# SUMMARY OF 2013 ATLANTIC TROPICAL CYCLONE ACTIVITY AND VERIFICATION OF AUTHORS' SEASONAL AND TWO-WEEK FORECASTS

The 2013 Atlantic hurricane season was much quieter than predicted in our seasonal outlooks. While many of the large-scale conditions typically associated with active seasons were present (e.g., anomalously warm tropical Atlantic, absence of El Niño conditions, anomalously low tropical Atlantic sea level pressures), very dry mid-level air combined with mid-level subsidence and stable lapse rates to significantly suppress the 2013 Atlantic hurricane season. These unfavorable conditions were likely generated by a significant weakening of our proxy for the strength of the Atlantic Multi-Decadal Oscillation/Atlantic Thermohaline Circulation during the late spring into the early summer. Overall activity in 2013 was approximately 30% of the 1981-2010 median.

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This forecast as well as past forecasts and verifications are available via the World Wide Web at http://hurricane.atmos.colostate.edu

Kortny Rolston, Colorado State University Media Representative, (970-491-5349) is available to answer various questions about this verification.

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As of 19 November 2013

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## ATLANTIC BASIN SEASONAL HURRICANE FORECASTS FOR 2013*

| Forecast Parameter and 1981-2010 Median (in parentheses) | 10 April 2013 | Update 3 June 2013 | Update 2 Aug 2013 | Observed 2013 Total | % of 1981-2010 Median |
|---|---|---|---|---|---|
| Named Storms (NS) (12.0) | 18 | 18 | 18 | 13 | 108% |
| Named Storm Days (NSD) (60.1) | 95 | 95 | 84.25 | 35.75 | 59% |
| Hurricanes (H) (6.5) | 9 | 9 | 8 | 2 | 31% |
| Hurricane Days (HD) (21.3) | 40 | 40 | 35 | 3.75 | 18% |
| Major Hurricanes (MH) (2.0) | 4 | 4 | 3 | 0 | 0% |
| Major Hurricane Days (MHD) (3.9) | 9 | 9 | 7 | 0 | 0% |
| Accumulated Cyclone Energy (ACE) (92) | 165 | 165 | 142 | 30 | 32% |
| Net Tropical Cyclone Activity (NTC) (103%) | 175 | 175 | 150 | 43 | 42% |

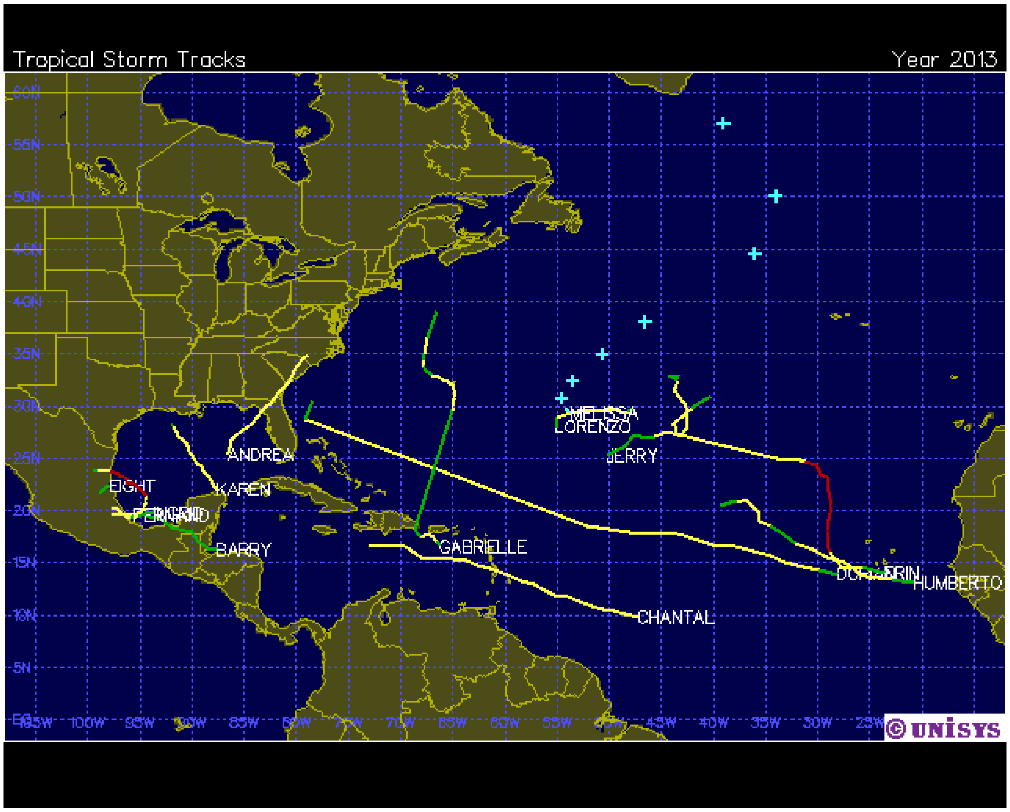


Figure courtesy of Unisys Weather (http://weather.unisys.com)

*Observed activity is through 18Z on November 18, 2013 as calculated from the National Hurricane Center's b-decks. Final season statistics will be included with the December qualitative outlook for 2014 issued on December 10.

# ABSTRACT

This report summarizes tropical cyclone (TC) activity which occurred in the Atlantic basin during 2013 and verifies the authors' seasonal Atlantic basin forecasts. Also verified are an October-November Caribbean-only forecast and six two-week Atlantic basin forecasts 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 2013 was issued on 10 April with updates following on 3 June and 2 August. These seasonal forecasts also contained estimates of the probability of U.S. and Caribbean hurricane landfall during 2013.

The 2013 hurricane season was one of the quietest seasons that we have observed in the past twenty years. While the season had near-average named storm activity, hurricane activity was well below normal. In addition, Accumulated Cyclone Energy (ACE) was the lowest that has been observed since 1983. This year's prediction was a significant bust, in that we expected a very active season. Unlike some previous busts, we do not think that El Niño - Southern Oscillation (ENSO) played a significant role in this year's bust.

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 predicted more activity than was observed. Our October-November Caribbean basin-only forecast predicted above-average activity for the final two months of the season in the Caribbean, while no activity was experienced in the Caribbean during these two months.

Integrated measures such as Net Tropical Cyclone (NTC) activity and Accumulated Cyclone Energy (ACE) were at well below-average levels. It appears that anomalously dry air and sinking motion at mid-levels in the atmosphere, combined with a stronger-than-normal trade wind inversion to significantly suppress the 2013 Atlantic hurricane season. These unfavorable conditions were likely generated by a significant weakening of our proxy for the strength of the Atlantic Multi-Decadal Oscillation/Atlantic Thermohaline Circulation during the late spring into the early summer.

Our expectations for cool neutral ENSO conditions verified quite well, which is one reason why we were so surprised to see the low levels of activity observed this year.

