The Outlook for the 2016 North Atlantic Hurricane Season

Hurricane Genesis & Outlook (HUGO) Project

(April 15, 2016)

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Summary

The 2015 Hurricane Season ended with a total of eleven “named” Tropical Storms (TS), including four Hurricanes (NH) and two Major Hurricanes (MH), i.e., Saffir-Simpson Categories 3, 4 & 5, with no hurricane having made landfall either on the United States (U.S.) Atlantic Eastern Seaboard (AES) or upon the U.S. states in the Gulf of Mexico (GOM). CCU’s prediction of a “below normal season” in TS, H, MH and land-falling NH number range were all highly accurate. The HUGO extended range outlook for the 2016 Hurricane Season (HS16) includes the overall tropical cyclone and hurricane activity across the entirety of the North Atlantic Ocean Basin as well as hurricane landfall numbers and probabilities along the East Coast (ECLF) and the GOM (GMLF). Based on the climate factors available in early April 2016 and projected climate signals in the up-coming several months, the CCU’s HUGO Team anticipates a “near to above normal” HS for 2016 (HS16). The HUGO Team has made a major advance in computing a key factor, the Accumulated Cyclone Energy (ACE) Index, from a combination of model output and analog analyses. The ACE for 2016 is estimated to range from 120 to 180 ($10^4 kt^2$); a near- normal to above normal range. With the assumption of a near normal to above normal hurricane season pattern, estimates are for the number of named Tropical Cyclones to be at 13 (range of 11~15), the Number of Hurricanes to be 7 (range of 6~10), Major Hurricanes (categories >= 3) of 4 (range of 2~5), a GMLF probability range of [1 to 2] and an ECLF probability range of [0 to 2]; with U.S. Gulf and East coastlines having the highest Poisson distribution probability of [1, 2, 0] and [0, 1, 2] respectively, in that collective order for 2016. It should be noted that the HS16 scenarios are highly dependent on the variations of climate factors in latter April, May, June and July, primarily the El Niño Southern Oscillation (ENSO), and the Atlantic Multi-decadal Oscillation (AMO). The key issues at this point in time are: 1) how quickly the current El Niño will weaken and turn into either a Neutral or a La Niña phase; and 2) how warm will the upper ocean of the North Atlantic Ocean become. The projected ENSO index (August - October) applied in this CCU HS16 outlook was obtained from the Japan Meteorological Agency (JMA).

I. Introduction

The North Atlantic Hurricane Season runs from June 1 to November 30 with a peak period extending from early August through the end of October. The North Atlantic Basin includes the North Atlantic Ocean per se, the Caribbean and the Gulf of Mexico. Hurricane spawned in and emanating from the North Atlantic Ocean Basin can impact the entirety of the U.S. coast: from Texas to the Florida Panhandle and on up to Maine.

There is considerable demand for a seasonal hurricane landfall prediction for the U.S.. The storms that most people really worry about are those that actually make landfall, which can have little correlation to the total number of storms in any given season. For example, 2010 was an extremely busy season, with 19 named storms and 12 hurricanes. However no hurricane, only one tropical storm, made landfall in the US that year. There are examples of other years when very few hurricanes formed and most of them made landfall. Basically, there is no correlation between the numbers that form and how many of those make landfall. A simple regression does not work in point of fact.

Yan (2006) and Yan et al (2006, 2010) presented new methodologies for selecting predictors to predict the overall North Atlantic Tropical Cyclone (TC) activity and with the number of hurricanes (NH) that would make landfall along the U.S. eastern seaboard (the ECLF), and the U.S. coastline of the Gulf of Mexico (the GMLF). Analysis of two-dimensional (2-D) climatic-oceanic and atmospheric data and their correlations with North Atlantic hurricane activity provide a new way to identify hurricane-related climate factors (Yan and Pietrafesa, 2010). Recently, a new Atlantic Cyclone Energy (ACE) based methodology addressed the seasonal landfall prediction challenge for the U.S. (Yan et al, 2015). A set of mathematical models applied with this methodology was tested and showed excellent hind-casting skills for the past six decades. The key to this new methodology is the classification of hurricane season types and the assumption that landfall hurricane distributions not only depend on overall Atlantic hurricane activity (season types of hyperactive, active, above normal, near normal, and below normal), but also on specific hurricane track-related climate parameters that also correlate closely with overall hurricane activity. The statistics of ACE and hurricane activity over the past six decades (1950-2015), shows that landfall hurricane frequency is closely associated with hurricane-track related climate factors and weather patterns that link up to overall hurricane activity in the North Atlantic Ocean.

For the year of 2016, the CCU HUrricane Genesis & Outlook (HUGO) will cover: 1) the overall Tropical Cyclone activity across the entirety of the North Atlantic Ocean Basin; 2) the number of hurricanes (NH) which will form; 3) the number of major hurricanes which will form; and 4) the U.S. hurricane landfall activity from Texas to Maine, with landfall counts along the U.S. coastline of the Gulf of Mexico (GMLF) and the U.S. Atlantic eastern seaboard (ECLF). Our forecasting scheme assumes that atmospheric and oceanic behaviors can be viewed as a Markov Process, i.e. the atmosphere and the ocean will continue to behave in the future as they had in the past (now at 66 years). Prediction is therefore possible based on historical records and pre-existing and also projected climate conditions. Note that we are predicting tropical cyclones using the well-known Saffir/Simpson Hurricane Category Scale.

