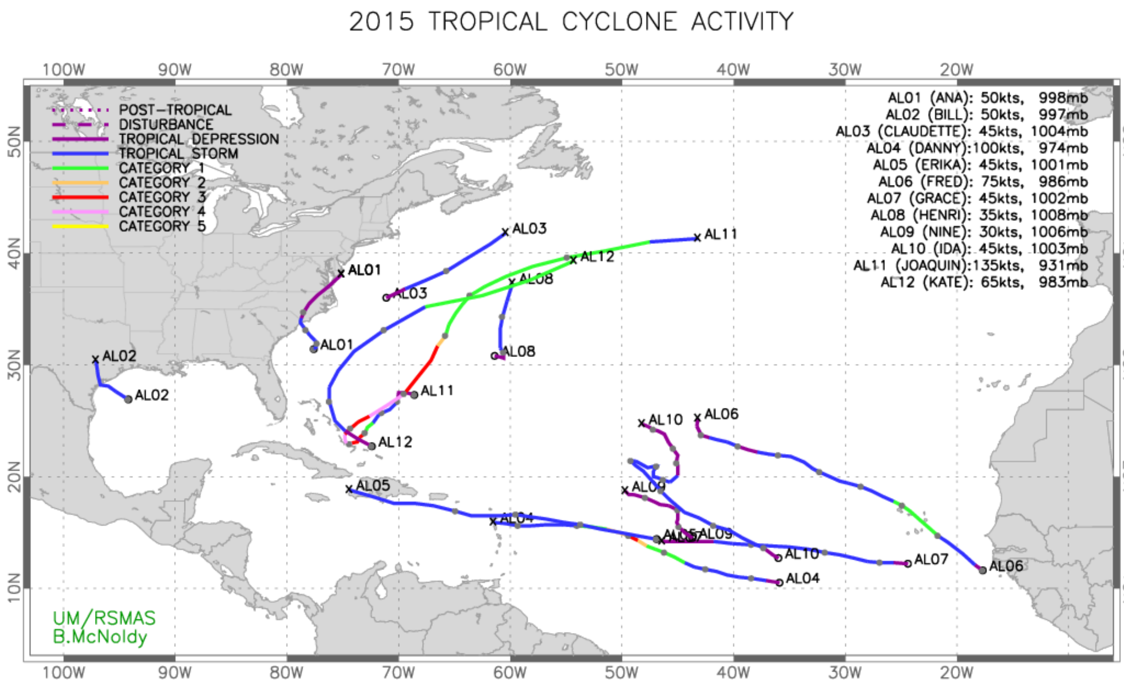
ATLANTIC BASIN SEASONAL HURRICANE FORECASTS FOR 2015

Forecast Parameter and 1981-2010 Median (in parentheses)	Issue Date 9 April 2015	Issue Date 1 June 2015	Issue Date 1 July 2015	Issue Date 4 August 2015	Observed 2015 Activity	% of 1981-2010 Median
Named Storms (NS) (12.0)	7	8	8	8	11	67%
Named Storm Days (NSD) (60.1)	30	30	30	25	46.25	58%
Hurricanes (H) (6.5)	3	3	3	2	4	92%
Hurricane Days (HD) (21.3)	10	10	10	8	11.50	81%
Major Hurricanes (MH) (2.0)	1	1	1	1	2	100%
Major Hurricane Days (MHD) (3.9)	0.5	0.5	0.5	0.5	4	90%
Accumulated Cyclone Energy (ACE) (92)	40	40	40	35	62	70%
Net Tropical Cyclone Activity (NTC) (103%)	45	45	45	40	82	79%



Atlantic basin tropical cyclone tracks in 2015. Figure courtesy of Brian McNoldy at the University of Miami. Eleven named storms and one tropical depression occurred in 2015.

ABSTRACT

This report summarizes tropical cyclone (TC) activity which occurred in the Atlantic basin during 2015 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 primarily based on the phase of the Madden-Julian Oscillation (MJO).

Our first quantitative seasonal forecast for 2015 was issued on 9 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 2015.

The 2015 hurricane season was relatively quiet. The season was characterized by slightly below-average numbers of named storms, hurricanes and major hurricanes. This year's seasonal forecast slightly under-estimated Accumulated Cyclone Energy (ACE) and Net Tropical Cyclone (NTC) activity levels. Notably, nearly half of this season's ACE was generated by just one storm (Joaquin).

We issued six consecutive two-week forecasts during the peak months of the Atlantic hurricane season from August-October. These forecasts were primarily based on predicted activity by the global forecast models and the phase of the Madden-Julian Oscillation (MJO). These two-week forecasts generally verified quite well.

Integrated measures such as Net Tropical Cyclone (NTC) activity and Accumulated Cyclone Energy (ACE) were at below-average levels. The primary inhibitor to TC formation this year was very strong vertical wind shear, especially in the central tropical Atlantic and Caribbean. Several TCs formed in the eastern Atlantic, only to be sheared apart as they approached the Lesser Antilles.

We expected a strong El Niño to develop during the Atlantic hurricane season, and this expectation verified. The primary large-scale condition that surprised us this year was the strong anomalous warming that occurred in the tropical Atlantic from June to October. Below-average SST anomalies across the tropical Atlantic in June were replaced with record-warm SST anomalies across the tropical Atlantic by October.

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

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).

The second author gratefully acknowledges the valuable input to his CSU seasonal forecast research project over many years by former graduate students and now colleagues 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. Table 1 displays the average of the five most active seasons (as ranked by NTC) compared with the five least active seasons (as ranked by NTC) since 1944. Note how large the ratio differences are between very active versus very inactive seasons, especially for major hurricanes (16.5 to 1) and major hurricane days (63 to 1). Major hurricanes, on a normalized basis, bring about 80-85% of hurricane-related destruction (Pielke et al. 2008).

Table 1: Comparison of the average of the five most active seasons since 1944 compared with the five least active seasons since 1944. The active/inactive ratio is also provided.

	NS	NSD	H	HD	MH	MHD	ACE	NTC
Five Most Active Seasons	17.2	102.9	10.8	52.8	6.6	18.9	231	240
Five Least Active Seasons	6.0	23.2	3.0	6.7	0.4	0.3	31	35
Most Active/Least Active Ratio	2.9	4.4	3.6	7.9	16.5	63.0	7.6	6.9

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.

The global atmosphere and oceans in combination have stored memory buried within them that can provide clues as to how active the upcoming Atlantic basin hurricane season is likely to be. The benefit of such empirical investigation (or data mining) is such that any precursor relationship that might be found can immediately be utilized without having to have a complete understanding of the physics involved.

Analyzing the available data in the 1980s, we 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. We now find that our most reliable forecasts utilize a combination of three or four variables.

A cardinal rule we have always 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 we now use are available back to 1948. This gives us more than 60 years of hindcast information. We also utilize newer reanalyses that have been developed on the past ~30 years of data (e.g., the ERA-Interim and CFSR Reanalyses). We also have been exploring longer-term reanalysis products such as the 20^{th} Century Reanalysis from the Earth System Research Laboratory.

The 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 we can always be confident in applying. We have learned that precursor relations can change with time and that one must be alert to these changing relationships. For instance, our 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 we have had to substitute other precursor signals in their place. As we gather new data and new insights in 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 2015

Figure 1 and Table 2 summarize Atlantic basin TC activity which occurred in 2015. Overall, the season was characterized by below-average activity. Online entries from Wikipedia (http://www.wikipedia.org) are available for physical discussions of each TC that occurred in 2015.

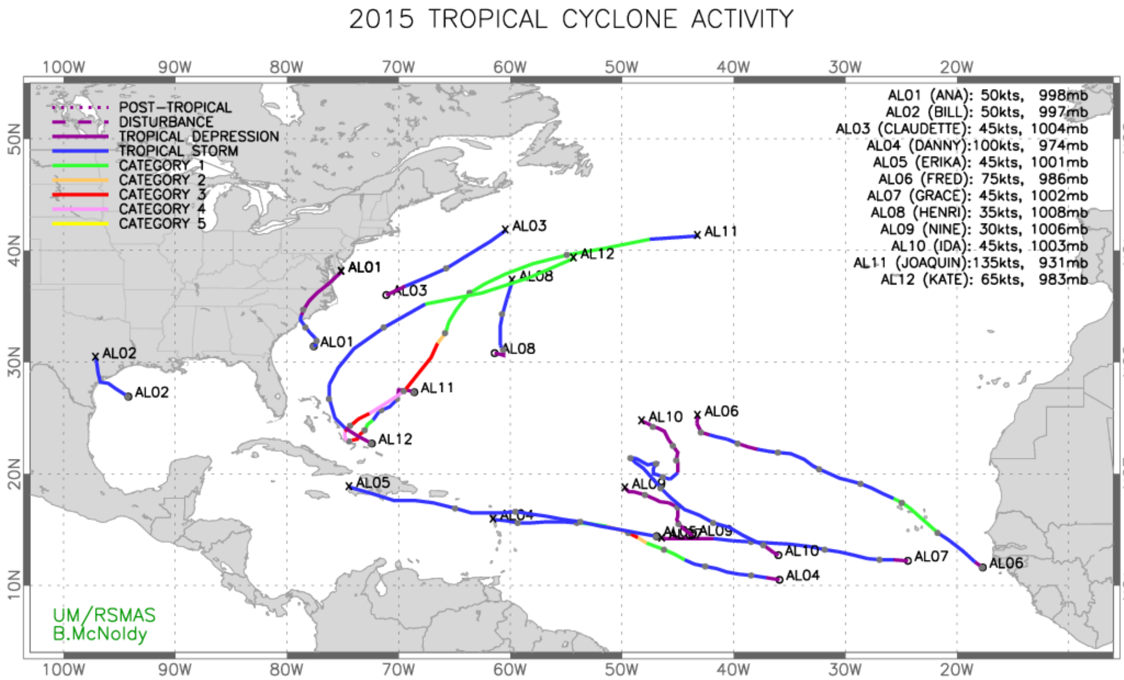


Figure 1: Atlantic basin tropical cyclone tracks in 2015. Figure courtesy of Brian McNoldy at the University of Miami. Eleven named storms and one tropical depression occurred in 2015.