# NOTICE OF FORECAST SUSPENSION

The Tropical Meteorology Project has been issuing forecasts for the past thirty years. These predictions have served as a valuable information tool for insurance interests, emergency managers and coastal residents alike. While these forecasts were largely developed utilizing funding from various government agencies, recent attempts at obtaining continued grant funding have been unsuccessful. Funding from several insurance companies enabled the continuation of these forecasts in recent years. However, the forecast team has recently lost some of its financial support from industry. Consequently, new sources of revenue are required to keep the forecast going. Interested parties are invited to contact Phil Klotzbach directly via email at philk@atmos.colostate.edu for additional discussion of potential sponsorship opportunities.

The Tropical Meteorology Project will suspend issuing seasonal forecasts beginning in April 2014, unless additional funding for the forecasts is forthcoming. The CSU forecast team is currently seeking partnerships with the private sector in order to continue these predictions. Please see the sponsorship brochure if you are interested in supporting the forecast team.

# DEFINITIONS AND ACRONYMS

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

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

This year's forecasts were funded by private and personal funds. 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 much statistical analysis and advice 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 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).

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 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 2013

Figure I and Table 2 summarize Atlantic basin TC activity which occurred in 2013. The season was characterized by about average named storm activity but significantly below-average hurricane activity.

## 3 Individual 2013 Tropical Cyclone Characteristics

The following is a brief summary of each of the named tropical cyclones in the Atlantic basin for the 2013 season. Figure A shows the tracks of all of this season's tropical cyclones, and Table 2 gives statistics for each of these tropical cyclones. TC statistics were calculated from the National Hurricane Center's b-decks for all TCs. Online entries from Wikipedia (http://www.wikipedia.org) were very helpful in putting together these tropical cyclone summaries.

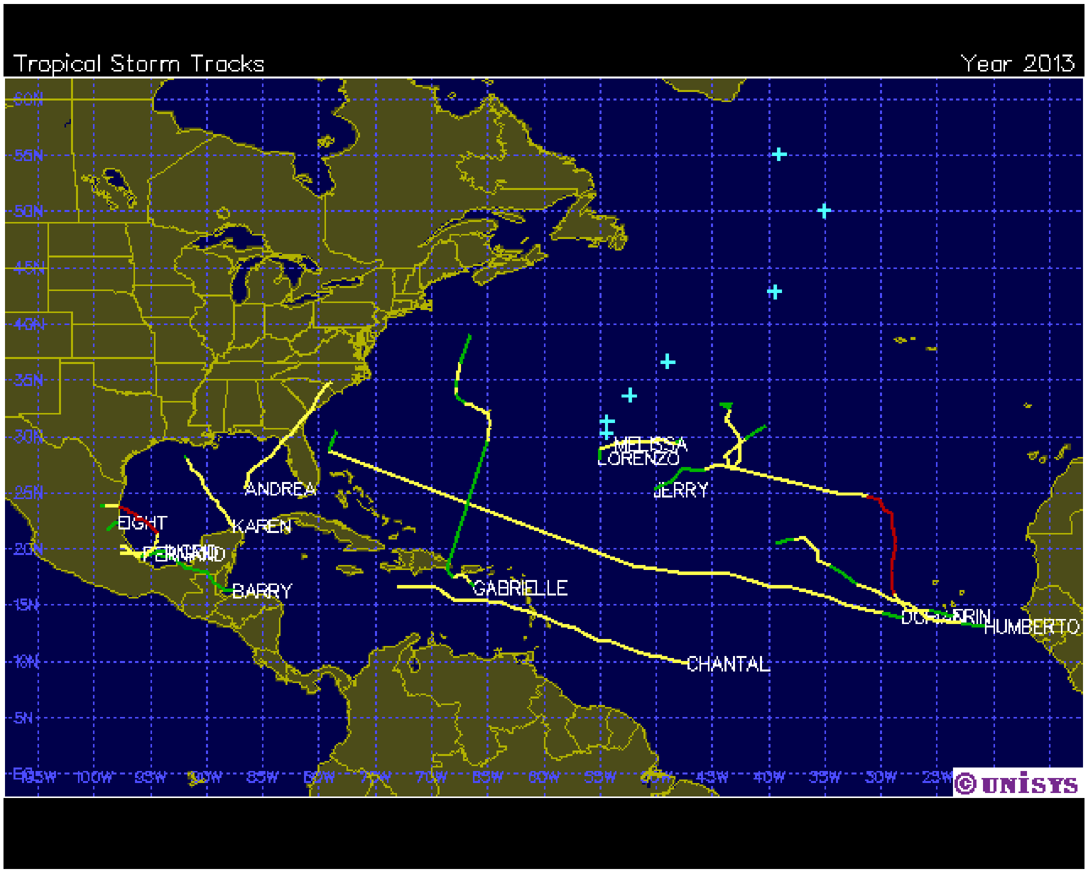


Figure I: Tracks of 2013 Atlantic Basin tropical cyclones. Figure courtesy of the Unisys Weather (http://weather.unisys.com).

Table 2: Observed 2013 Atlantic basin tropical cyclone activity through November 18.

| Highest Category | Name | Dates | Peak Sustained Winds (kts)/lowest SLP (mb) | NSD | HD | MHD | ACE | NTC |
|---|---|---|---|---|---|---|---|---|
| TS | Andrea (1) | June 5 - 7 | 55 kt/992 mb | 2.00 | | | 1.5 | 2.4 |
| TS | Barry (2) | June 19 - 20 | 40 kt/1003 mb | 1.00 | | | 0.6 | 2.1 |
| TS | Chantal (3) | July 8 - 10 | 55 kt/1003 mb | 2.75 | | | 2.1 | 2.7 |
| TS | Dorian (4) | July 24 - 27 | 50 kt/999 mb | 3.50 | | | 2.6 | 2.9 |
| TS | Erin (5) | August 15 -18 | 35 kt/1006 mb | 2.25 | | | 1.1 | 2.5 |
| TS | Fernand (6) | August 25 - 26 | 50 kt/999 mb | 1.00 | | | 0.7 | 2.1 |
| TS | Gabrielle (7) | September 5, September 10 - 13 | 50 kt/1004 mb | 3.00 | | | 1.9 | 2.8 |
| H-1 | Humberto (8) | September 9 - 14, September 16 - 18 | 75 kt/980 mb | 6.75 | 2.00 | | 8.8 | 8.2 |
| H-1 | Ingrid (9) | September 13 - 16 | 75 kt/983 mb | 3.50 | 1.75 | | 4.8 | 6.9 |
| TS | Jerry (10) | September 30 - October 3 | 45 kt/1005 mb | 3.00 | | | 1.7 | 2.8 |
| TS | Karen (11) | October 3 - 6 | 55 kt/999 mb | 3.00 | | | 2.4 | 2.8 |
| TS | Lorenzo (12) | October 21 - 23 | 45 kt/1003 mb | 2.50 | | | 1.7 | 2.6 |
| TS | Melissa (13) | November 18 - | | 0.50 | | | 0.5 | 1.9 |
| | | | | | | | | |
| Totals | 13 | | | 35.75 | 3.75 | 0.00 | 30.3 | 42.9 |

