QUALITATIVE DISCUSSION OF ATLANTIC BASIN SEASONAL HURRICANE ACTIVITY FOR 2017

We currently provide qualitative discussions of the factors which will determine next year's Atlantic basin hurricane activity with our early December outlook. Two big questions with the upcoming hurricane season are what will happen with the current weak La Niña as well as to what trends occur with the Atlantic Multidecadal Oscillation.

Our first quantitative forecast for 2017 will be issued on Thursday, April 6.

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.

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

As of 14 December 2016

Project Sponsors:

---

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

ABSTRACT

We are providing a qualitative discussion of features likely to impact the 2017 Atlantic basin hurricane season rather than a specific numbers forecast. This outlook for 2017 will give our assessment of the probability of five potential scenarios for Accumulated Cyclone Energy (ACE).

The current way that we assess the following year's activity in the December outlook is in terms of two primary physical parameters:

1. the strength of the Atlantic Multi-Decadal Oscillation (AMO) or Atlantic thermohaline circulation (THC)

2. the phase of ENSO

Following three quiet Atlantic hurricane seasons in a row, the 2016 Atlantic hurricane season had somewhat above-average activity. This continues the debate as to whether or not we remain in an active AMO/THC phase (Klotzbach et al. 2015). Another big question for 2017 is what trends El Niño-Southern Oscillation (ENSO) will have over the next few months. There is considerable model disagreement as to what the phase of ENSO will look like for the summer and fall of 2017.

For the 2017 hurricane season, we anticipate five possible scenarios with the probability of each as indicated on the next page:

1. AMO/THC becomes very strong in 2017 and no El Niño occurs (resulting in a seasonal average Accumulated Cyclone Energy (ACE) activity of ~ 170) – **20% chance**.
2. AMO/THC is above average and no El Niño occurs (ACE ~ 130) – **40% chance**.
3. AMO/THC is above average and El Niño occurs (ACE ~ 80) – **10% chance**.
4. AMO/THC is below average and no El Niño occurs (ACE ~ 80) – **20% chance**.
5. AMO/THC is below average and El Niño develops (ACE ~ 50) – **10% chance**.

Typically, seasons with the above-listed ACE values have TC activity as follows:

170 ACE – 14-17 named storms, 9-11 hurricanes, 4-5 major hurricanes
120 ACE – 12-15 named storms, 6-8 hurricanes, 2-3 major hurricanes
80 ACE – 8-11 named storms, 3-5 hurricanes, 1-2 major hurricanes
50 ACE – 5-7 named storms, 2-3 hurricanes, 0-1 major hurricane

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.

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

1 Introduction

This is the 34th year in which the CSU Tropical Meteorology Project has made forecasts of the upcoming season's Atlantic basin hurricane activity. Our research team has shown that a sizable portion of the year-to-year variability of Atlantic tropical cyclone (TC) activity can be hindcast with skill exceeding climatology. These forecasts are based on a statistical methodology derived from 30-60 years of past data. Qualitative adjustments are added to accommodate additional processes which may not be explicitly represented by our statistical analyses. These evolving forecast techniques are based on a variety of climate-related global and regional predictors previously shown to be related to the forthcoming seasonal Atlantic basin TC activity and landfall probability. We believe that seasonal forecasts must be based on methods that show significant hindcast skill in application to long periods of prior data. It is only through hindcast skill that one can demonstrate that seasonal forecast skill is possible. This is a valid methodology provided that the atmosphere continues to behave in the future as it has in the past.

The best predictors do not necessarily have the best individual correlations with hurricane activity. The best forecast parameters are those that explain the portion of the variance of seasonal hurricane activity that is not associated with the other forecast variables. It is possible for an important hurricane forecast parameter to show little direct relationship to a predictand by itself but to have an important influence when included with a set of 2-3 other predictors.

A direct correlation of a forecast parameter may not be the best measure of the importance of this predictor to the skill of a 2-3 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. No one can completely understand the full complexity of the atmosphere-ocean system. But, it is still possible to develop a reliable statistical forecast scheme which incorporates a number of the climate system's non-linear interactions. Any seasonal or climate forecast scheme must show significant hindcast skill before it is used in real-time forecasts.

2 The Influence of the Atlantic Ocean Thermohaline Circulation (THC) and the Strength of the Atlantic Gyre on Atlantic Hurricane Activity

Over the next few pages, we discuss two large-scale physical features which we know are fundamental for how active the 2017 Atlantic hurricane season is likely to be.