Table 2: Observed 2015 Atlantic basin tropical cyclone activity.

Highest Category	Name	Dates	Peak Sustained Winds (kts)/lowest SLP (mb)	NSD	HD	MHD	ACE	NTC
TS	Ana (1)	May 7 – 10	50 kt/998 mb	3.50			2.6	2.9
TS	Bill (2)	June 15 – 17	50 kt/997 mb	2.25			1.6	2.5
TS	Claudette (3)	July 13 – 14	45 kt/1004 mb	1.50			1.1	2.2
MH-3	Danny (4)	August 18 – 24	100 kt/974 mb	5.75	2.00	0.25	9.2	16.3
TS	Erika (5)	August 24 – 29	45 kt/1001 mb	5.00			3.2	3.4
H-1	Fred (6)	August 30 – September 5	75 kt/986 mb	6.00	1.25		5.7	7.4
TS	Grace (7)	September 5 -7	45 kt/1002 mb	2.25			1.5	2.5
TS	Henri (8)	September 10 – 11	35 kt/1008mb	1.75			0.9	2.3
TS	Ida (9)	September 19 – 24	45 kt/1003 mb	5.50			3.4	3.5
MH-4	Joaquin (10)	September 29 – October 8	135 kt/931 mb	9.25	7.00	3.75	28.7	32.2
H-1	Kate (11)	November 9 – 12	65 kt/983 mb	3.50	0.75		4.4	6.3
Totals	11			46.25	11.50	4.00	62.1	81.7

3 Special Characteristics of the 2015 Hurricane Season

The 2015 hurricane season had the following special characteristics:

- Eleven named storms (NS) formed in 2015. This is the second year in a row that NS activity has been below the 1981-2010 median. The last time that NS were below the 1981-2010 median in two consecutive years was 1993-1994.

- Four hurricanes formed in 2015, which brings the combined 2013-2015 total to 12 hurricanes. This is the lowest three-year total since 1992-1994 (11 hurricanes).

- Two major hurricanes formed in 2015, which brings the combined 2013-2015 total to 4. No three-year average has been lower since 1992-1994 (2 major hurricanes).

- Joaquin's maximum intensity was 135 knots. The most recent Atlantic TC stronger than Joaquin was Felix (150 knots) in 2007.

- Joaquin was the first Category 4-5 hurricane to impact the Bahamas during October since 1866.

- September ACE was only 11. Three-year (2013-2015) summed September ACE for the Atlantic was only 44, the lowest since 1912-1914 when only 29 ACE was recorded during September.

- No major hurricanes made US landfall in 2015. The last major hurricane to make US landfall was Wilma (2005), so the US has now gone ten years without a major hurricane landfall. The US has never had a ten-year period without a major hurricane landfall, eclipsing the previous record of eight years set from 1861-1868.

- Florida has gone without a hurricane impact since 2005 (ten years). This is the longest consecutive year period on record that Florida has not had a landfall (since 1851). The longest previous record was only five years set from 1980-1984.

- June-October-averaged 200-850-mb vertical wind shear in the Caribbean (10-20°N, 90-60°W) was 28.5 knots which was the strongest on record (since 1979).

5 Verification of Individual 2015 Lead Time Forecasts

Table 4 is a comparison of our forecasts for 2015 for four different lead times along with this year's observations. The 2015 Atlantic hurricane season was characterized by somewhat below-average levels of overall basinwide activity.

Table 4: Verification of our 2015 seasonal hurricane predictions.

Forecast Parameter and 1981-2010 Median (in parentheses)	Issue Date 9 April 2015	Issue Date 1 June 2015	Issue Date 1 July 2015	Issue Date 4 August 2015	Observed 2015 Activity	% of 1981-2010 Median
Named Storms (NS) (12.0)	7	8	8	8	11	67%
Named Storm Days (NSD) (60.1)	30	30	30	25	46.25	58%
Hurricanes (H) (6.5)	3	3	3	2	4	92%
Hurricane Days (HD) (21.3)	10	10	10	8	11.50	81%
Major Hurricanes (MH) (2.0)	1	1	1	1	2	100%
Major Hurricane Days (MHD) (3.9)	0.5	0.5	0.5	0.5	4	90%
Accumulated Cyclone Energy (ACE) (92)	40	40	40	35	62	70%
Net Tropical Cyclone Activity (NTC) (103%)	45	45	45	40	82	79%

Table 5 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 two 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 quite good.

Table 5: Verification of our 2015 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. 27 out of 32 (84%) of seasonal forecast parameters were within one standard deviation of observations for the 2015 seasonal forecast. 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)	9 April 2015	Update 1 June 2015	Update 1 July 2015	Update 4 August 2015	Observed 2015 Total
Named Storms (NS) (12.0)	**7** (±3.5)	**8** (±2.9)	**8** (±2.6)	**8** (±2.2)	11
Named Storm Days (NSD) (60.1)	**30** ±(20.7)	**30** (±19.9)	**30** (±18.1)	**25** (±16.3)	46.25
Hurricanes (H) (6.5)	**3** (±2.1)	**3** (±2.0)	**3** (±1.8)	**2** (±1.7)	4
Hurricane Days (HD) (21.3)	**10** (±11.1)	**10** (±10.7)	**10** (±10.1)	**8** (±9.5)	11.50
Major Hurricanes (MH) (2.0)	**1** (±1.3)	**1** (±1.4)	**1** (±1.2)	**1** (±0.9)	2
Major Hurricane Days (MHD) (3.9)	**0.5** (±4.0)	**0.5** (±3.7)	**0.5** (±3.9)	**0.5** (±4.1)	4
Accumulated Cyclone Energy (ACE) (92)	**40** (±42)	**40** (±40)	**40** (±36)	**35** (±31)	62
Net Tropical Cyclone Activity (NTC) (103%)	**45** (±42)	**45** (±40)	**45** (±36)	**40** (±31)	82

5.1 Preface: Aggregate Verification of our Last Seventeen 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 6 displays how frequently our forecasts have been on the right side of climatology for the past seventeen 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 6: The number of years that our tropical cyclone forecasts issued at various lead times have correctly predicted above- or below-average activity for each predictand over the past seventeen years (1999-2015).

Tropical Cyclone Parameter	Early April	Early June	Early August
NS	14/17	15/17	14/17
NSD	13/17	13/17	13/17
H	13/17	13/17	13/17
HD	11/17	12/17	13/17
MH	12/17	13/17	13/17
MHD	11/17	12/17	13/17
NTC	11/17	12/17	14/17
Total	**85/119 (71%)**	**90/119 (76%)**	**93/119 (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 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 online at http://tropical.atmos.colostate.edu/Includes/Documents/Publications/forecast_verifications.xls. Verifications are currently available for all of our prior seasons from 1984-2014. This spreadsheet will be updated with 2015's values once the National Hurricane Center finishes its post-season analysis of all storms that formed this year.

5.2 Verification of Two-Week Forecasts

This is the seventh 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 7.

Table 7: 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 8 displays the six two-week forecasts that were issued during the 2015 hurricane season and shows their verification. We correctly predicted four of the six two-week periods, with a significant under-forecast in the fifth two-week period due to Hurricane Joaquin becoming much stronger than anticipated on the date that the forecast was issued.

Table 8: Two-week forecast verification for 2015. 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 (3 or Fewer)**	**0**
8/18 – 8/31	**Below-Average (13 or Fewer)**	**15**
9/1 – 9/14	**Below-Average (18 or Fewer)**	**5**
9/15 – 9/28	**Below-Average (16 or Fewer)**	**3**
9/29 – 10/12	**Average (7-12)**	**29**
10/13 – 10/26	**Below-Average (5 or Fewer)**	**0**

The MJO was fairly weak and disorganized during most of the peak of the Atlantic hurricane season in 2015, with most of the period from late August through early October spent in the middle of the circle (indicating an amplitude of the MJO of less than one) (Figure 2). There has been a significance increase in MJO amplitude over the past few weeks.