Tropical Storm Andrea (#1): Andrea developed on June 5 from an area of low pressure in the eastern Gulf of Mexico. It slowly intensified as it moved northeast and then accelerated northeastward ahead of an upper-level trough. Andrea reached a peak intensity of 55 knots just before making landfall along the Big Bend of Florida late on June 6. It rapidly weakened after landfall, becoming a post-tropical cyclone on June 7. Andrea's post-tropical remnants were responsible for three fatalities in North Carolina

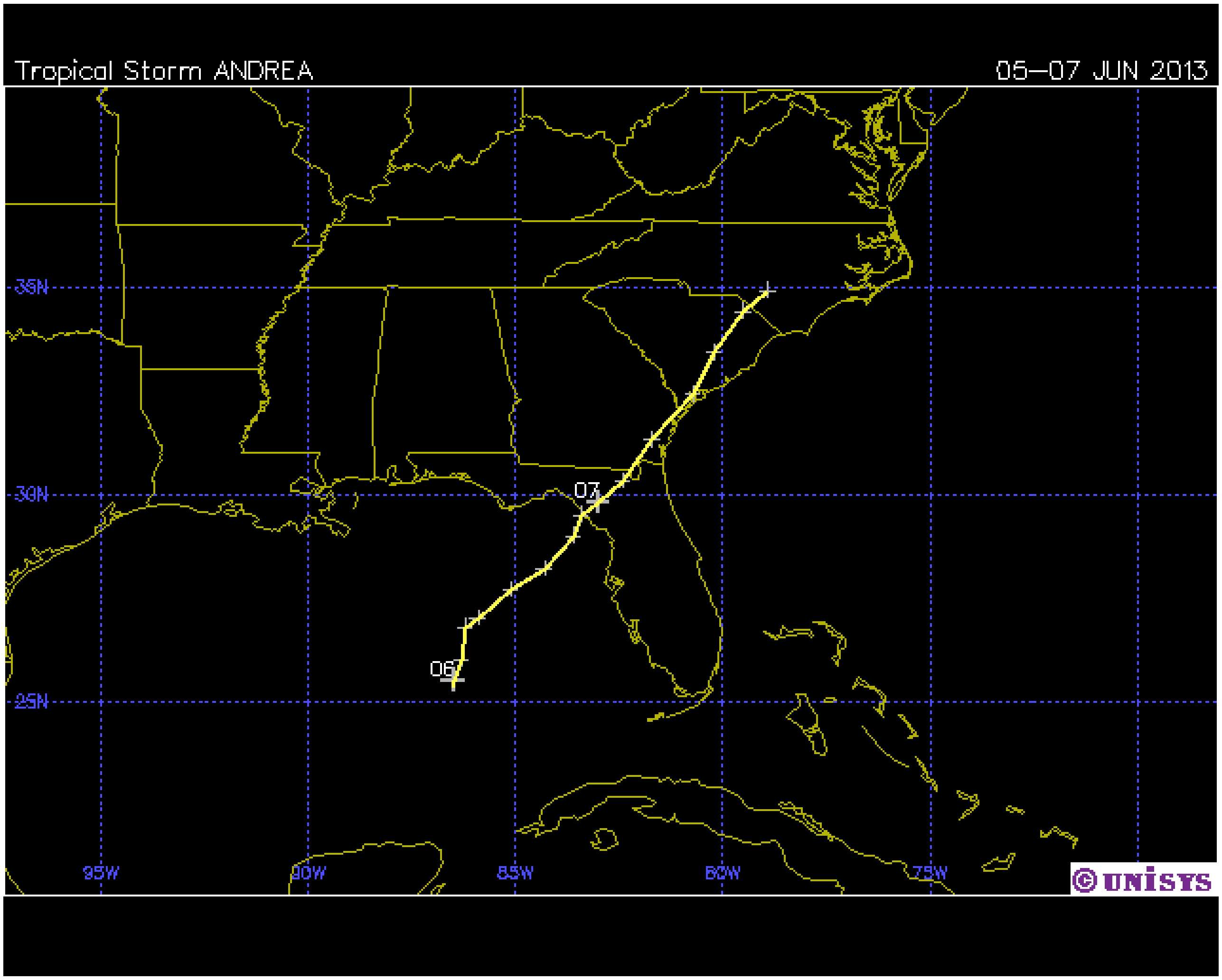


Figure 1: Track of Tropical Storm Andrea. Figure courtesy of Unisys Weather. The yellow line indicates a system at tropical storm strength.

| Name | NSD | HD | MHD | ACE | NTC |
|---|---|---|---|---|---|
| Andrea | 2.00 | 0.00 | 0.00 | 1.5 | 2.4 |

Tropical Storm Barry (#2): Barry formed from an area of low pressure in the northwestern Caribbean Sea on June 17 (Figure 2). It drifted across Belize as a tropical depression, nearly being downgraded to a remnant low in the process, before intensifying into a tropical storm when it emerged over the southern Bay of Campeche on June 19. A ridge over the southern Gulf of Mexico steered Barry westward, and it made landfall in the state of Veracruz, Mexico on June 20 with maximum sustained winds near 40 knots at landfall. It rapidly weakened over the course of the day, being downgraded to a tropical depression a few hours after landfall and then a remnant low later that day. Three fatalities in Mexico and Belize have been attributed to Barry.