The longer-period SST changes which the Atlantic Ocean experiences are due primarily to variations in the strength of the southwest to northeast upper branch of the THC in the high latitude Atlantic, which are then reflected in changes in the AMO. The

THC (which is observed and modeled to vary considerably in strength on multi-decadal timescales) is strong when there is an above-average poleward advection of warm tropical waters to the high latitudes of the Atlantic. This poleward-moving water can then sink to deep levels if it has high enough salinity content. This sinking process is known as North Atlantic Deep Water Formation (NADWF). The deep water then moves southward into the Southern Hemisphere. The amount of North Atlantic water that sinks is roughly proportional to the water's density which at high latitudes, where water temperatures are low, is primarily dependent on salinity content. The strong association between our proxy for the AMO/THC and North Atlantic salinity in the far North Atlantic (50-60°N, 50-10°W) is shown in Figure 1. High salinity implies higher rates of NADWF. When the salinity rates are lower, less NADWF formation occurs. During these periods, the water tends to recirculate and increase the ocean's clockwise circulating gyre motion.

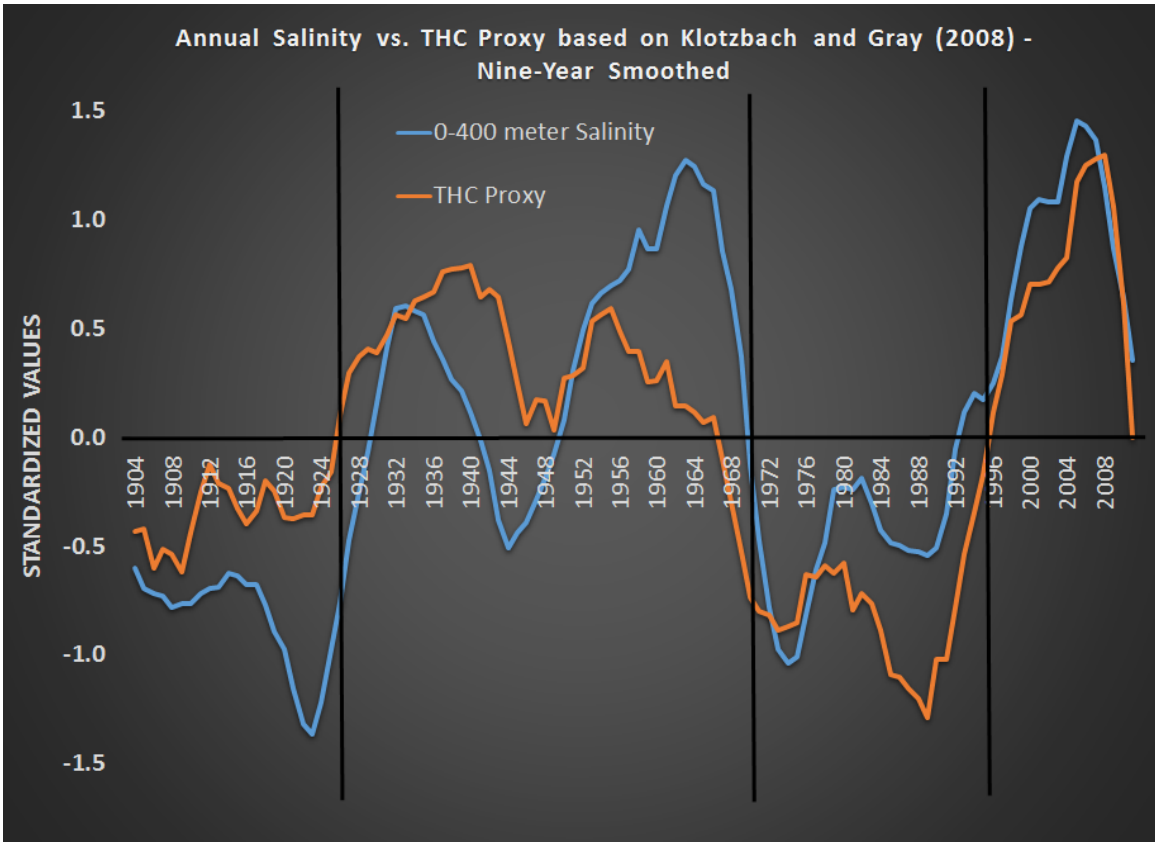


Figure 1: Illustration of the strong association of yearly average North Atlantic THC proxy and North Atlantic salinity content from 1900-2015.

Through a progression of associations the strength of the NADWF and inverse strength of the Atlantic gyre is hypothesized to bring about alterations of the tropospheric vertical wind shear, trade wind strength, SSTs, middle-level water vapor, and other conditions in the Atlantic Main Development Region (MDR – 7.5-22.5°N; 20-75°W). Changes of SST in the MDR are a consequence of a combination of the THC's influences on a variety of other parameters in the MDR (Figure 2). A stronger than average THC causes more ocean sinking in area 1. This in turn reduces the strength of the Atlantic gyre. There is then a change in all of the other conditions shown in Figure 2 to bring about more or less favorable parameters in the MDR for TC formation and intensification. This figure illustrates how the changing rate of southward advection of cold water in the east Atlantic (2) brings about alterations of SLP (3), SST (4), and rainfall (5). These changes in turn lead to changes in trade wind strength (6) and 200 mb zonal wind (7). Changes in hurricane activity and especially major hurricane activity follow (8). It is also found that in periods with a strong THC, El Niño frequency and intensity is typically reduced (9) and tropical South Atlantic SSTs are decreased (10).