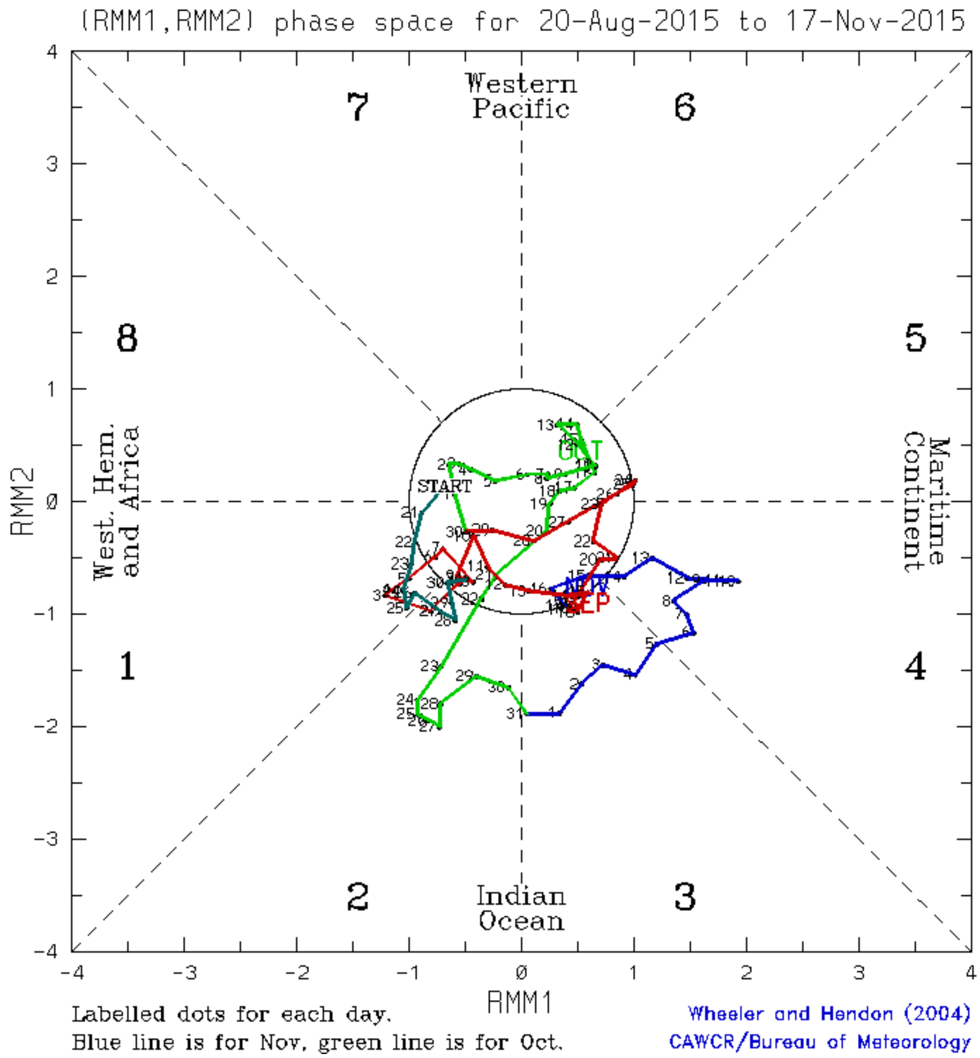


Figure 2: Propagation of the Madden-Julian Oscillation (MJO) based on the Wheeler-Hendon classification scheme over the period from August 20 to November 17. The MJO was generally weak during the peak months of this year's Atlantic hurricane season. The Maritime Continent refers to Indonesia and the surrounding islands. RMM stands for Real-Time Multivariate MJO. The dark green line represents August values, the red line represents September values, the light green line represents October values, and the blue line represents November values.

6 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 9 gives verifications of our landfall probability estimates for the United States and for the Caribbean in 2015.

Landfall probabilities for the 2015 hurricane season were estimated to be well below their long-period averages for all predictions due to the forecasts of a below-average hurricane season. The 2015 hurricane season was quiet from a U.S. landfall perspective, with only one two named storms (Ana and Bill) and no hurricanes 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.

Two tropical cyclones passed through the Caribbean (10-20°N, 60-88°W) during 2015. Both Danny and Erika were at tropical storm strength as they tracked through the Caribbean.

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 at http://www.e-transit.org/hurricane.

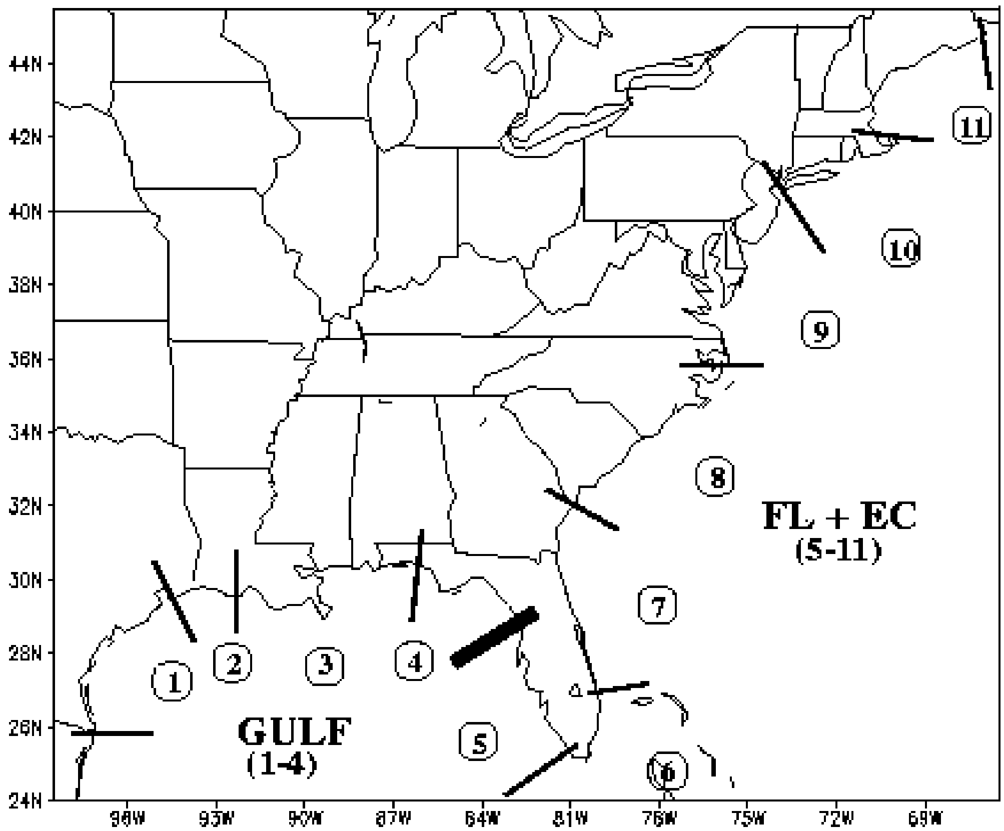


Figure 3: Location of the 11 coastal regions for which separate hurricane landfall probability estimates are made. These subdivisions were determined by the historical frequency of landfalling major hurricanes.

Table 9: 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 2015 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

	9 Apr.	1 June	1 July	4 August	Observed Number
TS	51%	51%	51%	42% (80%)	2
HUR (Cat 1-2)	40%	40%	40%	33% (68%)	0
HUR (Cat 3-4-5)	28%	28%	28%	23% (52%)	0
All HUR	57%	57%	57%	48% (84%)	0
Named Storms	79%	79%	79%	70% (97%)	2

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

	9 Apr.	1 June	1 July	4 August	Observed Number
TS	33%	33%	33%	27% (59%)	1
HUR (Cat 1-2)	22%	22%	22%	18% (42%)	0
HUR (Cat 3-4-5)	15%	15%	15%	12% (30%)	0
All HUR	34%	34%	34%	27% (60%)	0
Named Storms	55%	55%	55%	47% (83%)	1

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

	9 Apr.	1 June	1 July	4 August	Observed Number
TS	27%	27%	27%	22% (51%)	1
HUR (Cat 1-2)	23%	23%	23%	18% (45%)	0
HUR (Cat 3-4-5)	15%	15%	15%	12% (31%)	0
All HUR	35%	35%	35%	28% (61%)	0
Named Storms	52%	52%	52%	44% (81%)	1

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

	9 Apr.	1 June	1 July	4 August	Observed Number
TS	54%	54%	54%	45% (82%)	2
HUR (Cat 1-2)	32%	32%	32%	26% (57%)	0
HUR (Cat 3-4-5)	22%	22%	22%	17% (42%)	0
All HUR	46%	46%	46%	38% (75%)	0
Named Storms	75%	75%	75%	66% (96%)	2

7 Summary of Atmospheric/Oceanic Conditions

In this section, we go into detail discussing large-scale conditions that we believe significantly impacted the 2015 Atlantic basin hurricane season in either a favorable or unfavorable manner.

7.1 ENSO

A strong El Niño event was well predicted by most of the dynamical and statistical model guidance. Our forecast assessment also correctly anticipated a strong El Niño, especially as the peak of the hurricane season approached. For most ENSO indices, this season's El Niño ranked as either the strongest or 2nd strongest (behind 1997) event since 1950. Here are a few quotes from our various forecasts discussing the current and predicted state of ENSO.