II. Prediction Categories

The following variables are predicted:

1. North Atlantic Accumulated Cyclone Energy (ACE)
2. The total number of “Named” Tropical Storms (TS)
3. The Number of Hurricanes to form in the entire North Atlantic Ocean Basin (including the North Atlantic Ocean per se, the Gulf of Mexico and the Caribbean Sea) (NH).
4. The number of Major Hurricanes (Saffir-Simpson Categories 3, 4, and 5) (MH)
5. The Poisson distribution of the most likely number of land-falling hurricane strikes along the U.S. Eastern Seaboard (ECLF)

6. The Poisson distribution of the most likely number of land-falling hurricane strikes along the U.S. coastline of the Gulf of Mexico (GMLF)
7. The Poisson distribution of the most likely total number of land-falling hurricanes for all U.S. coastlines

III. Model and Predictors

A number of statistical prediction models were developed with the application of the Statistical Analysis Software (SAS) Generalized Linear Model (GENMOD) which fits a generalized linear model to the data via a maximum likelihood estimation of the response variable. The distribution of response variables (e.g. ACE, landfall hurricane count) is specified as Poisson, and the link function is chosen to be logarithmic (Yan et al, 2015). Principal Component Analysis (PCA) of the North Atlantic (NA) Hurricane Track Density Function (HTDF) yields three dominant Empirical Orthogonal Function analysis (EOF) modes (Yan, 2006). The 1st EOF Mode represents overall NA hurricane activity; the 2nd and 3rd modes demonstrate dipole structures, which are associated with hurricane track accumulation in the east-west (E-W) and north-south (N-S) directions, respectively. Analysis of correlations between those EOF modes and climatic atmospheric and oceanic factors (Yan 2006 and Yan et al. 2006) determines the principal predictors.

The Atlantic Multi-decadal Oscillation (AMO) represents a cycle in the large-scale atmospheric flow and ocean currents in the North Atlantic Ocean that combine to alternately increase and decrease Atlantic Sea Surface Temperatures (SSTs). The AMO is defined as the mean SST between 75°W to 7.5°W and 0^{o} to 60°N. The AMO is thought to strongly influence the incidence of intense hurricanes (Mann and Emanuel, 2006; Shiver and Huber, 2006). They show that averages of intense hurricane counts during the warm phase of the AMO are more than double the counts during cool phase years. In a recent study Yan et al (2014) found that The AMO itself has oscillations at multiple well defined frequencies. Via employing the Hilbert-Huang Transform (HHT), Huang et al. (1998), the CCU analysis revealed that the first mode of the AMO in the high frequency (period of 1-2 years) domain is in sync with actual ACE variations. Lower frequency oscillations of 3-5 years, 5-7 years and beyond in the AMO are known to be driven by cyclic variations in large-scale atmospheric and oceanic conditions in the North Atlantic Ocean with multi-year and multi-decadal year periods. However the factors that control high frequency variability are still unresolved. Using the AMO for the ACE forecasts must be done with extreme caution as they are not always in phase. For the mean AMO index of January-March, 2016, the CCU HUGO Team finds that the first AMO mode has a value 0.4583, which is nominally consistent with the observed AMO value (0.5769). The number of landfall strikes along the East Coast of the U.S. demonstrates a strong positive correlation with the phase of the AMO. For example, an average of 0.89 hurricanes per year landed on the U.S. Eastern Seaboard during the recent AMO warm phase (1995-2015), while only 0.36 hurricanes per year made landfalls during the last AMO cool phase (1970-1994). The AMO Index from January to March is applied in the April prediction models.

The Tropical Atlantic Dipole Mode (ADM) or Atlantic Meridional Mode (AMM) is characterized by the mean SST anomaly differences between the Tropical North Atlantic and the Tropical South Atlantic as proposed by Sutton (2000). In Yan (2006), the AMM of the tropical Atlantic SST anomaly was shown to strongly correlate with all of the three dominant HTDF EOF Modes. This implies that the AMM is not only associated with overall North Atlantic hurricane activity, but it is also associated with hurricane track patterns. The influence of the AMM on ECLF has been discussed in Yan (2006). It suggests that the AMM, coupled with tropical and subtropical atmospheric circulation, control the steering of hurricanes. Therefore AMM indices are chosen as a predictor in the model.

The Tropical South Atlantic SST index (TSA) is the anomaly of the average of the monthly SST over 0°~20°S and 10°E~30°W, which is identified having the largest sensitivity to changes in vertical shear (Goldenberg and Shapiro, 1996). This index demonstrates strong positive correlation with the number of hurricanes that pass west of 75°W. The warmer SSTs in the tropical South Atlantic Ocean enhance low-level vortices and convergence, and consequently lower sea-level pressure, and reduce vertical shear in the trade wind zone. The above normal SST conditions in this area are favorable for hurricanes to be developed.

As discussed above, the spatial distribution of SST in the North Atlantic Ocean Basin plays a crucial role in TC genesis and development. Based on the past 66 years (1950-2015) of the historical record, correlations between hurricanes predicted categories (ACE, TS, NH, MH, ECLF, GMLF) and 2-dimensional SST anomalies in the Atlantic Ocean Basin were analyzed. For each category, mean SST in the most significant correlation region is calculated and anomalous SST time series are extracted from those significant correlation domains, and applied as predictors. For ACE prediction, the anomalous SST time series is taken from longitude 22ºW to 50ºW, and latitude 0ºN to 10ºN. For TS & NH forecasts, SST is taken from longitude 22ºW to 48ºW and latitude from 0º to 15ºN. For the MH forecast, SST is taken from longitude 24ºW to 50ºW and latitude from 0º N to 18ºN. For the ECLF forecast, SST is taken from longitude 24 ºW to 40ºW and latitude 18º S to 40ºS. For the GMLF forecast, SST is taken from longitude 36ºW to 0ºE and latitude 2ºS to 18ºS. SST index associated with prediction categories are shown in **Figure 1**