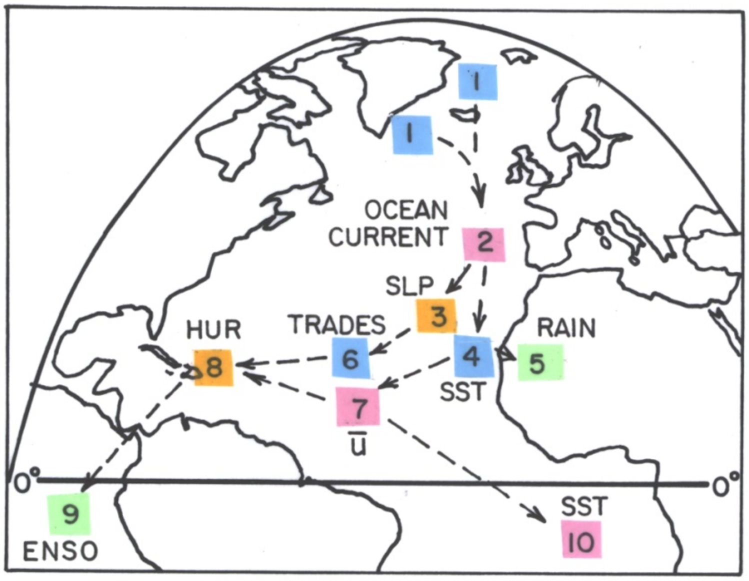


Figure 2: Idealized analysis of how changes in North Atlantic SST and salinity (area 1) lead to progressive ocean current, wind, pressure, SST, vertical shear and rain changes as portrayed in nine areas. It is this complete package of Atlantic/eastern Pacific ocean/atmosphere parameter changes on multi-decadal time scales which cause large changes in Atlantic major hurricanes on this time scale.

One of the primary physical drivers for active versus inactive Atlantic basin hurricane seasons is the strength of the THC or AMO (Gray et al. 1996, Goldenberg et al. 2001, Klotzbach and Gray 2008). A positive phase of the AMO (or strong phase of the THC) typically leads to 3-5 times more major Atlantic basin hurricane activity than does a negative phase. The typical period of the THC is about 60 years, with the period length varying between as short as 40-50 years and as long as 70-80 years. This means that we typically have 25-35 years of above-average Atlantic basin major TC activity and similar length periods with considerably reduced amounts of major TC activity. Recently, we had three quiet Atlantic hurricane seasons in a row (e.g., 2013-2015) which led us to question whether we have moved out of the active era that began in 1995 (Klotzbach et al. 2015). The relatively active 2016 Atlantic hurricane season clouds the issue as to whether the Atlantic remains in an active era.

While the THC typically remains in an above-average or in a below-average state for periods of 25-35 years, there can be monthly, seasonal or longer breaks up to a year or two within these decadal periods when the THC (or AMO) conditions of features such as SST, salinity, pressure, wind, and moisture become substantially weaker in positive THC phases or stronger during negative THC phases.

There is a strong inverse relationship between the strength of the THC and the strength of the Atlantic gyre (Bermuda-Azores High). This has been well documented in our analysis of various yearly and seasonal gyre and THC proxy variations. Hurricane activity, particularly the most intense hurricane activity, is much more frequent when the Atlantic Bermuda-Azores gyre circulation system is weak and the Atlantic Ocean THC system is strong. Hurricane activity is generally reduced when the reverse conditions occur. Increased gyre strength acts to bring about cooler air (and reduced moisture) and cooler ocean water advection in the eastern half of the Atlantic. This acts to increase the strength of the trade winds and increase the low latitude (5-20°N) south to north tropospheric temperature gradient and the upper tropospheric westerly winds. All of these changes are inhibiting factors for hurricane formation and intensification.

We currently monitor a THC proxy that utilizes SST in the region from 50-60°N, 50-10°W and SLP in the region from 0-50°N, 70-10°W (Figure 3). The index is created by weighing the two parameters as follows: 0.6*SST – 0.4*SLP. The AMO is currently running at near-normal levels (Figure 4).