(9 April 2015) –

"The average of the various ECMWF ensemble members is calling for a September Nino 3.4 SST anomaly of approximately 1.7°C. There is a fairly widespread range in the outcomes predicted by the various ensemble members, which indicates the large degree of uncertainty in future ENSO conditions (Figure 14). In general, we put more credence in the ECMWF prediction than in forecasts from the other models, and consequently, we are calling for at least a moderate strength El Niño event."

(1 June 2015) –

"Our confidence that a significant El Niño event will develop during this year's hurricane season has remained high since early April. Anomalously strong low-level westerly flow has persisted for the past two months near the International Date Line, triggering eastward propagating Kelvin waves that have transported warm water from the western Pacific eastward. Based on the above information, we are currently anticipating a strong El Niño event that will significantly impact this year's Atlantic hurricane season."

(4 August 2015) –

"Strong El Niño conditions currently exist across the tropical Pacific. SST anomalies are at near-record high levels across the tropical Pacific. Table 7 displays July and May SST anomalies for several Nino regions. The eastern tropical Pacific has warmed considerably over the past two months, consistent with the development of a strong El Niño. We are very confident that a strong El Niño will persist through the remainder of the Atlantic hurricane season."

Warm neutral ENSO conditions transitioned rapidly to El Niño during the spring. We currently have a strong El Niño in place across the eastern and central tropical Pacific. Table 10 displays anomalies in the various Nino regions in January, April, July and October 2015, 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 2015 are in parentheses.

Region	January 2015 Anomaly (ºC)	April 2015 Anomaly (ºC)	July 2015 Anomaly (ºC)	October 2015 Anomaly (ºC)
Nino 1+2	-0.4	+1.4 (+1.8)	+2.9 (+3.3)	+2.5 (+2.9)
Nino 3	+0.4	+0.7 (+0.3)	+2.2 (+1.8)	+2.7 (+2.3)
Nino 3.4	+0.5	+0.8 (+0.3)	+1.6 (+1.1)	+2.5 (+2.0)
Nino 4	+0.9	+1.2 (+0.3)	+1.0 (+0.1)	+1.1 (+0.2)

The only El Niño event since 1950 of comparable strength to the current one is 1997. Figure 4 shows mid-November SST anomalies in 2015 minus mid-November SST anomalies in 1997. The current El Niño event is warmer in the central Pacific and is much cooler in the eastern Pacific. However, a downwelling (warming) Kelvin wave that is currently propagating across the tropical Pacific may lead to some warming in the eastern tropical Pacific in the next few weeks (Figure 5).

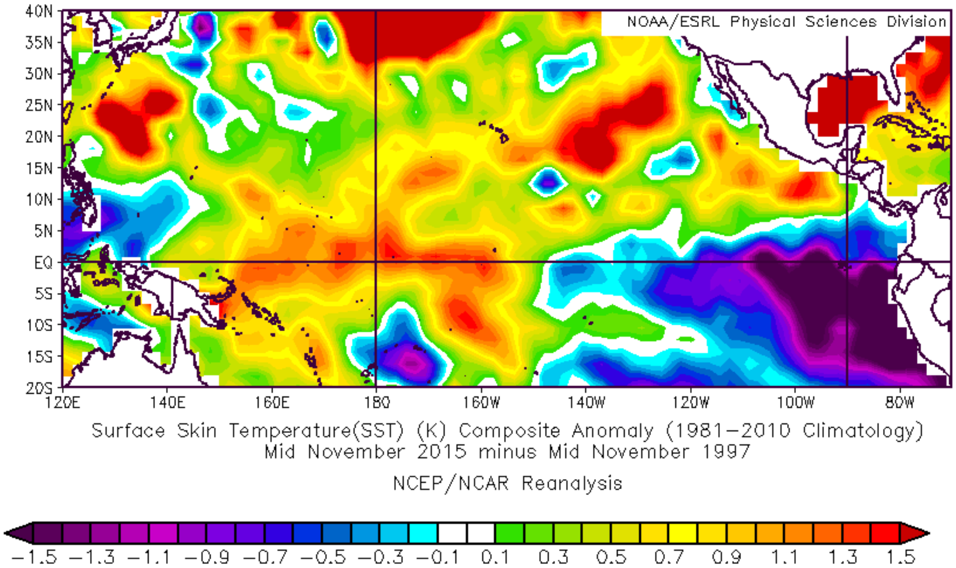


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Figure 4: Mid-November 2015 minus mid-November 1997 SSTs. The central tropical Pacific is warmer than in 1997 while the eastern tropical Pacific is considerably cooler.

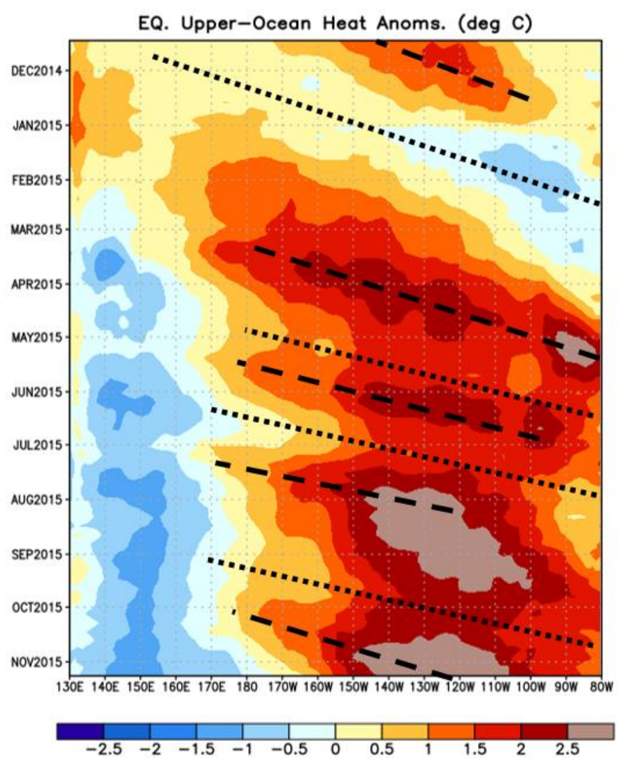

Figure 5: Upper ocean (0-300 meter) heat content anomalies in the eastern and central tropical Pacific from November 2014 – November 2015. Dashed lines highlight downwelling (warming) Kelvin waves, while dotted lines highlight upwelling (cooling) Kelvin waves.

7.2 Intra-Seasonal Variability

Intra-seasonal (MJO) variability was relatively weak during the peak months of this year's Atlantic hurricane season. Most of the period from late August through early October was spent in the middle of the circle (indicating an amplitude of the MJO of less than one) (Figure 6). More recently, the MJO has amplified into Phases 2, 3 and 4. Table 11 displays the number of TC formations by MJO phase during the 2015 Atlantic hurricane season. In general, more TC formations occurred in Phases 8, 1, and 2, while suppressed activity was observed in Phases 6 and 7, which is typical of the longer-term relationships shown in Table 12.

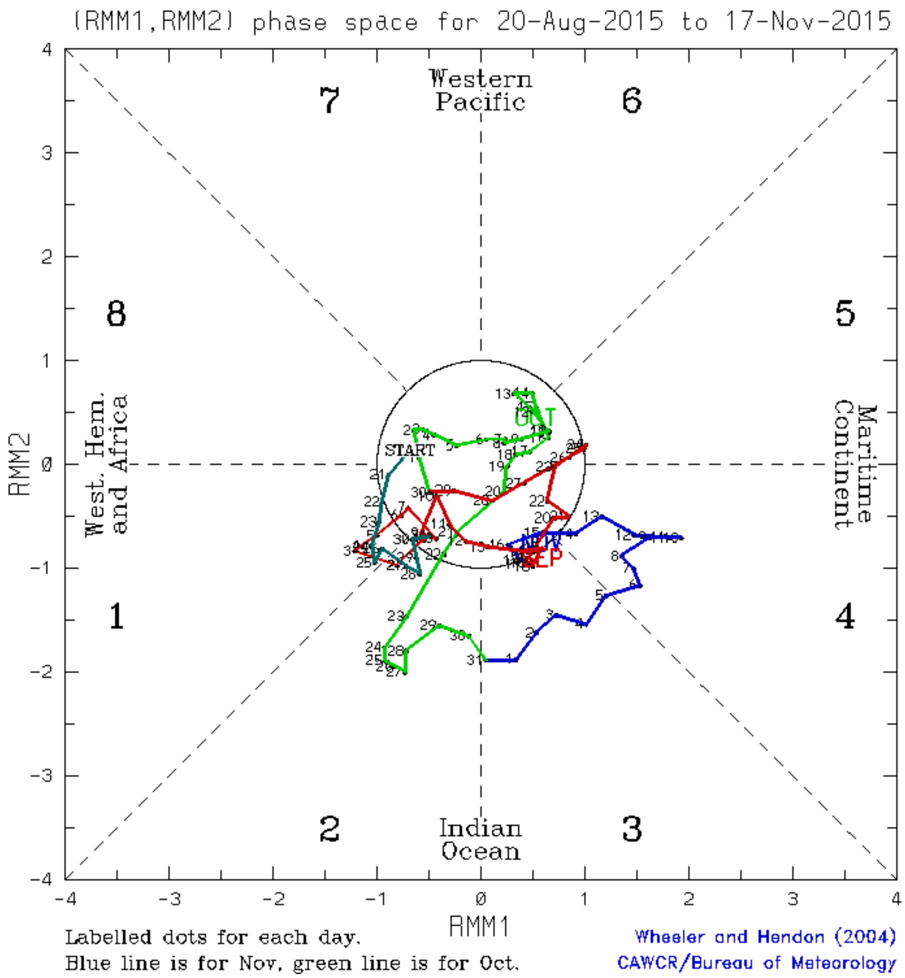

Figure 6: Propagation of the Madden-Julian Oscillation (MJO) based on the Wheeler-Hendon classification scheme over the period from August 20 to November 17. The MJO was generally weak during the peak months of this year's Atlantic hurricane season. The Maritime Continent refers to Indonesia and the surrounding islands. RMM stands for Real-Time Multivariate MJO. The dark green line represents August values, the red line represents September values, the light green line represents October values, and the blue line represents November values.