Figure 1

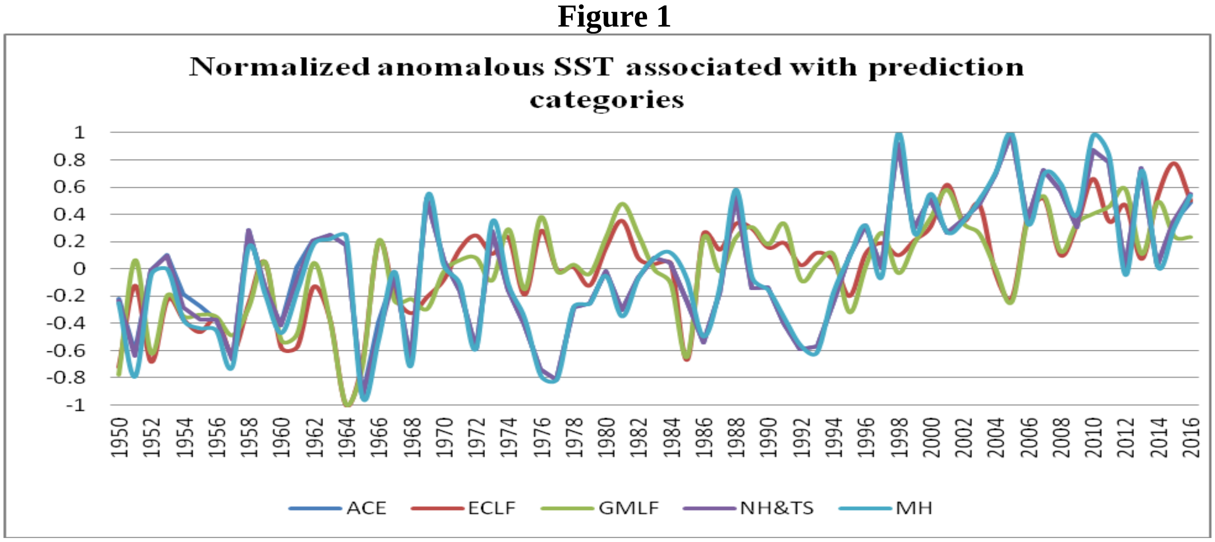

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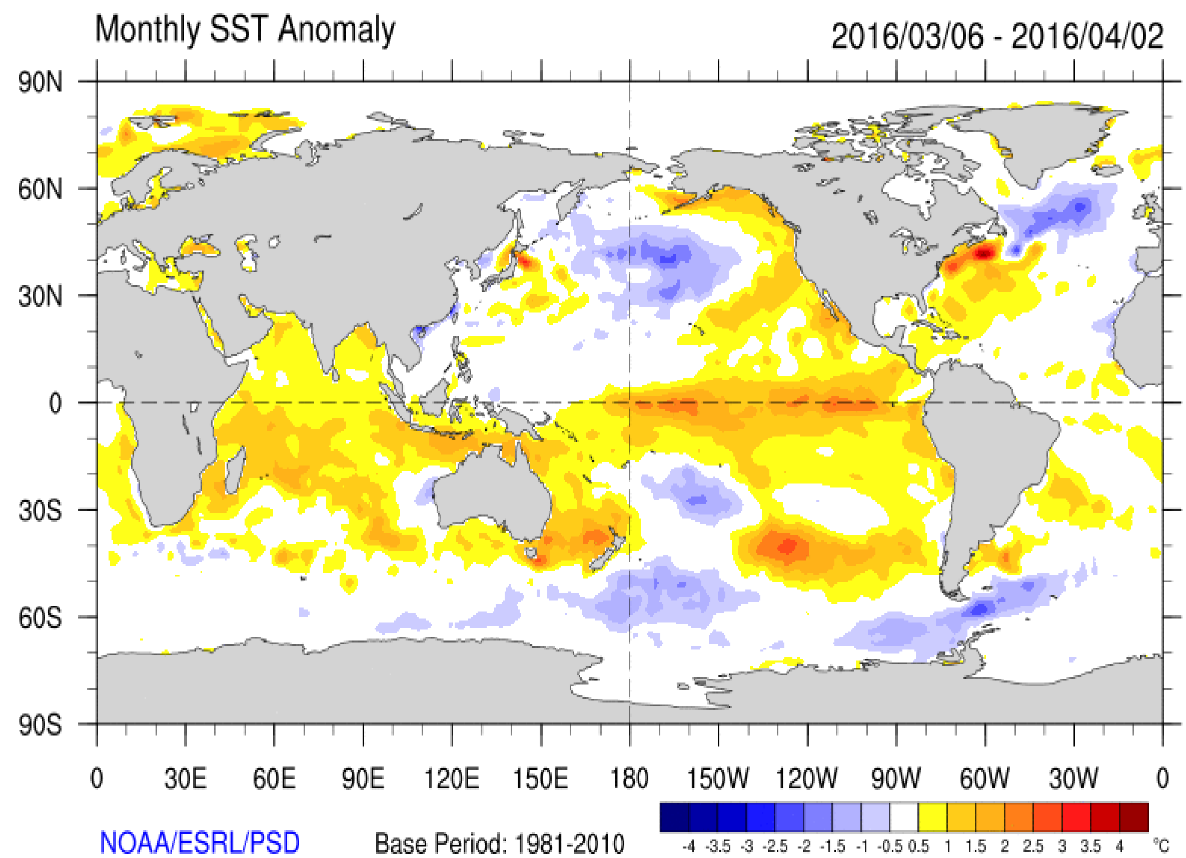
Figure 2 displays the mean anomalous SST distribution of the Atlantic and Pacific Ocean Basins from January to March. From comparisons, the SST structure from January to March shows very little change. Anomalous SST in the Tropical Atlantic (20°S ~20°N) region is slightly above normal. Mean anomalous SST in the Subtropical North Atlantic (30~50°N) is above normal while Subtropical South Atlantic SST anomalies (30~50°S) are near normal. This type of SST structure supports a favorable condition for North Atlantic overall hurricanes activity and favorable conditions for hurricanes making landfall along the U.S. Eastern Seaboard (Yan, et al, 2010).

Figure 2



It is well documented that hurricane activity in the North Atlantic basin is affected by the ENSO through changes in the Atlantic atmospheric circulation via vertical wind shear. Hurricane activity is constrained when an El-Nino event occurs and enhanced when a La-Nina event prevails (Gray 1984; Shapiro 1987). Gray (1984) has also shown a 3 to 1 ratio in continental U.S. land-falling number of hurricanes, with 0.74 hurricanes per year striking during non-El Niño years and only 0.25 hurricanes per year during El Niño events. Bove et al. (1998) analyzed all continental U.S. land-falling hurricanes and intense hurricanes of the 20th Century and found that the probability of at least two hurricanes striking the U.S. is 28% during El Niño years compared with 48% during neutral years and 66% during La Niña years. Based on previous 66-year (1950-2015) observations, we found that the mean ENSO index from September to October demonstrates a significant negative correlation with North Atlantic ACE ($R = -0.43$, $p < 0.01$), and the May-June mean index is strongly associated with number of hurricanes in the North Atlantic Ocean and the ECLF. Daily anomalous SST on April 8, 2016 (**Figure 3**) shows the sea surface temperature anomalies of the NINO3.4 region (5S-5N, 170W-120W), which NOAA uses to define an El Niño and its strength, is about 1.5 deg C, which is still within the threshold of a strong El Niño (1.5 deg C) state.