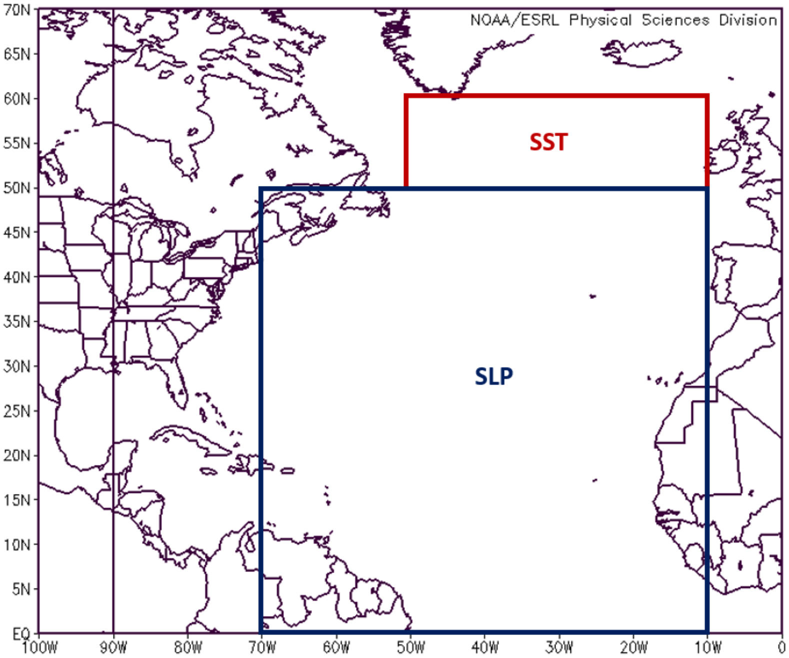


Figure 3: Regions which are utilized for calculation of our THC/AMO index. These regions are as defined in Klotzbach and Gray (2008).

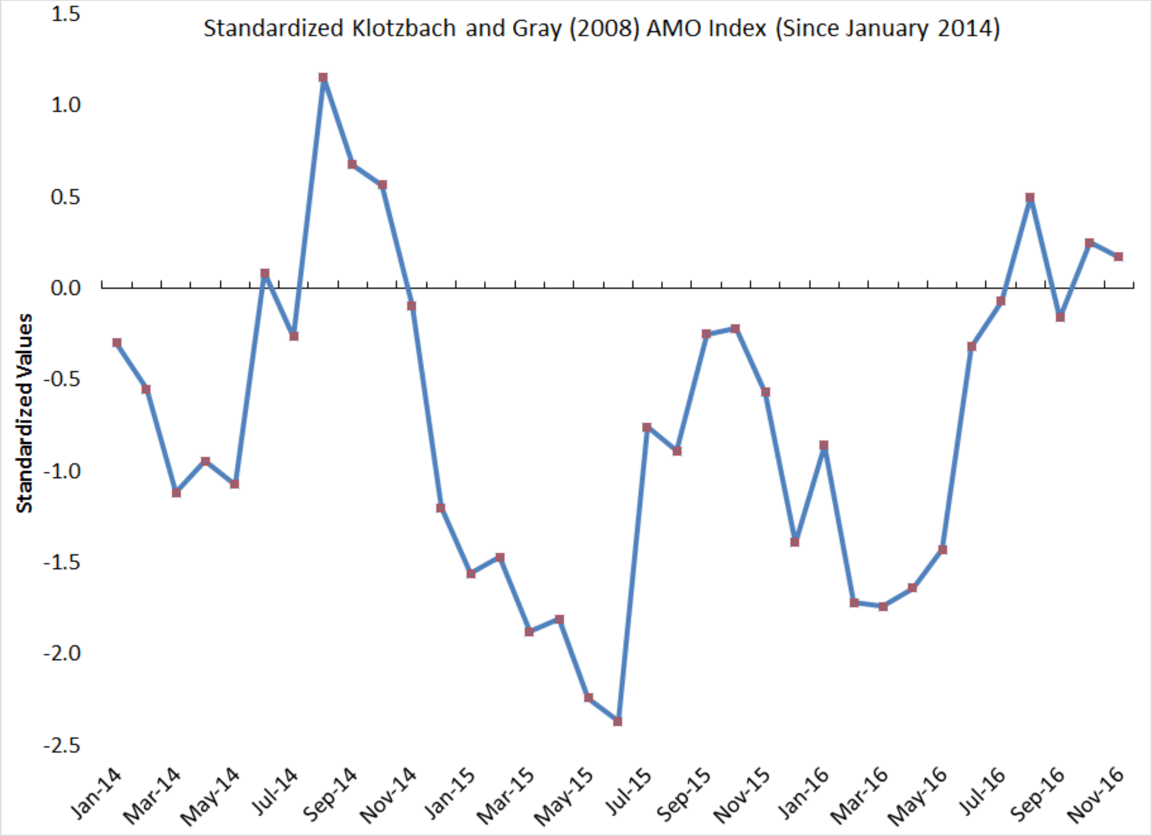


Figure 4: Standardized values of the THC/AMO index by month since January 2014.

3 ENSO

There is currently a weak La Niña in place across the tropical Pacific (Figure 5). One of the important questions for the upcoming hurricane season is to what the ENSO state will look like during the peak of the Atlantic hurricane season in 2017. Several forecast models are calling for the potential to transition back to El Niño conditions by next summer (Figure 6). The European Center for Medium-Range Weather Forecasts (ECMWF) model is one of the more aggressive models at calling for warming, with ~30% of all ensemble members calling for El Niño conditions by June (Figure 7). The ECMWF model has been shown to be one of the most skillful models at predicting future ENSO conditions.