Table 11: TC formations by MJO phase during the 2015 Atlantic hurricane season.

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

Table 12: 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

7.3 Atlantic SST

As has been the case the past two years, the Atlantic was characterized by significant changes in SST over the course of 2015. The SST pattern observed during June 2015 was much more indicative of a weak THC, with cold anomalies observed in the tropical and North Atlantic and warm anomalies off of the US East Coast (Figure 7).

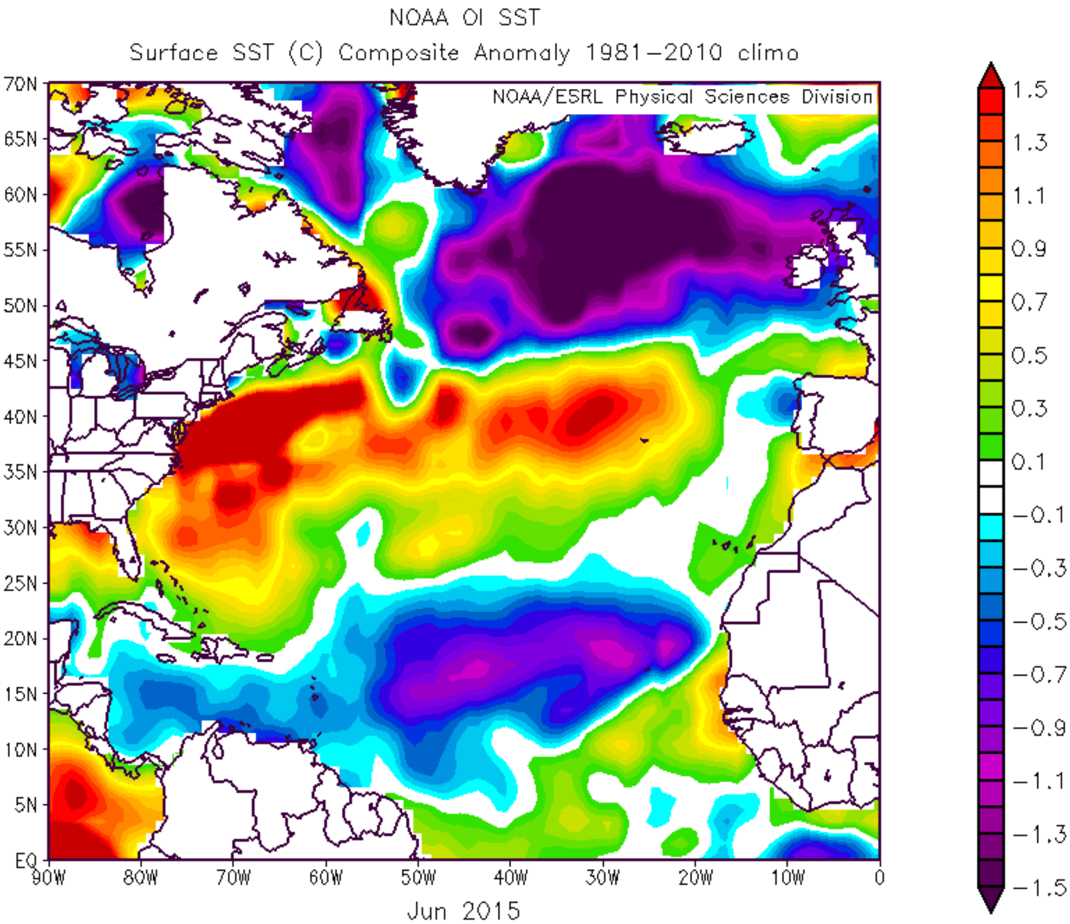

Figure 7: June 2015 SST anomalies across the Atlantic basin. Note the cold anomalies that pervaded both the tropical and far North Atlantic.

However, over the next several months, a negative North Atlantic Oscillation (NAO) developed. Associated with this negative NAO were anomalously weak trade winds which reduced mixing and upwelling in the tropical and subtropical Atlantic, causing warming (Figure 8). In addition, tropical Atlantic aerosol anomalies were below-average during July through September, resulting in increased solar radiation reaching the sea surface (Amato Evan, personal communication).

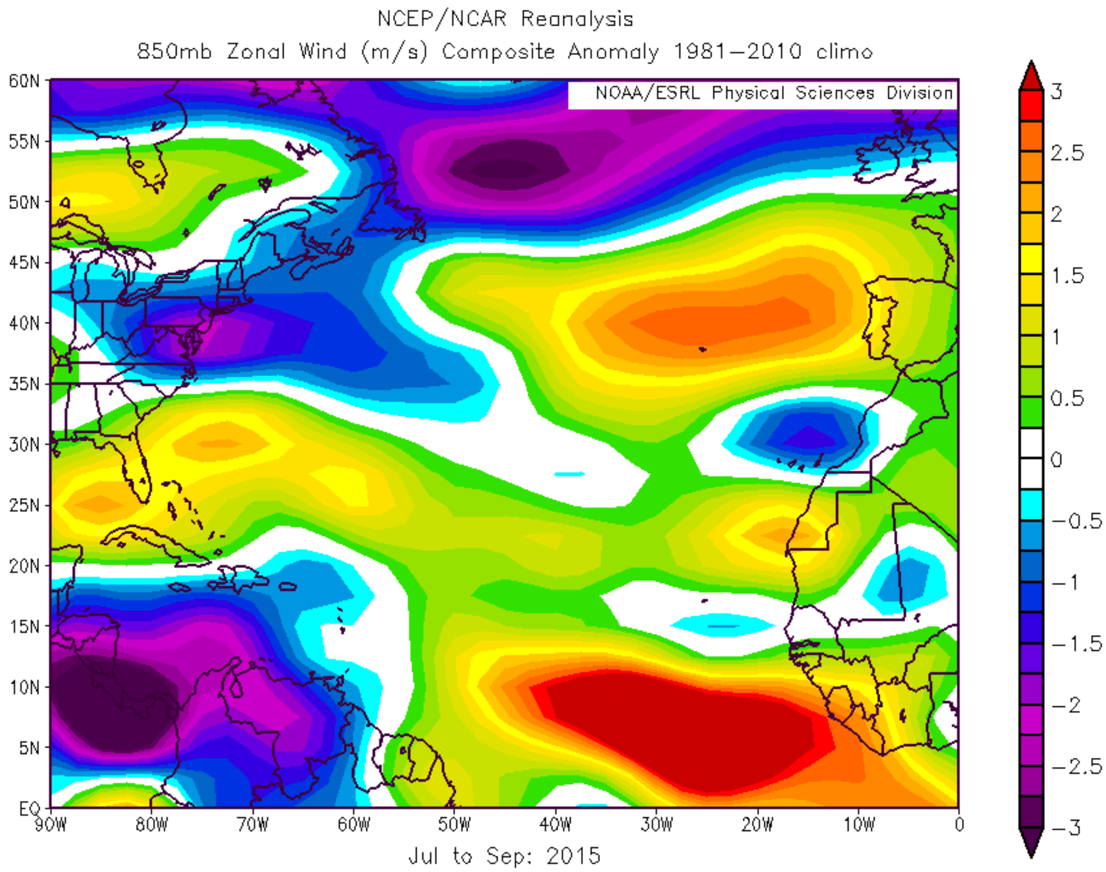

Figure 8: Anomalous 850-mb zonal winds across the Atlantic basin during July through September 2015. In general, trade winds were weaker than normal, generating less mixing and evaporation of the ocean surface, leading to warmer SSTs.

Figure 9 displays the anomalous SST pattern change that took place across the Atlantic from late June to late October. Note the significant anomalous warming that took place, especially in the tropical Atlantic. October 2015 SST anomalies in the tropical Atlantic (10-20°N, 60-20°W) were the warmest October anomalies on record (since 1982 when the NOAA Optimal Interpolation SST product became available) (Figure 10). These anomalously warm SSTs are likely one of the reasons why several TCs were able to form in the far eastern tropical Atlantic this year. The anomalous SST warming of the tropical Atlantic is probably the biggest surprise of the 2015 hurricane season.