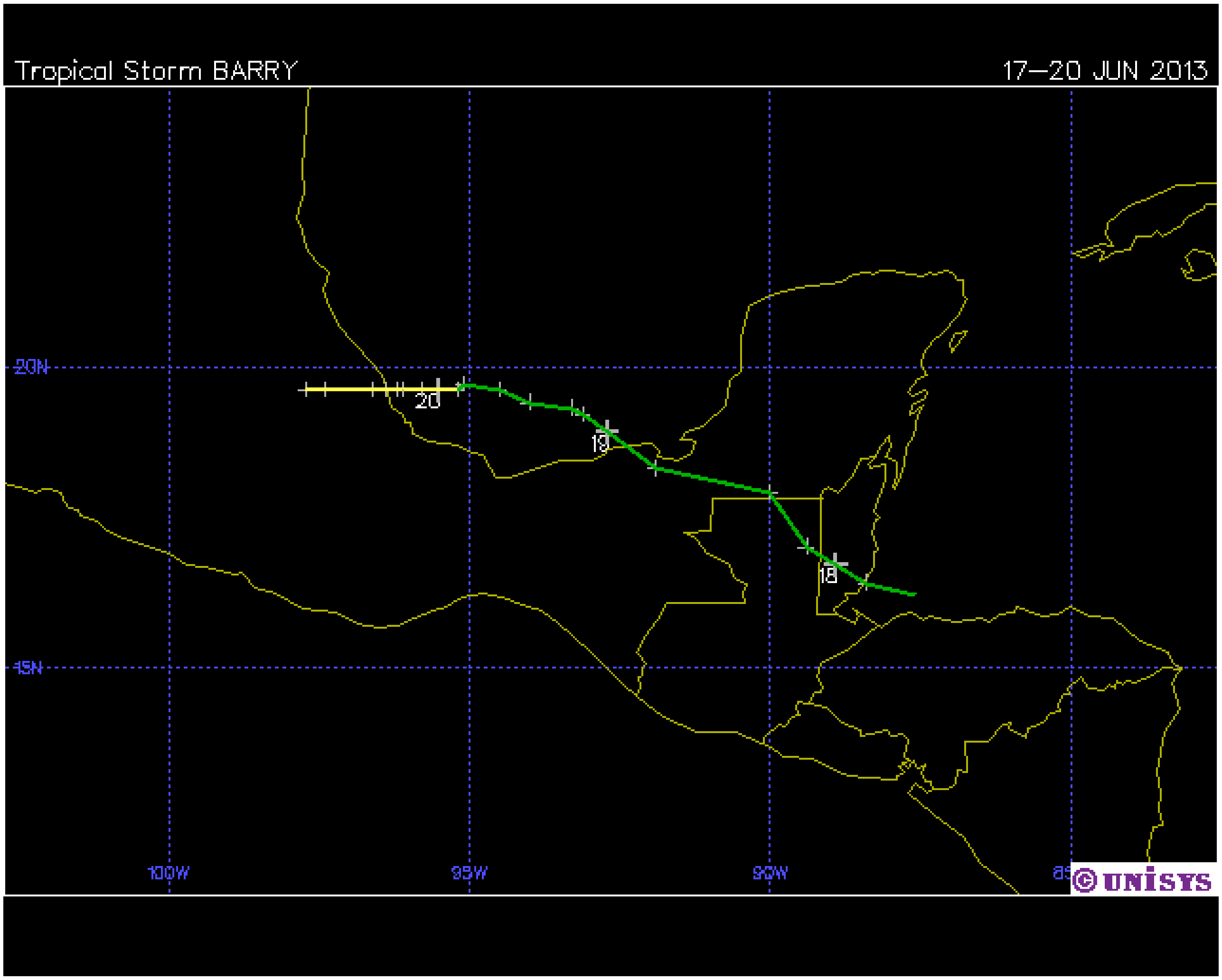


Figure 2: Track of Tropical Storm Barry. Figure courtesy of Unisys Weather. The yellow line indicates a system at tropical storm strength, while the green line indicates tropical depression strength.

| Name | NSD | HD | MHD | ACE | NTC |
|---|---|---|---|---|---|
| Barry | 1.00 | 0.00 | 0.00 | 0.6 | 2.1 |

Tropical Storm Chantal (#3): Chantal developed from an easterly wave in the central tropical Atlantic late on July 7 (Figure 3). It moved rapidly westward as it was steered by a strong ridge to its north. Despite its accelerated speed, Chantal intensified slowly over the next day, due to relatively light vertical wind shear. It reached its maximum intensity of 55 knots on July 9. Strong westerly shear soon interacted with the system, and Chantal weakened rapidly. It degenerated into an open wave on July 10. Chantal's remnants caused heavy flooding in Hispaniola and killed one individual in the Dominican Republic.

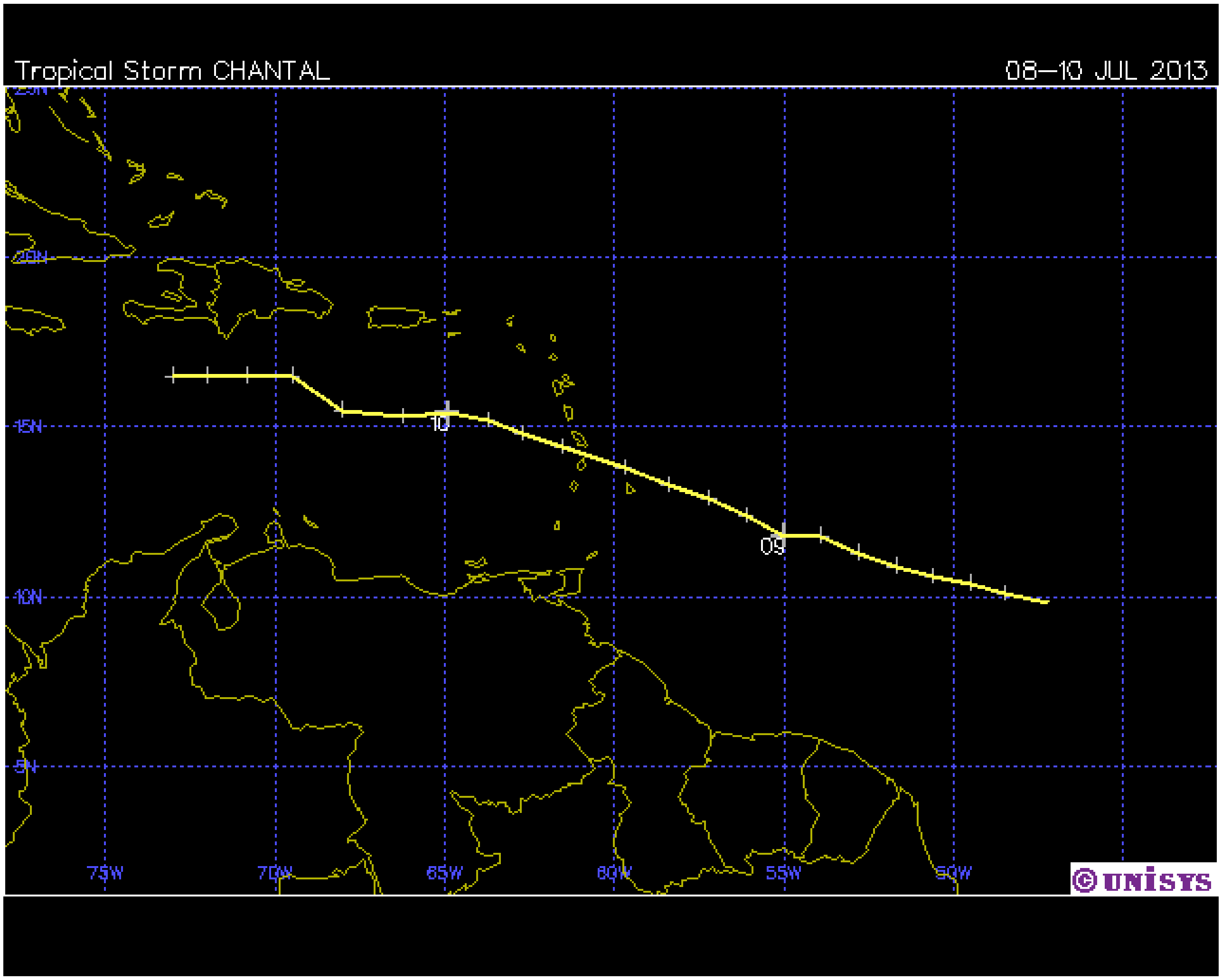


Figure 3: Track of Tropical Storm Chantal. Figure courtesy of Unisys Weather. The yellow line indicates a system at tropical storm strength.