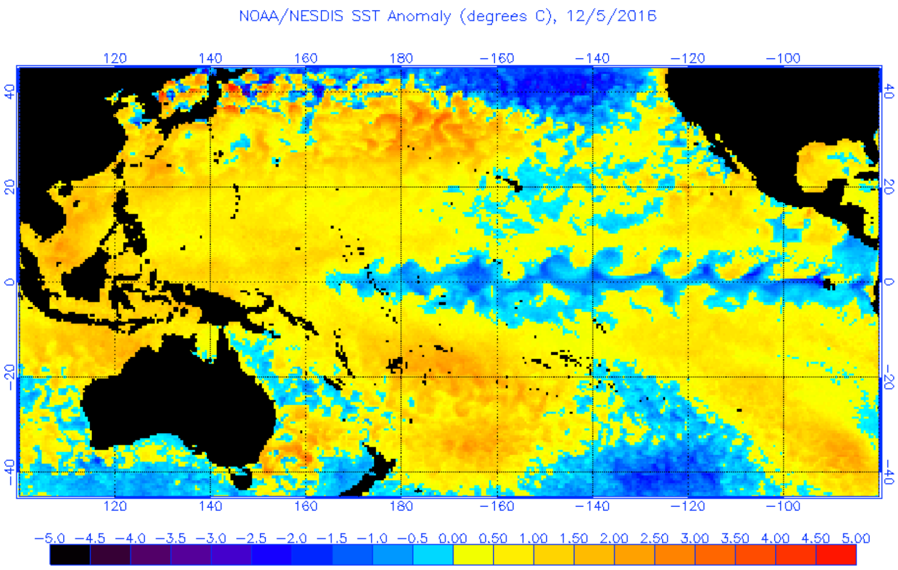


Figure 5: Early December SST anomalies across the Pacific Ocean. Cool anomalies prevail across the central and eastern tropical Pacific, indicative of weak La Niña conditions.

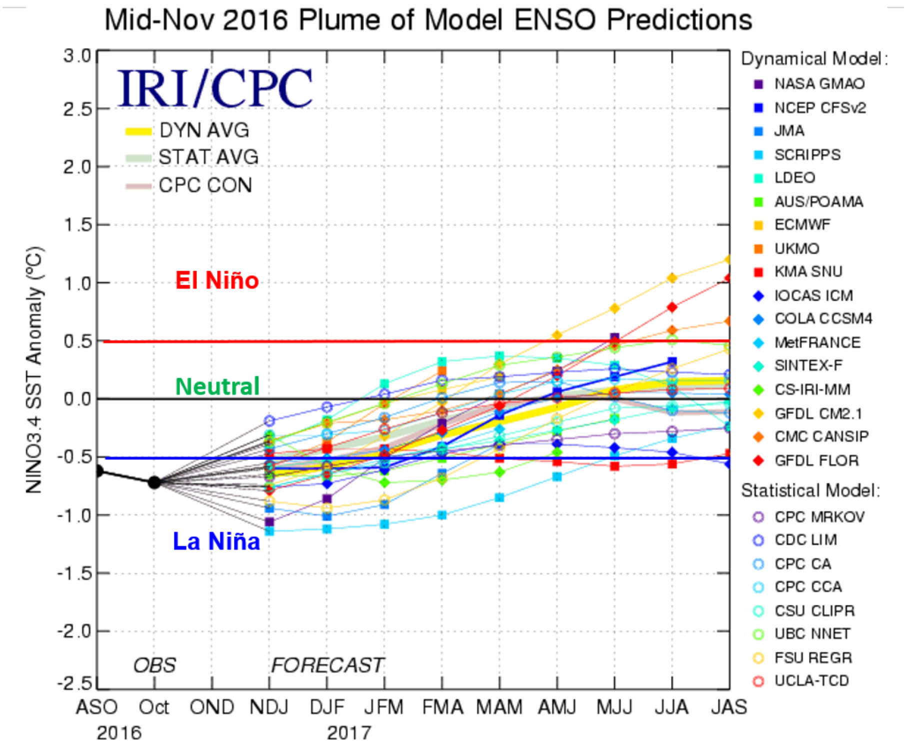


Figure 6: ENSO model prediction plume from mid-November for the next several months. Several forecast models are calling for a transition to El Niño conditions by the upcoming Atlantic hurricane season. Figure courtesy of the International Research Institute for Climate and Society.