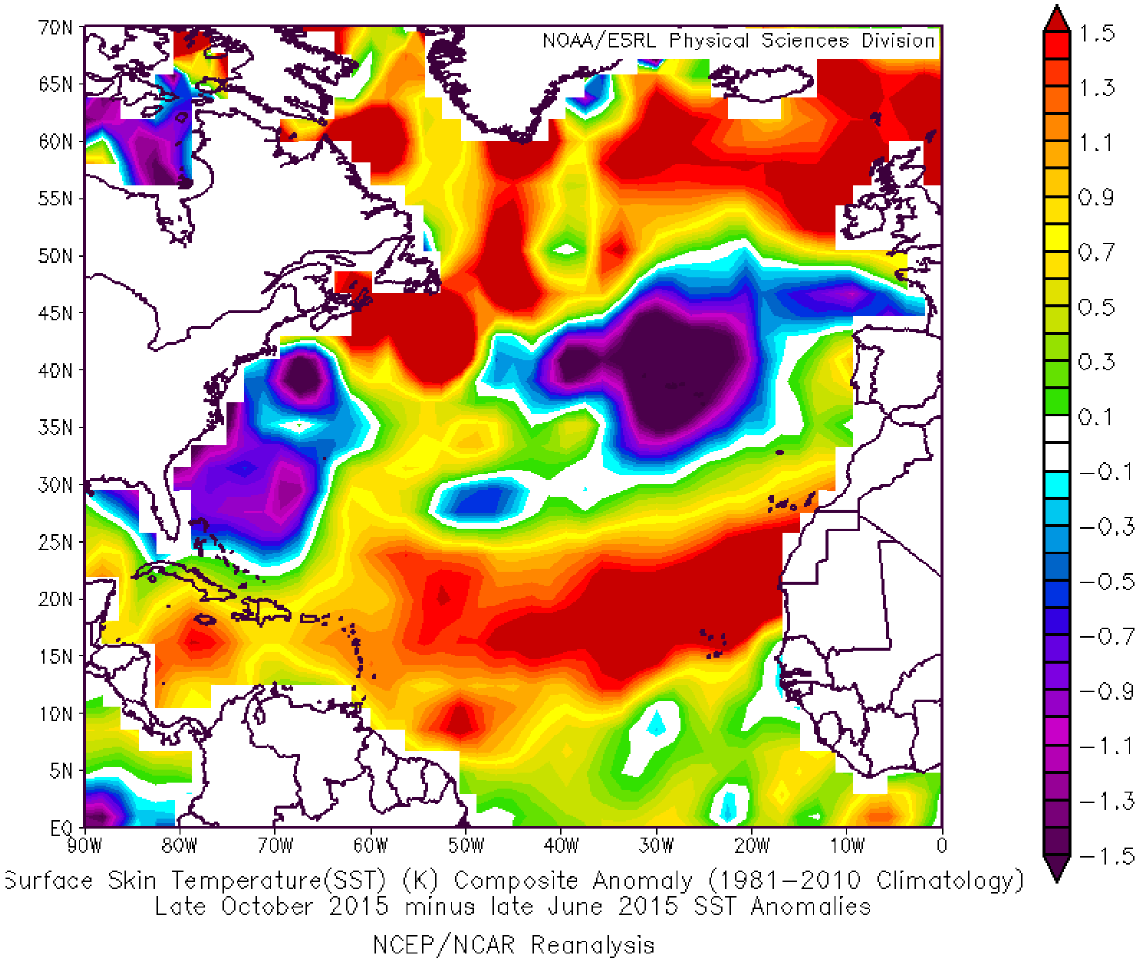

Figure 9: Late October 2015 minus late June 2015 anomalous SST change across the Atlantic basin. Note the anomalous warming that occurred in the tropical and far North Atlantic.

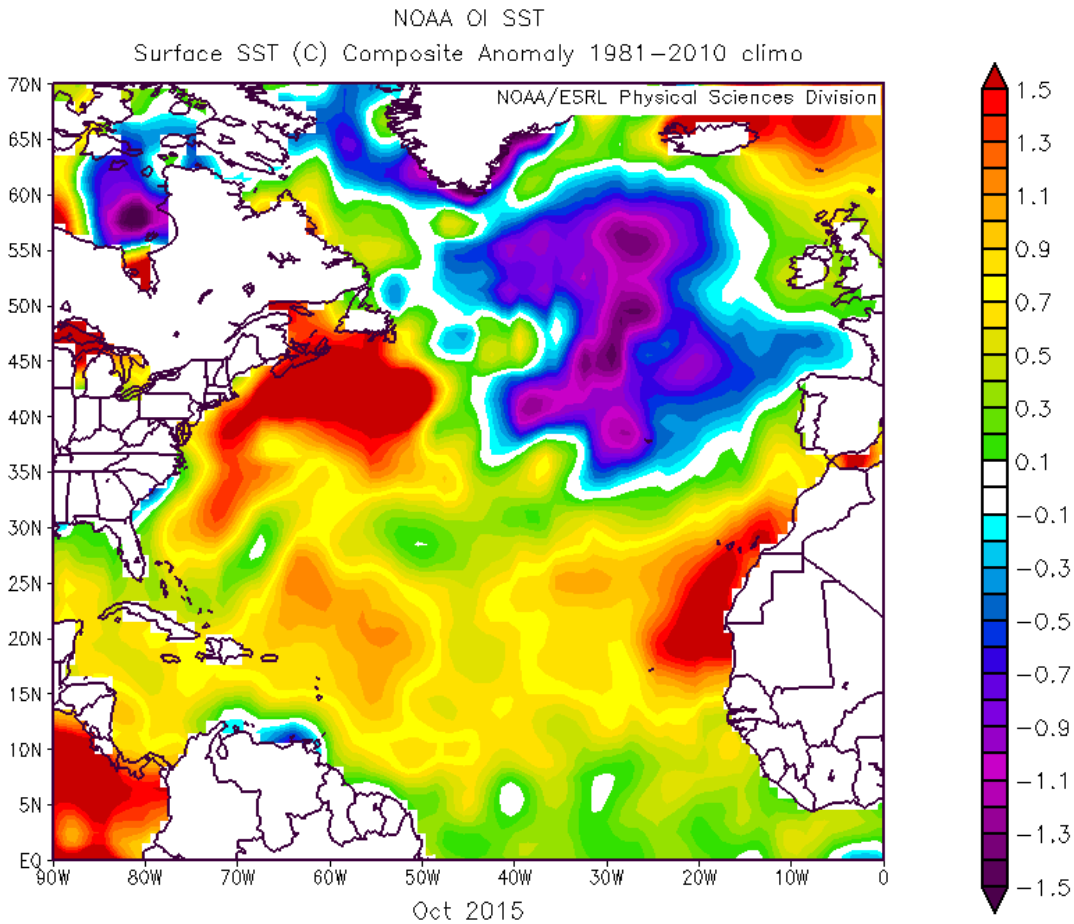

Figure 10: October 2015 SST anomalies.

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 2015 Atlantic hurricane season was characterized by below-normal sea level pressures across the tropical Atlantic. Figure 11 displays August-October 2015 tropical and sub-tropical sea level pressure anomalies in the North Atlantic.

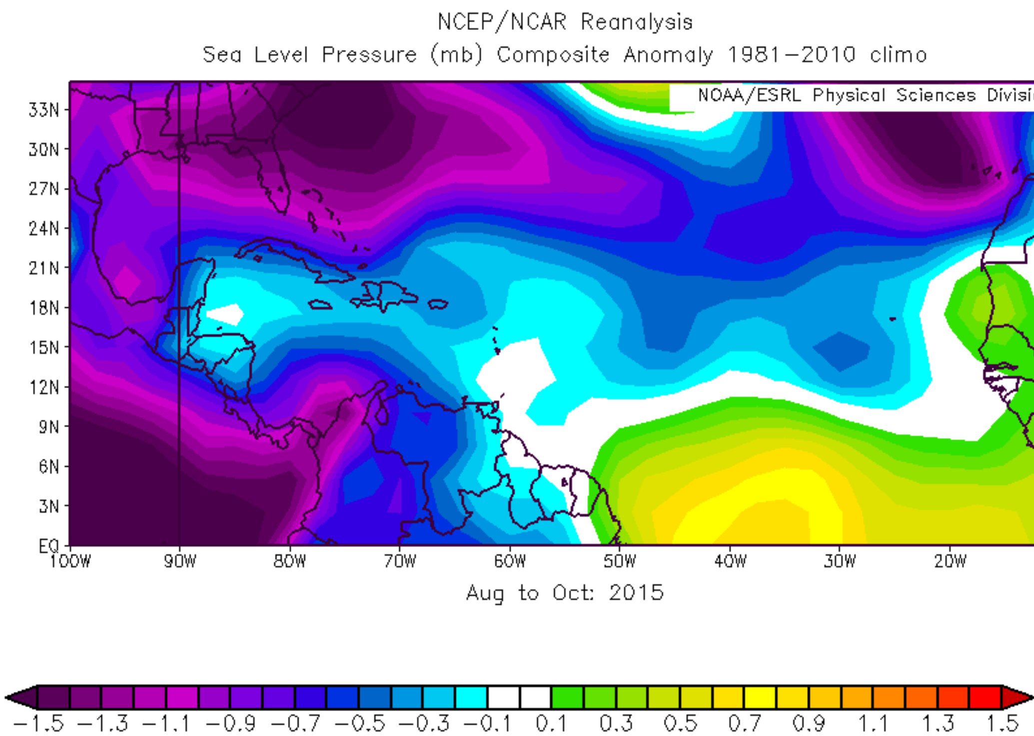

Figure 11: August-October 2015 tropical and sub-tropical North Atlantic sea level pressure anomalies.