Figure 3

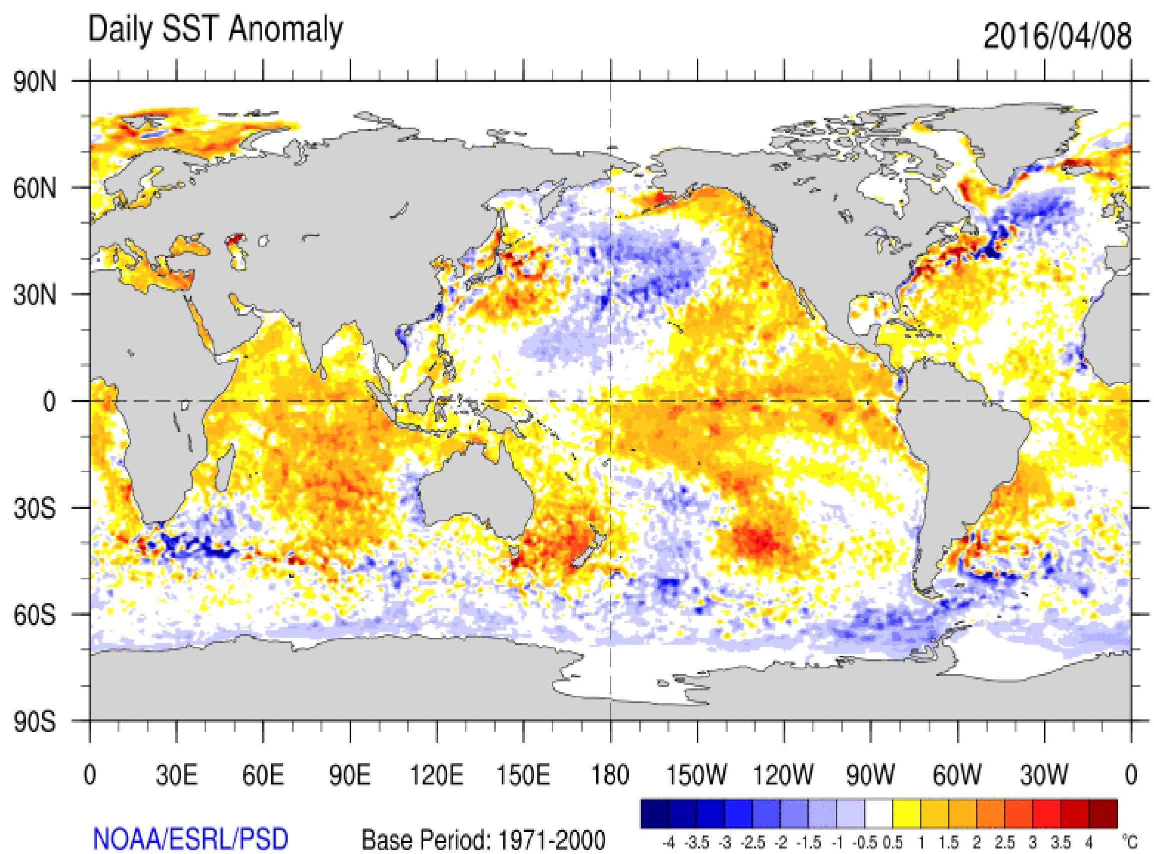


Figure 4 summaries ENSO forecast outputs made by dynamical and statistical models for SST in the Nino 3.4 region for nine overlapping 3-month periods. Majority models, including leading models from NCEP, JMA, NASA and ECMWF, have predicted a La Niño condition during the boreal summer of 2016, though the tropical East-Pacific sea surface temperature anomaly still passed the +0.5C threshold in April (**Figure 3**).

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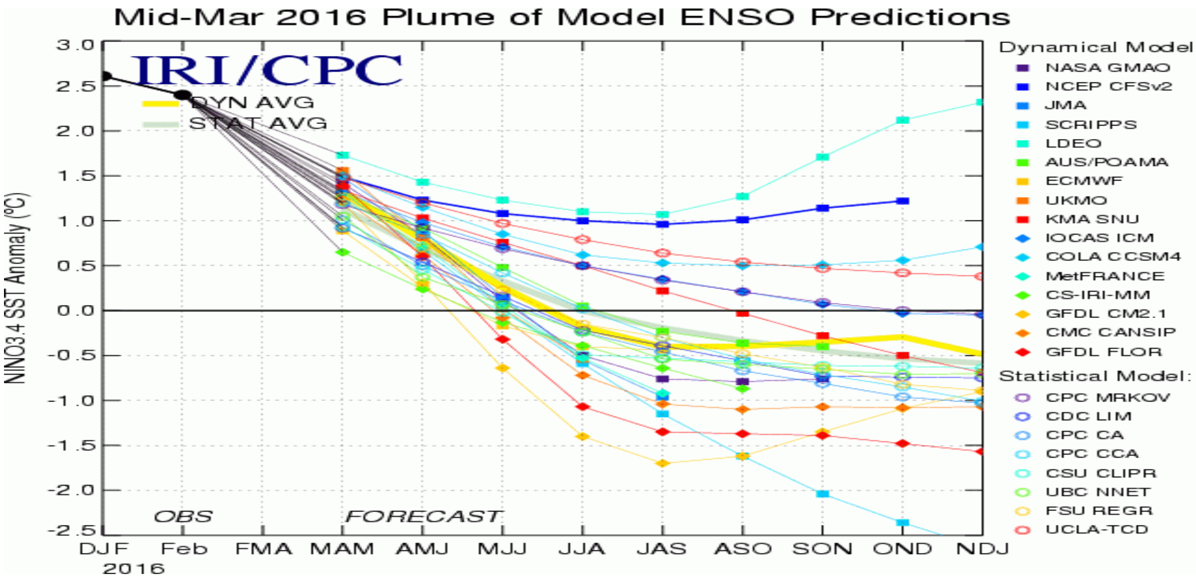
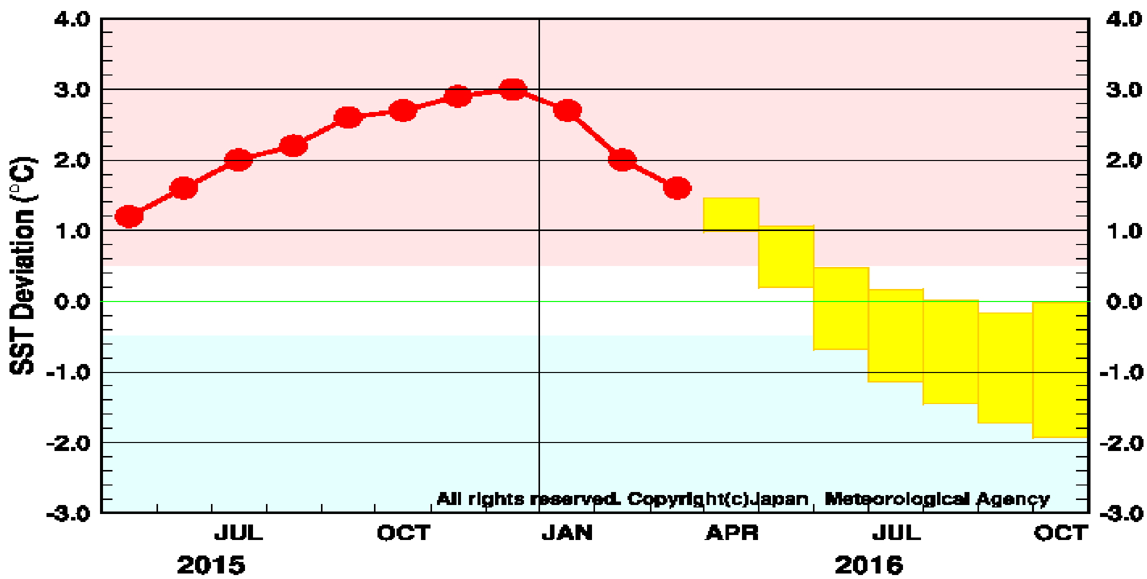
Figure 4