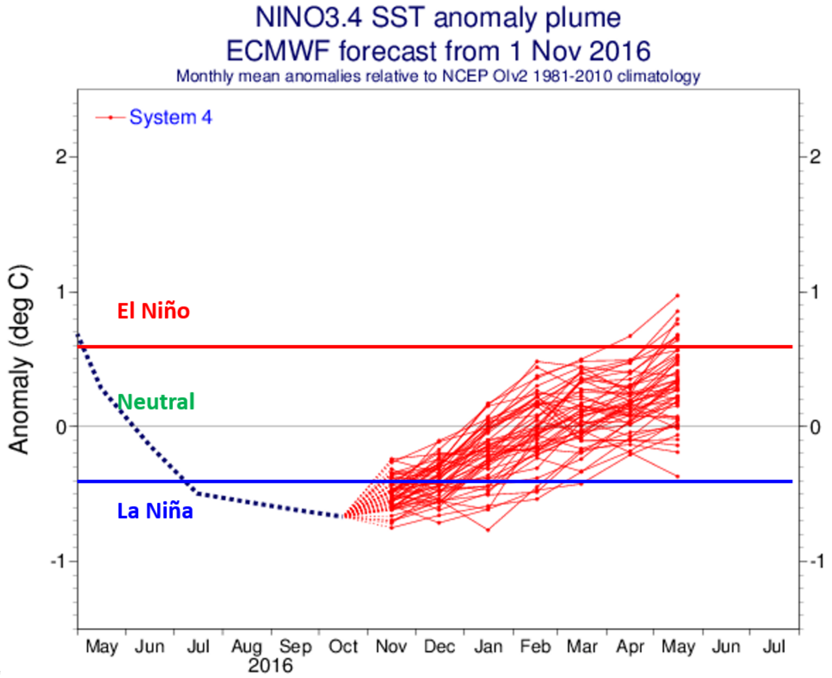


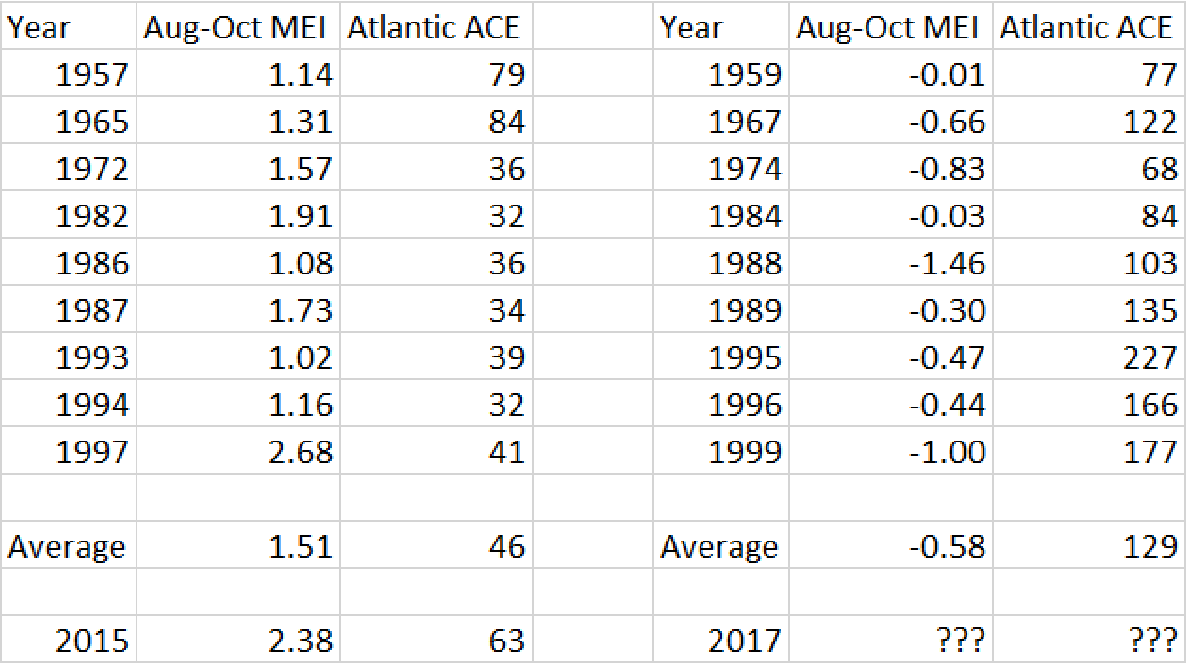
Figure 7: Ensemble ECMWF forecast plume for Nino 3.4 SSTs over the next few months. About 25-30% of all forecast members are calling for El Niño conditions by May.

It would be quite unusual to have a repeat of El Niño conditions in 2017, just two years after the strong El Niño of 2015, based on historical data. Table 1 displays the years with moderate to strong El Niño events during August-October based on the Multivariate ENSO Index (MEI) since 1950, along with ACE accrued in these years. We take all August-October periods where the MEI exceeded 1 standard deviation as moderate to strong El Niño events. The MEI utilizes a combination of atmospheric and oceanic indicators to assess the state of ENSO. We find that the MEI correlates better with Atlantic hurricane activity than any oceanic-only ENSO index. More information on the MEI is available. Also displayed are the MEI and ACE values for the 2nd year following the moderate to strong El Niño. Of the 9 years with moderate to strong El Niño conditions in August-October since 1950, none had a repeat of El Niño conditions two years later.