7.5 Tropical Atlantic Vertical Wind Shear

Vertical wind shear was well above-average across the Caribbean and during the peak three-month period from August to October (Figure 12). Farther to the east across the tropical Atlantic, vertical wind shear was actually somewhat below average. Typically, strong vertical wind shear from El Niño events extends farther to the east. This reduction in vertical wind shear was likely one of the reasons why several TCs were able to form in the eastern tropical Atlantic this year. However, these TCs weakened rapidly as they reached the area of strong vertical wind shear across the central tropical Atlantic and Caribbean. Vertical wind shear across the Caribbean (10-20°N, 90-60°W) from June through October was the strongest on record (Figure 13) (since 1979 when the Climate Forecast System Reanalysis began).

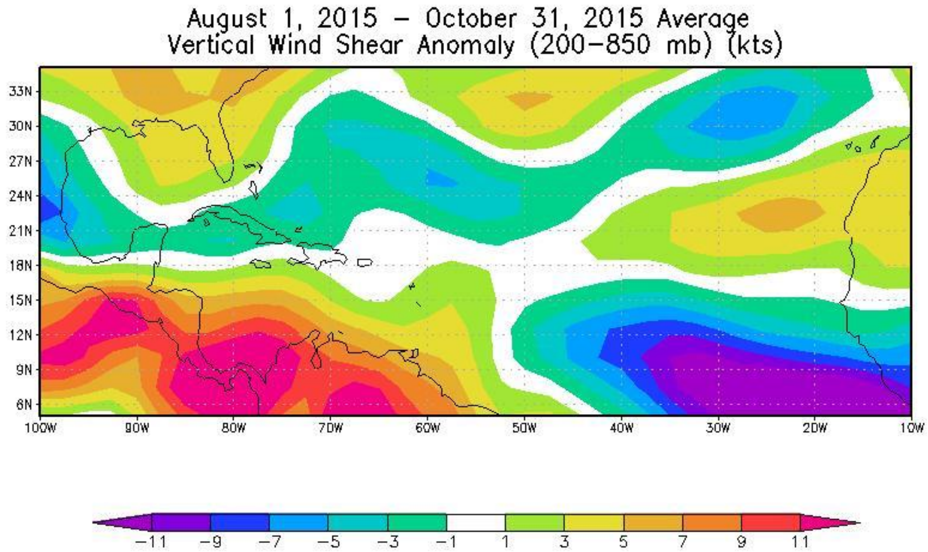

Figure 12: Anomalous vertical wind shear observed across the Atlantic from August 1 – October 31, 2015.

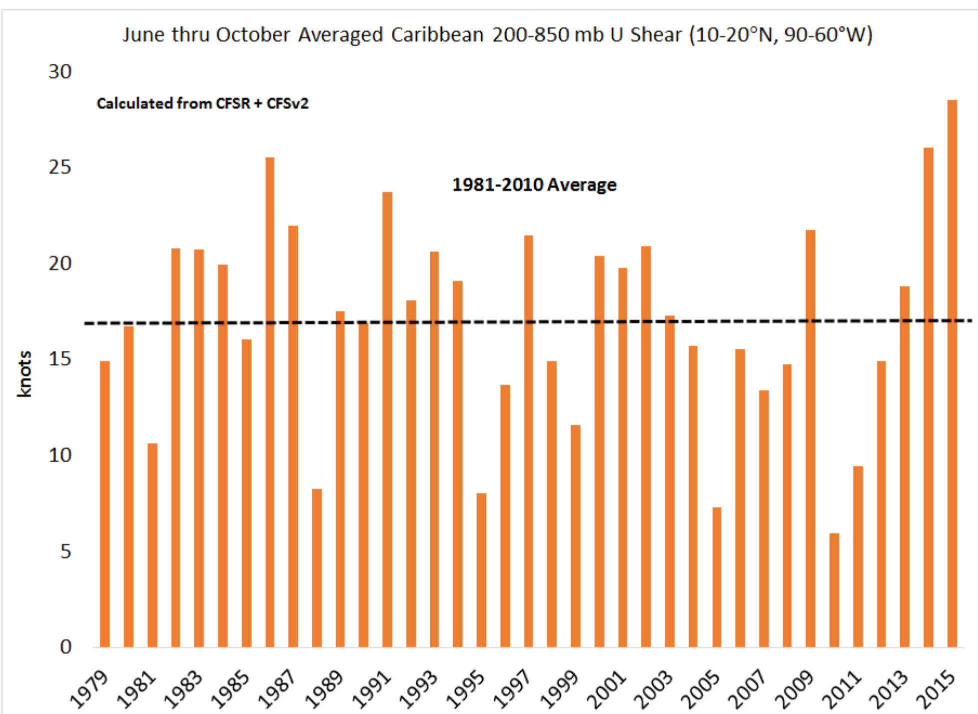

Figure 13: June through October-averaged vertical wind shear anomalies across the Caribbean. Anomalies in 2015 were the strongest on record.

7.6 Tropical Atlantic Moisture

As has been the case the past couple of years, the tropical Atlantic was quiet dry through most of this year's hurricane season. The peak months of August-October were characterized by very dry middle levels of the atmosphere (Figure 14). The combined tropical Atlantic and Caribbean (10-20°N, 90-20°W) had its lowest 600 mb relative humidity anomalies on record for August-October. Reliable records of tropical Atlantic moisture likely go back to around 1980. This dryness was most pronounced over the Caribbean, which is a typical feature associated with El Niño events.

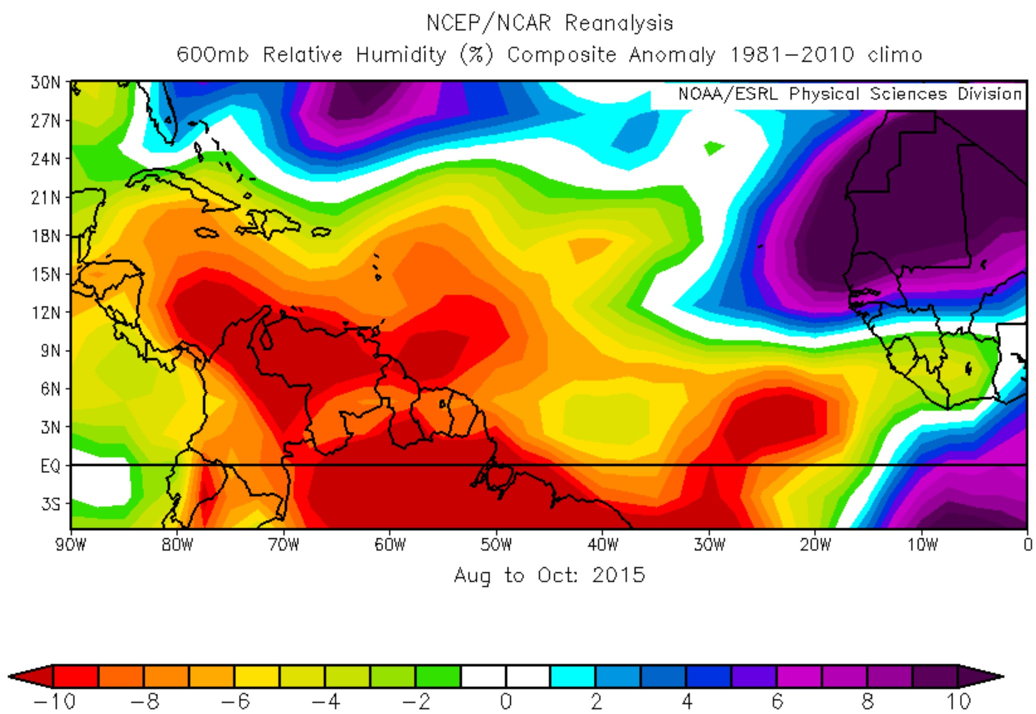

Figure 14: August-October 2015 600-mb RH anomalies. Note the anomalous dryness across most of the tropical Atlantic and especially the Caribbean this year.

7.7 Steering Currents

As has been the case for the past several years, anomalous troughing dominated the United States Southeast this year from August through October (Figure 15). The predominant steering flow was such to keep TCs that did form away from the United States mainland. In addition, strong vertical wind shear in the central tropical Atlantic and Caribbean tore apart several weak TCs as they approached the Lesser Antilles. The United States has now gone ten years without a landfalling major hurricane, the longest period on record. The old record was eight years from 1861-1868.