(From http://iri.columbia.edu/our-expertise/climate/forecasts/enso/current/)

In this report, the averaged JMA forecasted ENSO index in May and June (0.2) is used for the ECLF forecast and the mean ENSO index of September and October (-0.95) is used for overall ACE forecast (**Figure 5**). Based on JMA project ENSO index and historical data analysis, the likely upcoming La Niño condition will dramatically enhance North Atlantic hurricane activity.

Figure 5 ENSO forecast by JMA



IV. April 2016 Outlook (forecast) for the 2016 hurricane season

Table 1 provides a list of predictors applied in April 2016 ACE forecasting scheme.

Table1. Listing of April 2016 predictors: A plus (+) means that positive values of the parameter indicate increased hurricane activity this year, and a minus (-) means that positive values of the parameter indicate decreased hurricane activity this year.

Predictors		Anomalies for April 2016 forecast
a) Atlantic Multi-decadal Oscillation (AMO) (January-March)	(+)	0.5769
b) Atlantic Multi-decadal Oscillation (AMO) (December 2015 -January)	(+)	0.6011
c) Tropical Atlantic Meridional Mode (AMM) (February-March)	(+)	-0.1717
d) Tropical South Atlantic (TSA) (January-March)	(+)	0.6772
e) SST anomaly selected for ACE prediction (January-March)	(+)	0.4891
f) SST anomaly selected for TS/NH prediction (January-March)	(+)	0.5522
g) SST anomaly selected for MH prediction (January-March)	(+)	0.5418
h) SST anomaly selected for ECLF prediction (January-March)	(-)	0.5021
i) SST anomaly selected for GMLF prediction (January-March)	(-)	0.2337
j) JMA El Nino-Southern Oscillation index (ENSO) (May-June)	(-)	0.20
k)JMA El Nino-Southern Oscillation index (ENSO) (September-October)	(-)	-0.95

All of above selected predictors demonstrate significant correlations with one or more prediction variables as described in part II. The objective statistical bootstrap technique shows that predictors having statistically significant correlations with predicting variables over the lengthy dataset period could add credibility to the forecast scheme. Most predictors listed in **Table 1** are observed values except those projected value of ENSO in May-June and September-October, which were delivered from JMA ENSO forecast model. In the following, prediction schemes for the listed category in Part II are analyzed.

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1) North Atlantic Accumulated Cyclone Energy (ACE)

Table 2. Analog years for 2016 ACE with associated predictors

Year	ACE	AMM	AMO	ENSO	SSTA
1952	87	-0.2234	0.583	-0.15	-0.0079
1954	113	0.0587	0.4483	-0.95	-0.1813
1961	205	-0.0366	0.3379	-1	0.0123
1962	36	0.3705	0.4859	-0.5	0.206
1964	170	-0.068	0.0843	-0.85	0.1726
1967	122	0.0318	0.2098	-1.05	-0.0457
1988	103	-0.2862	-0.0169	-1.25	0.547
1998	182	0.0879	0.7353	-0.75	0.9205
1999	177	-0.0882	0.2617	-0.9	0.2919
2010	165	0.5819	0.542	-1.05	0.8753
2011	126	0.6228	0.378	-0.4	0.7816
2016	?	-0.1717	0.5769	-0.95	0.4891
1950-2015	100				

The ACE is a measure of total North Atlantic TC activity. It is defined as the sum of the squares of the maximum sustained surface wind speed (knots) measured every six hours for all named systems while they are at least of tropical storm strength (Bell, et al. 2000). The 66-year (1950-2015) long-term mean ACE is 100 (10^4 kt^2) and the median ACE value is 89.5. There were total eleven years in history with similar predictor combination to the year 2016 (**Table 2**), five of those eleven years fell in near normal hurricane season category (1952, 1954, 1964, 1967, 1988), five (1961, 1998, 1999, 2010, 2011) fell in above normal (hyperactive) category. We notice that the year 1962 is the only year among the eleven that fell into a below-normal category. In these analog years with El Nino incidence occurred, ACEs range from 103 to 205 with median (165) and average (155). The AMO based model estimation of this year's ACE is 165, which is 165% of the 1950-2015 average. The upper and lower bounds of the model estimation within the 70% confidence level (CFL) are [161, 170]. However, the model estimated ACE might be overestimated compared to those of the analog years. Combined the analog year observations and the model output, the CCU HUGO expectation for ACE in 2016 ranges from 120~180, centered at 150, which is about 120% ~ 180% of the 1950~2015 average (100).