Table 2 shows similar data but for moderate to strong El Niño events during August through October from 1871-1949. Only one of the eleven years with moderate to strong El Niño conditions in August-October had weak El Niño conditions two years later, with the rest either having neutral ENSO or La Niña conditions.

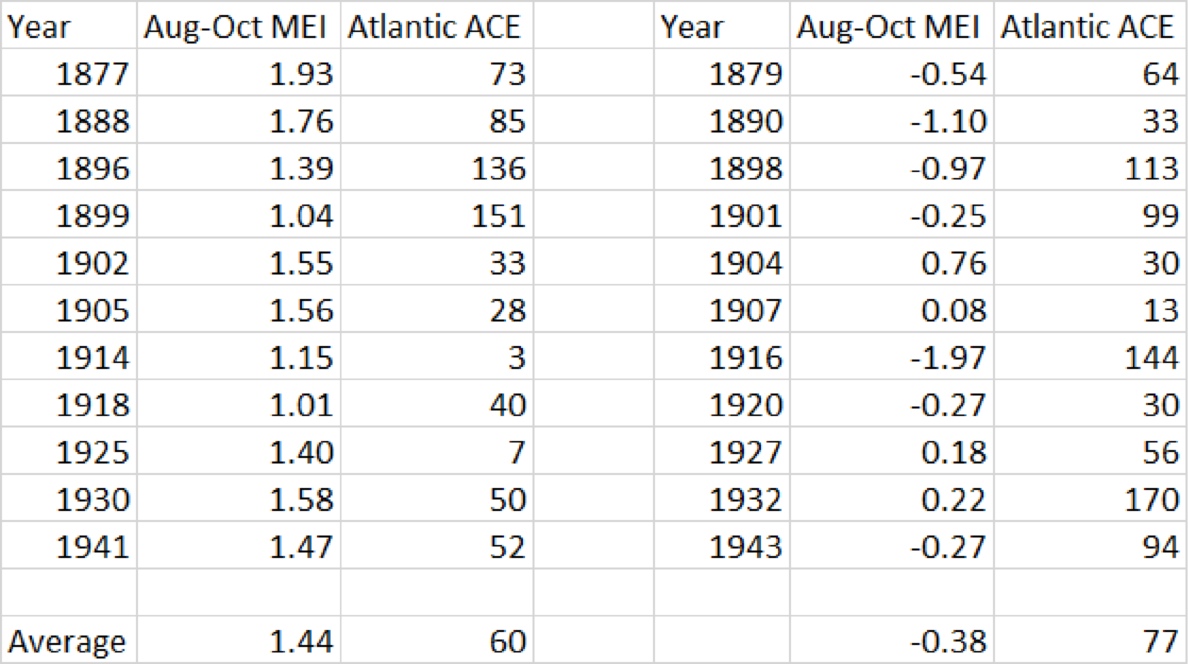
To summarize, a total of 20 moderate to strong El Niño events have occurred during August-October since 1871. Of these 20 events, only 1 had a return to El Niño conditions two years later.

Table 1: Moderate to strong El Niño events during August-October since 1950, with ACE generated in the Atlantic basin during that year. Also listed are the value of the August-October-averaged MEI and Atlantic ACE two years later.



Year	Aug-Oct MEI	Atlantic ACE		Year	Aug-Oct MEI	Atlantic ACE
1957	1.14	79		1959	-0.01	77
1965	1.31	84		1967	-0.66	122
1972	1.57	36		1974	-0.83	68
1982	1.91	32		1984	-0.03	84
1986	1.08	36		1988	-1.46	103
1987	1.73	34		1989	-0.30	135
1993	1.02	39		1995	-0.47	227
1994	1.16	32		1996	-0.44	166
1997	2.68	41		1999	-1.00	177
Average	1.51	46		Average	-0.58	129
2015	2.38	63		2017	???	???

Table 2: As in Table 1 but for 1871-1949.



Year	Aug-Oct MEI	Atlantic ACE		Year	Aug-Oct MEI	Atlantic ACE
1877	1.93	73		1879	-0.54	64
1888	1.76	85		1890	-1.10	33
1896	1.39	136		1898	-0.97	113
1899	1.04	151		1901	-0.25	99
1902	1.55	33		1904	0.76	30
1905	1.56	28		1907	0.08	13
1914	1.15	3		1916	-1.97	144
1918	1.01	40		1920	-0.27	30
1925	1.40	7		1927	0.18	56
1930	1.58	50		1932	0.22	170
1941	1.47	52		1943	-0.27	94
Average	1.44	60			-0.38	77

4 Climatological Landfall Probabilities

A significant focus of our recent research involves efforts to develop forecasts of the probability of hurricane landfall along the U.S. coastline and in the Caribbean. While we are not issuing a quantitative forecast in this early outlook, we can still provide interested readers with the climatological probabilities of landfall for various portions of the United States coastline.