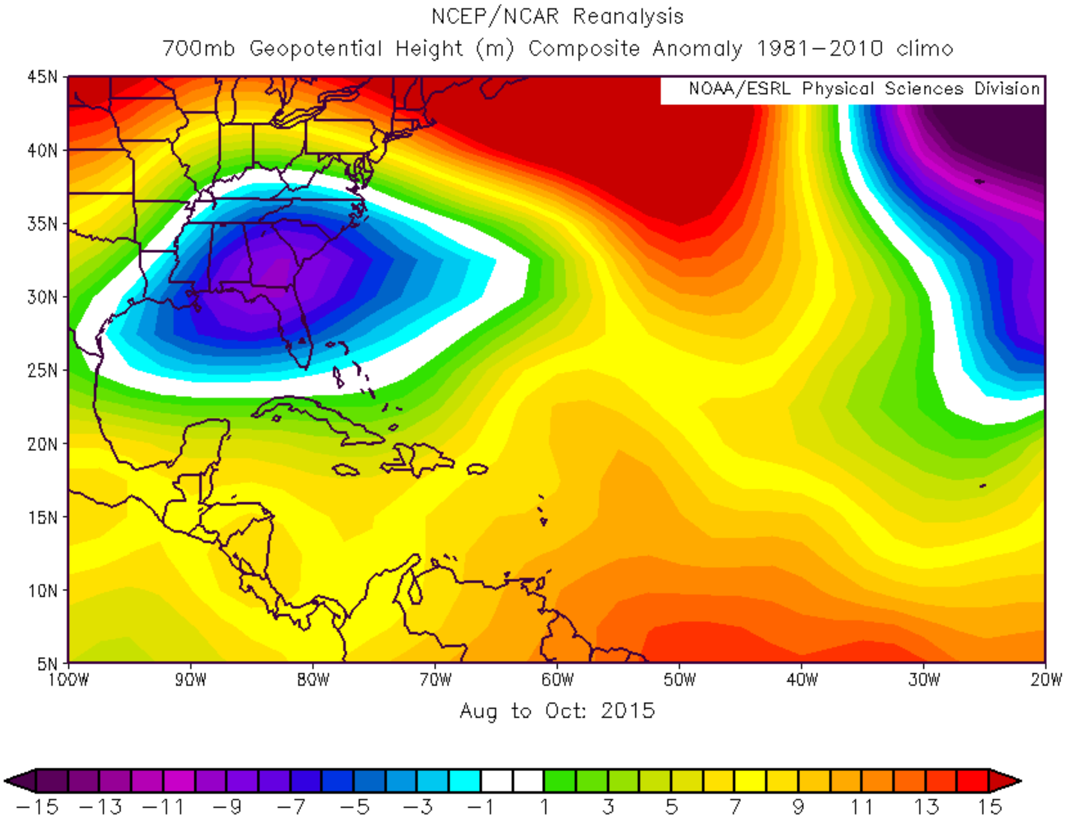

Figure 15: 700-mb height anomalies in the central and western part of the Atlantic from August through October 2015. Anomalous troughing dominated along the East Coast of the United States.

7.9 Atlantic Thermohaline Circulation (THC) Conditions

One of the big questions that has been raised, given the fact that we have had three quite Atlantic hurricane seasons in a row is: are we moving out of the active era? We recently addressed this in an article published in *Nature Geoscience* (Klotzbach et al. 2015). In short, while we believe it is too early to answer this question for sure, some indications in both North Atlantic SST patterns as well as salinity values indicate that this may be occurring.

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 16). This index reached very low levels earlier this year (associated with both colder than normal SSTs as well as higher than normal SLPs) (Figure 17). In the past few months, far North Atlantic SSTs have warmed somewhat, while SLPs have been below normal. However, far North Atlantic SSTs remain cooler than normal, while tropical Atlantic SSTs are at near record levels. This is not a typical North Atlantic SST pattern. It remains to be seen whether far North Atlantic SSTs will rebound, or if tropical Atlantic will anomalously cool during the winter months.

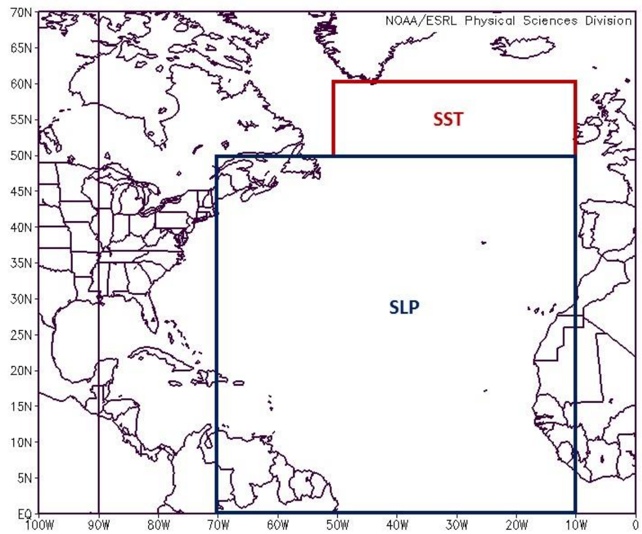

Figure 16: Regions which are utilized for the calculation of our AMO index.

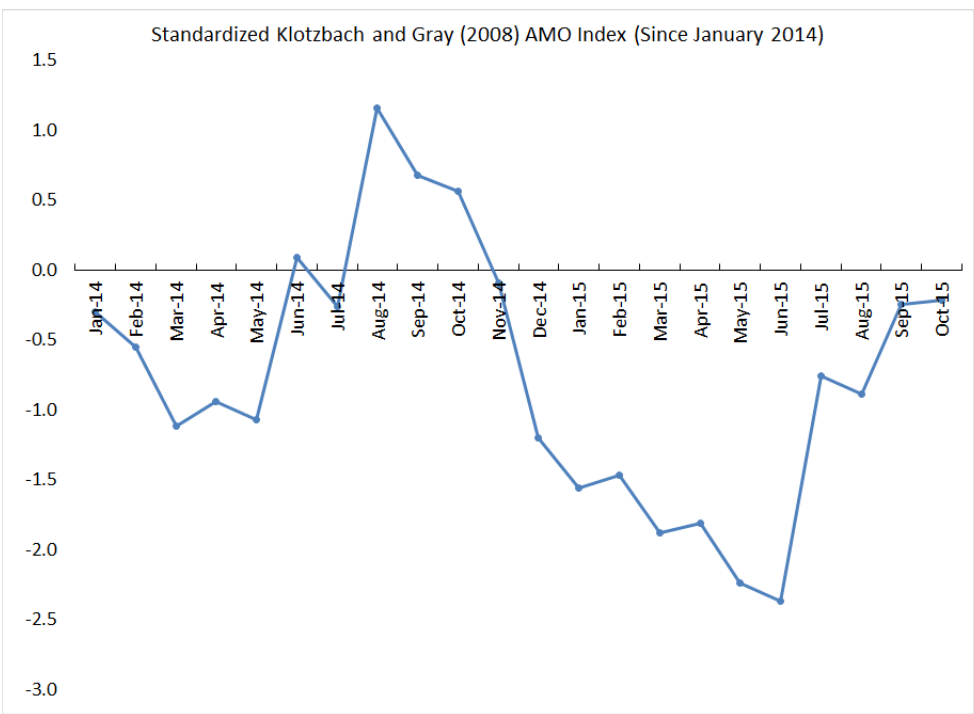

Figure 17: Standardized values of the AMO index by month since January 2014. The index was very low during the spring of 2015 but has since rebounded to near-normal levels.

8 Forecasts of 2016 Hurricane Activity

We will be issuing our first outlook for the 2016 hurricane season on Thursday, 10 December 2015. This forecast will provide a qualitative outlook for factors likely to impact the 2016 hurricane season. This December forecast will include the dates of all of our updated 2016 forecasts. All of these forecasts will be made available online at: http://hurricane.atmos.colostate.edu/Forecasts.

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 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. The second author would further like to acknowledge the encouragement he has received for this type of forecasting research application from Neil Frank, Robert Sheets, Robert Burpee, Jerry Jarrell, Max Mayfield, and Bill Read former directors of the National Hurricane Center (NHC), and the current director, Rick Knabb. 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 1984-2015. 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 27 of 32 years for named storms and 24 of 32 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
Average	**10.8**	**10.7**	**6.1**	**6.0**
1984-2015 Correlation		**0.60**		**0.52**

Table 14: Summary verification of the authors' five previous years of seasonal forecasts for Atlantic TC activity between 2010-2014. Verifications of all seasonal forecasts back to 1984 are available here: http://tropical.atmos.colostate.edu/Includes/Documents/Publications/forecast_verifications.xls

2010	9 Dec. 2009	Update 7 April	Update 2 June	Update 4 August	Obs.
Hurricanes	6-8	8	10	10	12
Named Storms	11-16	15	18	18	19
Hurricane Days	24-39	35	40	40	38.50
Named Storm Days	51-75	75	90	90	89.50
Major Hurricanes	3-5	4	5	5	5
Major Hurricane Days	6-12	10	13	13	11
Accumulated Cyclone Energy	100-162	150	185	185	165
Net Tropical Cyclone Activity	108-172	160	195	195	196

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