| Name | NSD | HD | MHD | ACE | NTC |
|---|---|---|---|---|---|
| Chantal | 2.75 | 0.00 | 0.00 | 2.1 | 2.7 |

Tropical Storm Dorian (#4): Dorian formed in the eastern tropical Atlantic from an easterly wave on July 24 (Figure 4). The system intensified into a tropical storm later that day as it moved rapidly westward. It reached its maximum intensity of 50 knots the following day while traveling through an area of relatively light shear. By July 26, Dorian began to encounter relatively strong southwesterly shear and drier air and began weakening. A large upper-level trough to the west of Dorian continued to impart strong southwesterly shear over the system, and it degenerated into a tropical wave the following day.

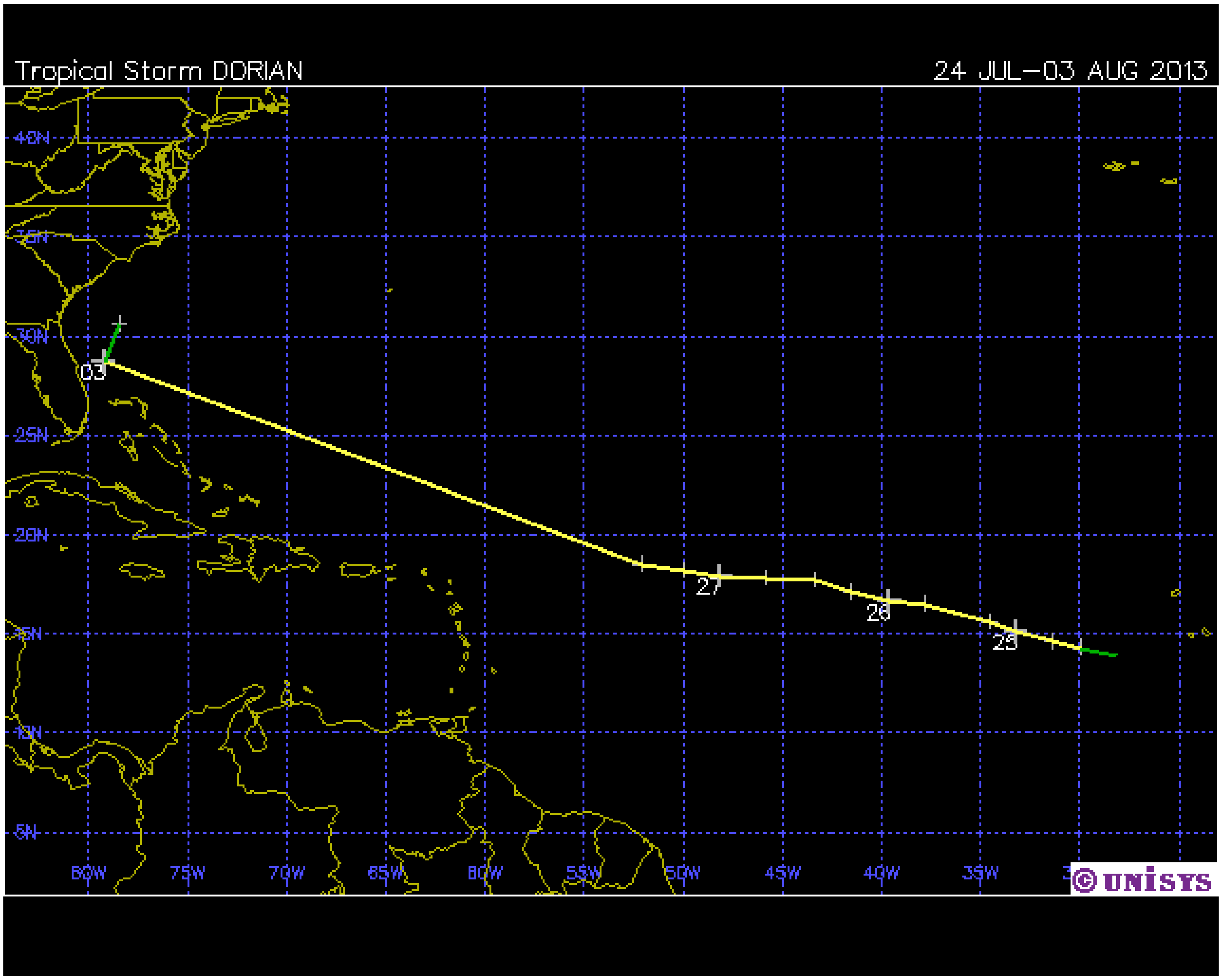


Figure 4: Track of Tropical Storm Dorian. Figure courtesy of Unisys Weather. The yellow line indicates a system at tropical storm strength, while the green line indicates a system at tropical depression strength. In this case, the portion of the yellow line where no hatching is drawn is when Dorian was an open wave.

| Name | NSD | HD | MHD | ACE | NTC |
|---|---|---|---|---|---|
| Dorian | 3.50 | 0.00 | 0.00 | 2.6 | 2.9 |

<u>Tropical Storm Erin (#5)</u>: Erin developed from a tropical wave in the eastern Atlantic on August 15. It was upgraded later that day to a tropical storm as it moved slowly northwestward. Erin soon moved into a drier environment and weakened to a tropical depression. It briefly re-intensified into a tropical storm before encountering very dry air and increasing vertical shear, which caused Erin to weaken back to a tropical depression. It was classified as post-tropical on August 18.