Table 3 lists climatological strike probabilities for the hurricane season for different TC categories for the entire U.S. coastline, the Gulf Coast and the East Coast including the Florida peninsula. We also issue probabilities for various islands and landmasses in the Caribbean and in Central America.

Table 3: Climatological probability (expressed in percent) of one or more landfalling tropical storms (TS), category 1-2 hurricanes (HUR), category 3-4-5 hurricanes, total hurricanes and named storms along the entire U.S. coastline, along the Gulf Coast (Regions 1-4), and along the Florida Peninsula and the East Coast (Regions 5-11). Probabilities of a tropical storm, hurricane and major hurricane tracking into the Caribbean are also provided.

Region	TS	Category 1-2 HUR	Category 3-4-5 HUR	All HUR	Named Storms
Entire U.S. (Regions 1-11)	79%	68%	52%	84%	97%
Gulf Coast (Regions 1-4)	59%	42%	30%	60%	83%
Florida plus East Coast (Regions 5-11)	50%	44%	31%	61%	81%
Caribbean (10-20°N, 60-88°W)	82%	57%	42%	75%	96%

We have also calculated probabilities of each state being impacted by a tropical cyclone, using the impacts database available from the National Hurricane Center. Table 4 displays the climatological probabilities for each state along the United States coastline being impacted by a hurricane and major hurricane, respectively.

Table 4: Climatological probability of each state along the United States coastline being impacted by a hurricane and major hurricane, respectively.

State	Hurricane	Major Hurricane
Texas	33%	12%
Louisiana	30%	12%
Mississippi	11%	4%
Alabama	16%	3%
Florida	51%	21%
Georgia	11%	1%
South Carolina	17%	4%
North Carolina	28%	8%
Virginia	6%	1%
Maryland	1%	<1%
Delaware	1%	<1%
New Jersey	1%	<1%
New York	8%	3%
Connecticut	7%	2%
Rhode Island	6%	3%
Massachusetts	7%	2%
New Hampshire	1%	<1%
Maine	4%	<1%

The Landfall Probability Website has additional probability information including county-level probabilities for 205 coastal counties from Brownsville, Texas to Eastport, Maine. These probabilities will be updated on Thursday, April 6 with our first quantitative outlook for 2017.

5 Forthcoming Updated Forecasts of 2017 Hurricane Activity

We will be issuing seasonal updates of our 2017 Atlantic basin hurricane forecasts on **Thursday April 6**, **Thursday 1 June**, **Monday 3 July, and Wednesday 2 August**. We will also be issuing two-week forecasts for Atlantic TC activity during the climatological peak of the season from August-October. A verification and discussion of all 2017 forecasts will be issued in late November 2017. All of these forecasts will be available on our project’s website.

6 Acknowledgments

Besides the individuals named on page 3, 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.

7 Citations and Additional Reading

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Gray, W. M., J. D. Sheaffer and C. W. Landsea, 1996: Climate trends associated with multi-decadal variability of intense Atlantic hurricane activity. Chapter 2 in “Hurricanes, Climatic Change and

Socioeconomic Impacts: A Current Perspective", H. F. Diaz and R. S. Pulwarty, Eds., Westview Press, 49 pp.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

8 Verification of Previous Forecasts

Table 5: Summary verification of the authors' five previous years of seasonal forecasts for Atlantic TC activity from 2012-2016.

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	26
Named Storm Days	40	50	52	99.50
Major Hurricanes	2	2	2	1
Major Hurricane Days	3	4	5	0.25
Net Tropical Cyclone Activity	75	90	105	121

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

2014	10 April	Update 2 June	Update 1 July	Update 31 July	Obs.
Hurricanes	3	4	4	4	6
Named Storms	9	10	10	10	8
Hurricane Days	12	15	15	15	17.75
Named Storm Days	35	40	40	40	35
Major Hurricanes	1	1	1	1	2
Major Hurricane Days	2	3	3	3	3.75
Accumulated Cyclone Energy	55	65	65	65	67
Net Tropical Cyclone Activity	60	70	70	70	82

2015	9 April	Update 1 June	Update 1 July	Update 4 August	Obs.
Hurricanes	3	3	3	2	4
Named Storms	7	8	8	8	11
Hurricane Days	10	10	10	8	11.50
Named Storm Days	30	30	30	25	43.75
Major Hurricanes	1	1	1	1	2
Major Hurricane Days	0.5	0.5	0.5	0.5	4
Accumulated Cyclone Energy	40	40	40	35	60
Net Tropical Cyclone Activity	45	45	45	40	81

2016	9 April	Update 1 June	Update 1 July	Update 4 August	Obs.
Hurricanes	6	6	6	6	7
Named Storms	13	14	15	15	15
Hurricane Days	21	21	21	22	26.25
Named Storm Days	52	53	55	55	78.25
Major Hurricanes	2	2	2	2	3
Major Hurricane Days	4	4	4	5	9.75
Accumulated Cyclone Energy	93	94	95	100	134
Net Tropical Cyclone Activity	101	103	105	110	145