It is of note that our April outlook for ACE is highly depending on how fast the concurrent El-Nino event is vanishing and how fast a La-Nino is developing in the next few month. The model output and analog analysis is largely dependent on the actual ENSO conditions during the period of August through October.

2) The number of hurricanes (NH) and tropical storms (TS) in the North Atlantic Ocean Basin, including the Gulf of Mexico and the Caribbean Sea

Over the past 66 years (1950-2015), the number of TS has ranged from 4 (1983) to 28 (2005). The TS Analog Table (**Table 3**) showed seven years in history with a similar predictor combination to that of 2016. The number for TS in those seven years ranges from 8 to 19, with a median of 12 and an average of 13. For the year 2016, the model predicted theoretical value for this category is 13.8. The range of the TS number at the 70% confidence level is 12 to 15. Combined with our analog analysis, the most likely range for the TS number for2016 is 11~15 which is 92~125% of the 66-year average (12).

Table 3. Analog years for 2016 with TS/NH with associated predictors

Year	NH	TS	ACE	AMM	AMO	ENSO	SSTA
1954	8	11	113	0.0587	0.4483	-0.95	-0.2813
1964	6	12	170	-0.068	0.0843	-0.85	0.1726
1967	6	8	122	0.0318	0.2098	-1.05	-0.0457
1998	10	14	182	0.0879	0.7353	-0.75	0.9205
1999	8	12	177	-0.0882	0.2617	-0.9	0.2919
2007	6	15	68	0.3705	0.5495	-1	0.7257
2010	12	19	165	0.5819	0.542	-1.05	0.8753
2016	?	?	150	-0.1717	0.5769	-0.95	0.5522
1950-2015	6	12	100				

3) The number of hurricanes (NH) in the North Atlantic Ocean Basin, including the Gulf of Mexico and the Caribbean Sea

The number of hurricanes across the North Atlantic Ocean Basin has varied across a large range over the past few decades. There was a low of 2 in 1982 and a record high of 15 in 2005. The average NH from 1950 to 2015 is 6. With the similar predictors applied in those analog years (**Table 3**), the average number of hurricanes (NH) is 8, varying in range from 6 to 12. The Prediction model estimation for this variable for 2016 is 7.05, which is 117% of the 1950-2015 average (6). The predicted range of NH with 70% confidence level is 6.18 to 8.04. Combined with the analog year analysis, the most likely NH range is 6 ~10, with the most likely number of 7. A probability forecast is presented in **Table 4**.

Table 4 Probabilities associated with our estimated NH for 2016

Number	3	4	5	6	7	8	9	10
Probability	5.07%	8.93%	12.59%	14.79%	14.90%	13.13%	10.28%	7.25%

4). Number of major hurricanes (MH) in the NAOB, including the Gulf of Mexico and the Caribbean Sea

The annual number of MH in history (1950-2015) has ranged from 0 to 8, with 2.5 being the average. From our analogue year analysis there were twelve years which had nominally similar predictors (**Table 5**). The MH number has varied from 1 (1962) to 7 (1961). The average MH number for the twelve analog years is 3.3. From our model, the estimated value is 3.48, and is at the 70% confidence level across the range from 2.83 to 4.27.

Table 5. Analog years for 2015 MH with associated predictors

Year	MH	ACE	SSTA	ENSO	AMM	AMO
1954	2	113	0.0587	0.4483	-0.95	-0.3749
1961	7	205	-0.0366	0.3379	-1	-0.1586
1962	1	36	0.3705	0.4859	-0.5	0.1845
1964	6	170	-0.068	0.0843	-0.85	0.2427
1967	1	122	0.0318	0.2098	-1.05	-0.0193
1988	3	103	-0.2862	-0.0169	-1.25	0.5852
1998	3	182	0.0879	0.7353	-0.75	1
1999	5	177	-0.0882	0.2617	-0.9	0.2629
2000	3	116	0.0307	0.0986	-0.25	0.5542
2006	2	79	0.2544	0.3345	1.25	0.3304
2007	2	68	0.3705	0.5495	-1	0.7045
2010	5	165	0.5819	0.542	-1.05	0.9841
2016	?	150	-0.1717	0.5769	-0.95	0.5418
1950-2015	2.5	100				

Combined with the above analog year analysis, the most likely number of major hurricanes (MH) ranges from 2 to 5 with 3 as the most probable number and with 4 and 2, jointly, as the second most probable numbers. The Probability distribution of the model estimation is given in **Table 6**.

Table 6 Probabilities associated with the estimated MH number

Number	0	1	2	3	4	5	6
Probability	3.1%	10.7%	18.65%	21.64%	18.83%	13.1%	7.6%

5) Land-falling hurricane numbers along the U.S. Atlantic Eastern Seaboard (ECLF).

HUGO's ECLF prediction model largely depends on the identification of the hurricane season type (Yan, et al 2015). According to NOAA's classification criteria of hurricane season type (Bell, et al. 2000), a near-normal season will typically have an ACE range of 66~111 x 10^4 kt^2

with tropical storm in range of 10~15, number of hurricanes 4~9, major hurricane 1 to 4. An above normal season typically has an ACE range above 111 x 104 kt2 (corresponding to 120% of the 1981-2010 median), with at least two of the following three conditions: 13 or more named storms, 7 or more hurricanes, and 3 or more major hurricanes (**Table 7**).