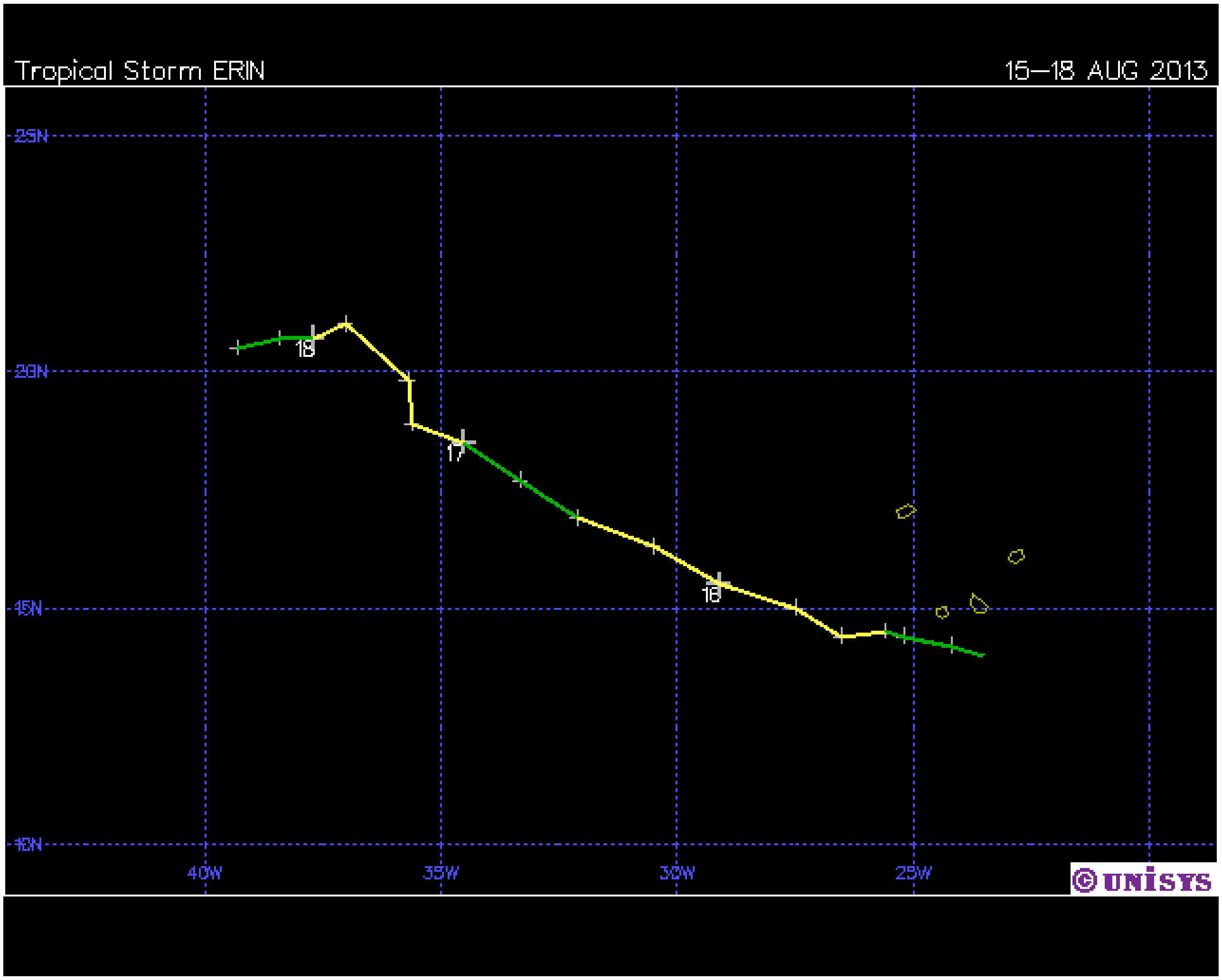


Figure 5: Track of Tropical Storm Erin. Figure courtesy of Unisys Weather. The yellow line indicates a system at tropical storm strength, while the green line indicates tropical depression strength.

| Name | NSD | HD | MHD | ACE | NTC |
|---|---|---|---|---|---|
| Erin | 2.25 | 0.00 | 0.00 | 1.1 | 2.5 |

Tropical Storm Fernand (#6): Fernand formed from an area of low pressure in the southwestern part of the Gulf of Mexico on August 25. It intensified into a tropical storm shortly thereafter. Fernand made landfall northwest of Veracruz, Mexico a few hours later with maximum sustained winds at landfall estimated at 45 knots. It dissipated over the mountains of eastern Mexico later on August 26. 14 fatalities in Mexico were attributed to Fernand, with most of the fatalities due to mudslides.

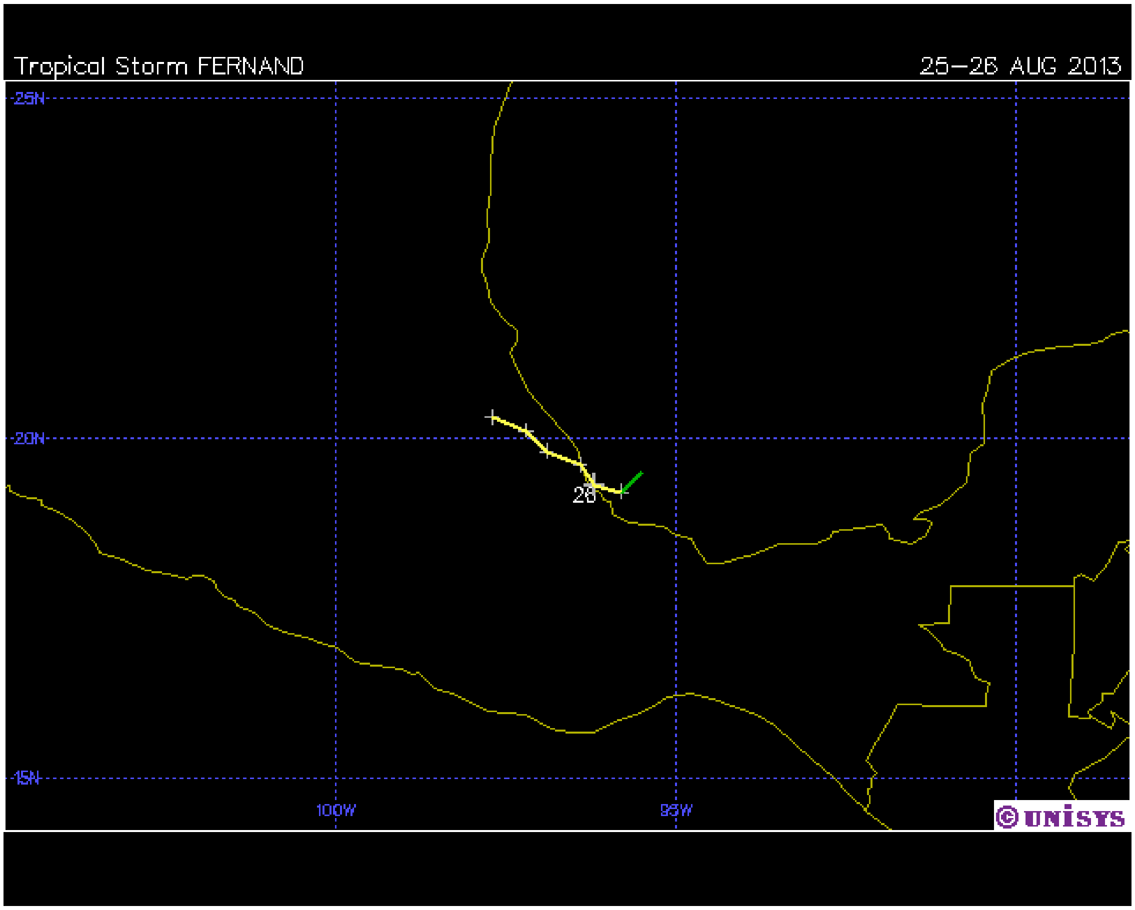


Figure 6: Track of Tropical Storm Fernand. Figure courtesy of Unisys Weather. The yellow line indicates a system at tropical storm strength, while the green line indicates tropical depression strength.

| Name | NSD | HD | MHD | ACE | NTC |
|---|---|---|---|---|---|
| Fernand | 1.00 | 0.00 | 0.00 | 0.7 | 2.1 |

Tropical Storm Gabrielle (#7): Gabrielle formed just south of Puerto Rico on September 4 (Figure 7). By early on September 5, Gabrielle strengthened into a tropical storm. It soon weakened to a tropical depression due to dry air and westerly shear and was classified as a remnant low a few hours later. The system moved generally north-northeastward over the next few days, and then reintensified into a tropical storm on September 10. It reached its maximum intensity of 50 knots later that day as it drifted slowly northward. Later that day, strong southwesterly shear impinged upon the cyclone, weakening Gabrielle to a tropical depression early on September 12. It briefly reintensified again into a tropical cyclone as it continued its northward trek across the western Atlantic. Gabrielle was downgraded to a depression for the final time on September 13 and underwent extra-tropical transition later that day.

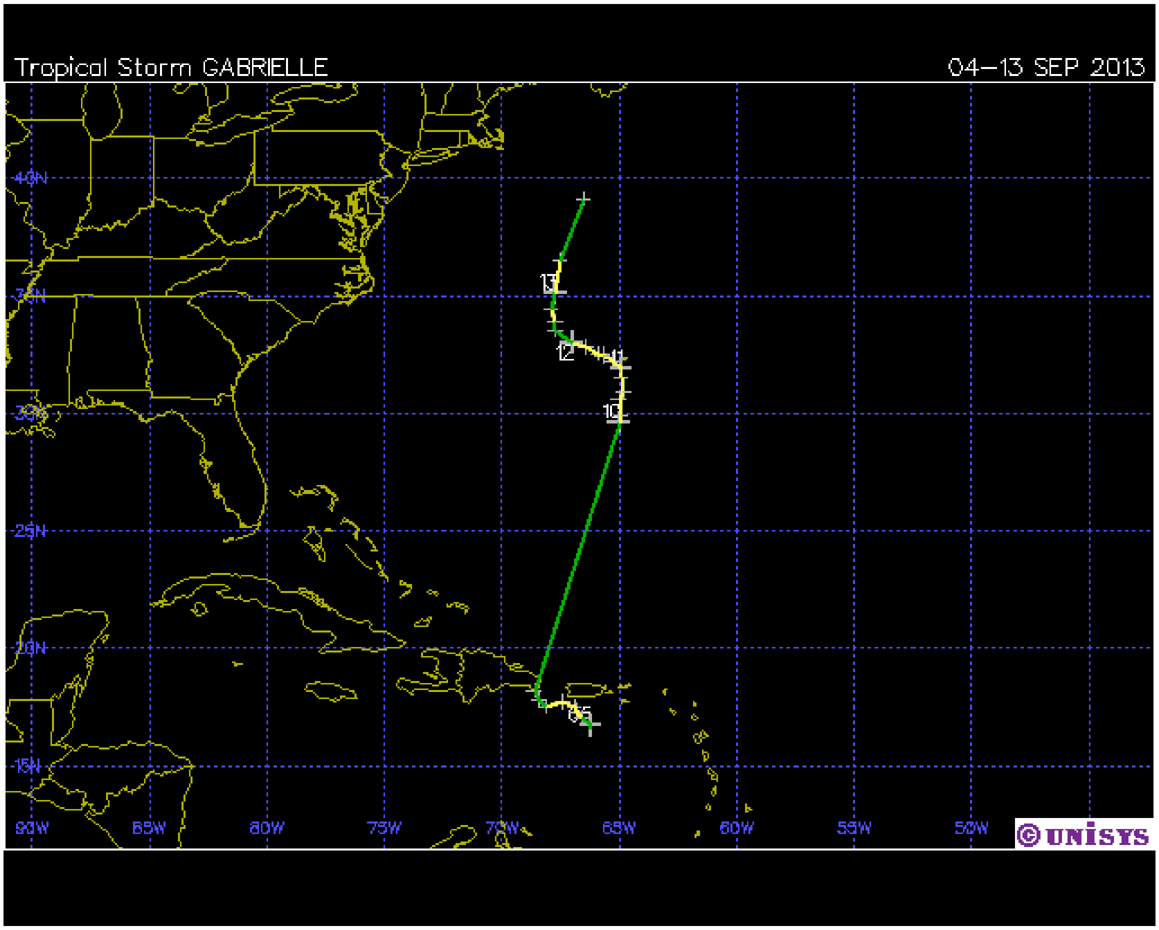


Figure 7: Track of Tropical Storm Gabrielle. Figure courtesy of Unisys Weather. The yellow line indicates a system at tropical storm strength, while the green line indicates tropical depression strength. The green line without the dashes represents a time when Gabrielle was an open wave.

| Name | NSD | HD | MHD | ACE | NTC |
|---|---|---|---|---|---|
| Gabrielle | 3.00 | 0.00 | 0.00 | 1.9 | 2.8 |

Hurricane Humberto (#8): Humberto formed southeast of the Cape Verde Islands on September 8 (Figure 8). It intensified into a tropical storm the following day as it traversed over an area of relatively weak vertical shear and warm SSTs. By September 11, Humberto intensified into the first hurricane of the 2013 Atlantic hurricane season, just beating the record set in 2002 for the latest date of a first hurricane in the satellite era (since 1966). A mid-level low weakened the subtropical ridge and caused Humberto to turn sharply northward. Humberto reached its maximum intensity of 75 knots later on September 11 and maintained that intensity until September 13, when cooler SSTs and stronger shear caused rapid weakening. It weakened to a tropical storm later on September 13 and became post-tropical on September 14. Humberto's remnants moved northwestward, and it regenerated into a tropical storm on September 16. A nearby upper-level low continued to impart relatively strong shear over Humberto, and it maintained only marginal tropical storm status until late on September 18, when it was downgraded to a tropical depression. Humberto became absorbed by a large extra-tropical cyclone on September 19.