Table 7 Classification of hurricane season type

Season Type	Mean # of Tropical Storms	Range of Tropical Storms	Mean # of Hurricanes	Range of Hurricanes	Mean # of Major Hurricanes	Range of Major Hurricanes
Above-Normal	16.5	12 to 28	9.7	7 to 15	4.8	3 to 7
Near-Normal	12.3	10 to 15	6.3	4 to 9	2.3	1 to 4

(From http://www.cpc.ncep.noaa.gov/products/outlooks/background_information.shtml)

HUGO's estimation of this year's ACE ranges from 120 ~ 180, the number of tropical storms ranges 11~15, the hurricane number ranges from 6~10, and the major hurricane number ranges from 2~5. Checking with the criteria listed in **Table 7**, If we only consider the upper bound of HUGO's estimation, the 2016 hurricane season would fall into the well above normal season type. If we consider the low bound of the estimation, the season would fall into the near normal season type. However our estimate from the ACE analog year analysis suggests a downward adjustment of the model outputs. Since ENSO is one of the most important factors for cyclogenesis, our model employed the projected ENSO Index for August through October of -0.95. Combining the above analysis, we therefore call for a near to above normal hurricane season, and the landfall prediction model was run for near to above normal season types.

From 1950 to 2015, a total of 44 (of the 66) or 2/3rd's of the years fall into the near and above normal season type categories. The Landfall numbers for those 44 years have varied from 0 to 3. No landfalls occurred in 19 of the years (43%), one landfall occurred in 16 years (36%), two landfalls occurred in 6 of the years (14%) and three landfalls occurred in 3 of the years (7%). The average landfall count in those 44 years is 0.84.

There are 10 years in history with similar predictor combinations alike those of 2016 (**Table 8**). There are zero landfalls in six of the years (1951, 1967, 1980, 2006, 2008 and 2010), one landfall in four of the years (1958, 1998, 1999 and 2011). Therefore based on our analog year analysis, the most likely range of the landfall number is 0 or 1; with 0 at a higher probability.

Table 8 Analog years of 2016 with predictors and associated landfall events listed

Year	ECLF	ACE	AMO	ENSO	SST
1951	0	137	0.3731	0.45	-0.1206
1958	1	121	0.2884	0.35	-0.2534
1967	0	122	0.3349	0.15	-0.1937
1980	0	147	0.0438	0.4	0.1585
1998	1	182	0.4879	0.85	0.1014
1999	1	177	0.5822	-0.4	0.2114
2006	0	79	0.5986	0.45	0.3985
2008	0	144	0.3294	0.4	0.1006
2010	0	165	0.3048	0.1	0.663
2011	1	126	0.6177	0.45	0.3479
2016	.	150	0.6011	0.2	0.5021

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The AMO (Dec 2015 – Jan 2016) value (0.6011) suggests an ocean - atmosphere condition favorable for hurricanes making landfall along the U.S. Atlantic Eastern Seaboard. The mean ENSO index (May to June) used in this scheme was derived from the JMA forecast model, which has a projected value of 0.20. Most of the ENSO prediction models (**Figure 3**) suggest that the existing El-Nino event is weakening in April. Since the projected ENSO index is one of the dominant predictors in the model, we will update it as new projections or observations of the ENSO index become available. The anomalous SST time series extracted from the domain (24 ºW to 40ºW, 18º S to 40ºS) displays a negative correlation with the ECLF (Yan, et al, 2010). Therefore, a positive value of SST (0.5021) in 2016 suggests an unfavorable condition for hurricanes making landfall. The predictors applied in this forecasting scheme are shown in **Figure 6**

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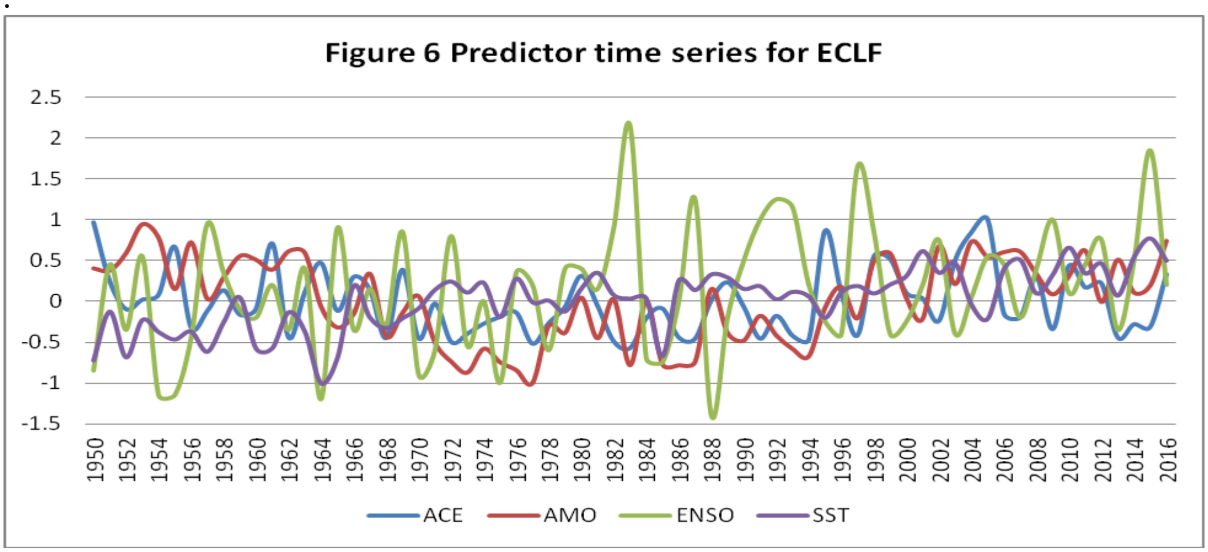

Using the CCU HUGO prediction model for near to above normal season types, the model yields an estimated intensity = 0.67, with the lower and upper bounds at the 70% confidence level: [0.46 and 0.96]. Since the 66-year (1950-2015) ECLF average is 0.63, we therefore estimate ECLF is only 106% of the long-term average. This percentage was computed via: Estimated intensity (0.67)/average landfall hurricane number per year (0.63)*100.

Following the computation of the Poisson distribution, a probability forecast for the ECLF is presented in **Table 9.** It shows that**:** 1) the maximum probability, 85%, is associated with 0 landfalls. Here the long term (1950-2015) mean of having zero landfall events is 57%; 2) the probability associated with having 1 landfall is 14%, where the long-term mean is 32%); and 3) the probability of realizing 2 or more landfalls is 1%, with a 63 year mean of 11%. So, the overall estimated probability for 0 or only 1 hurricane making landfall is 99%, and where the total 64 year mean is 89%, and for at least 2 landfalls is only 1%, where the 63 year mean is 11%.

Table 9 Probabilities for U.S. Eastern Seaboard landfall counts

Number	0	1	2 or more
Probabilities	51.2%	34.3%	14.5%
Average (1950-2015)	58.0%	31.0%	11.0%

It is of note that for near to above normal season types, our model performance is degraded due to a preponderance of zeros of landfall numbers, so our model estimate must be combined with our analog year analyses. Based on the CCU HUGO analog analyses of the past 66-years (1950-2015) and our model prediction output, we anticipate that the most likely range of ECLF in 2016 is 0 to 1, in that order. As input predictors of the ECLF improve with June and early August we will update our forecast.

6) Land-falling hurricanes along the coastline of U.S. Gulf of Mexico (GMLF) states

It must be stated up front that many of the climate factor predictors which we have found must be applied to make highly credible forecasts of GMLF are not yet available and will not be more fully available until July to early August. So an April forecast is problematic at best. However we will make a preliminary estimate at this time. Predictors available for this April forecast are the Tropical South Atlantic (TSA) index, the estimated ACE and SST anomalies extracted from the selected domain (Yan et al, 2010). TSA is derived from mean monthly SST anomalies from 0^{o} to 20ºS and from 10ºE to 30ºW. Its' normalized value to date is 0.6772, which suggests a favorable landfall condition. The 2016 hurricane season is expected to be near to above normal. A normalized ACE (0.3345) also signals a favorable condition. Anomalous SST in the selected domain in 2016 is slightly above normal (0.2337), which suggests an unfavorable condition.

Table 10 lists twelve analog years in the 66 year record that have similar predictor combinations to those to date in 2016. There were 0 landfalls in 4 of the years (1951, 2000, 2010 and 2011), 1 landfall in three of the years (2003, 2008, 2012), 2 landfalls in five of the years, and 3 landfalls in one year (2008). Based on our analog year analysis, we conclude that the most likely number is 2 (38.5%), followed by 0 (30.8%), 1 (23.1%) and 3 (7.6%). From analog year analysis, we can conclude the most likely range of GMLF is 0 to 2 (92.4%).

Table 10 Analog years of 2016 with predictors and associated landfall events listed

Year	GMLF	ACE	SST	TSA
1951	0	137	0.0643	0.2507
1966	2	145	0.205	0.3047
1980	1	147	0.2296	0.3182
1989	2	135	0.307	0.2372
1998	2	182	-0.0313	0.5545
1999	2	177	0.1897	0.5207
2000	0	116	0.3761	0.1089
2003	1	175	0.2572	0.5072
2004	2	225	-0.002	0.8447
2008	3	144	0.1269	0.2979
2010	0	165	0.405	0.4397
2011	0	126	0.4602	0.1427
2012	1	133	0.5847	0.2237
2016	?	150	0.2337	0.6772

The CCU HUGO Model estimated GMLF value is 1.19, with lower and upper bounds at the 70% confidence level at 0.85 and 1.65. The long-term (1950-2016) mean number of GMLF is 0.92. The model estimate is 129% of the 66-year average. **Table 11** displays the forecasted landfall probabilities associated with the model estimate.

Table 11 Landfall probability associated with Gulf of Mexico landfall counts

Number	0	1	2	3 or more
Probabilities	30.4%	36.2%	21.5%	11.9%
Climatology	38.7%	41.7%	15.1%	4.5%

The largest probability of one hurricane making landfall on the U.S. Gulf Coast is 36.2%, and the overall probability of landfalls falls in the range of 0 ~ 2 is 88.1%. Combined with our analog analysis, the most likely individual number of GMLF in 2016 is 1. A range with second and third likely occurrences is 0 and 2 in that order. However, we will update this GMLF forecast when more predictors become available in July and early August.

The Outlook for the 2016 North Atlantic Hurricane Season

Hurricane Genesis & Outlook (HUGO) Project

(April 15, 2016)

V. Conclusions

Analog year analyses for the CCU HUGO 2016 ACE prediction showed that over the 66 year period (1950~2015), ten of the total eleven analog years with similar predictor combinations to that of 2016 fell in near to above normal hurricane season category, and only one analog year (1962) fell in the below-normal category. Combined with prediction model outputs, the estimated ACE value is in the range of 120 ~ 180 ($10^4 kt^2$), which is 120% ~ 180% of the 1950-2015 average. ACE could fall in the upper-bound of the near-normal category (~$111x10^4kt^2$) or fall in the hyperactive category. The number of tropical storms is expected to be in the range of 11 ~ 15, the hurricane number in the range of 6 ~ 10, and the major hurricane number is in the range of 2 ~ 5. In keeping with NOAA's hurricane season classification criterion (Bell et al, 2000), we anticipate a near to above normal hurricane season for 2016.

Estimated landfall hurricane probabilities for 2016 are given for two target scenarios, strikes along the U.S. Eastern Seaboard, from Key West FL to Nova Scotia, and along the U.S. coastline of the Gulf of Mexico, from Brownsville TX to Key West FL. For the first scenario, the landfall number falls in the range 0~1 with the maximum estimated probability number 0. For the second scenario, the most likely landfall number is 1, a range with second and third likely occurrences is 0 and 2 in that order. If one adds the two then the present potential for landfalls along a U.S. coastline has a Forecast value of 1.86 which is 20% above the joint climatology which is 1.55. This suggests that as a Poisson distribution the range of landfalls should be in order of likelihood, [1, 0, 2, 3], hurricanes making landfall during HS16.

Table 12 Summary of the 2016 North Atlantic hurricane seasonal forecast for all six prediction categories

Table 12. 2016 Atlantic Basin Seasonal Hurricane Forecast (April)

Category	Forecast Value	Forecast Range	Order of LFs	Climatology
ACE	150	[120~180]		100
TS	13	[11~15]		12
NH	7	[6~10]		6.1
MH	3	[2~5]		2.7
ECLF	0.67	[0 - 2]	{0, 1, 2}	0.63
GMLF	1.19	[0 - 2]	{1, 2, 0}	0.92

VI. Acknowledgements

The CCU HUGO Team thanks Coastal Carolina University for supporting this initiative. President D. A. Decenzo and his staff have been very helpful in effecting the HUGO Project.

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