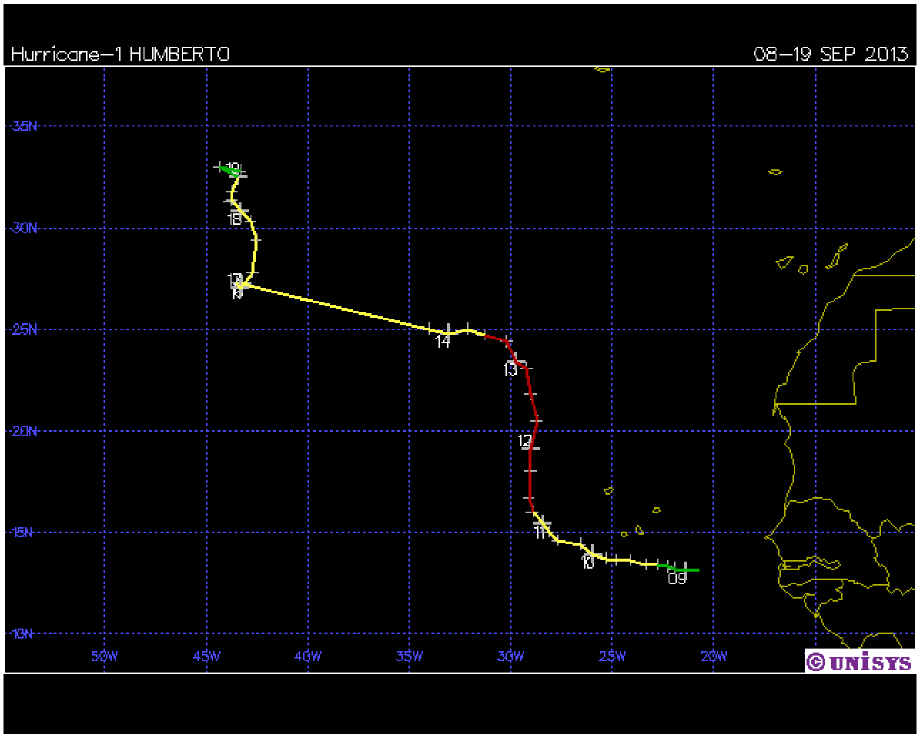


Figure 8: Track of Hurricane Humberto. Figure courtesy of Unisys Weather. The red line indicates a system at hurricane strength, the yellow line indicates a system at tropical storm strength, while the green line indicates tropical depression or tropical wave strength. The yellow line without the dashes represents a time when Humberto was an open wave.

| Name | NSD | HD | MHD | ACE | NTC |
|---|---|---|---|---|---|
| Humberto | 6.75 | 2.00 | 0.00 | 8.8 | 8.2 |

Hurricane Ingrid (#9). Ingrid formed in the Bay of Campeche on September 12 from an area of low pressure. It intensified into a tropical storm the following day while drifting slowly westward. Ingrid continued to slowly intensify over warm SSTs and moderate shear, due partially to Tropical Storm Manuel in the Northeast Pacific. It intensified into a hurricane late on September 14 as it moved northwest towards the Mexican coast. It reached its maximum intensity of 75 knots on September 15. Strong westerly shear began to disrupt the circulation of Ingrid, and it weakened to a tropical storm while making landfall near La Pesca, Mexico on September 16. Ingrid weakened to a tropical storm and then a tropical depression over the following day, as the mountainous terrain of eastern Mexico disrupted the circulation of the TC. It dissipated on September 17. 23 fatalities have been attributed to Ingrid, due to heavy rains and associated mudslides.

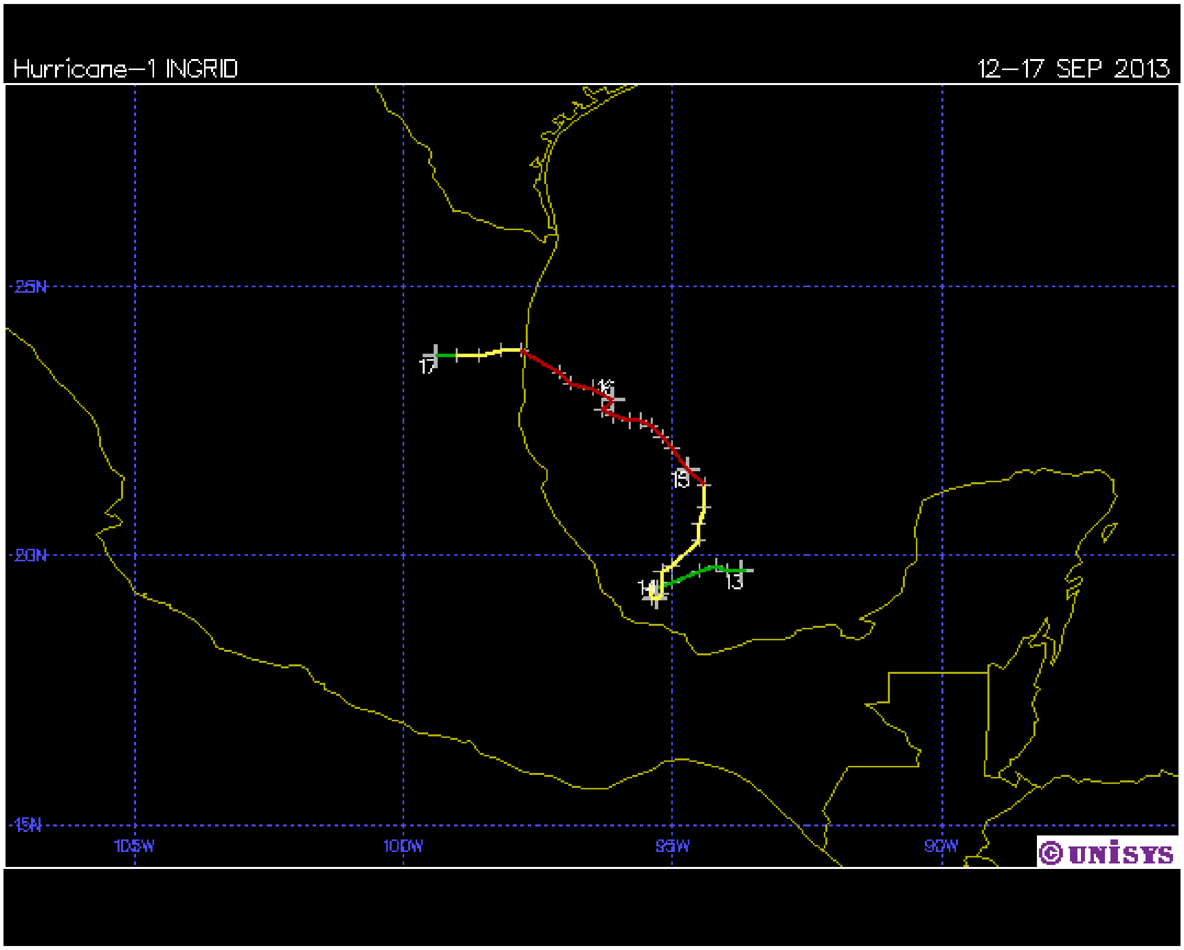


Figure 9: Track of Hurricane Ingrid. Figure courtesy of Unisys Weather. The red line indicates a system at hurricane strength, the yellow line indicates a system at tropical storm strength and the green line indicates a system at tropical depression strength.

| Name | NSD | HD | MHD | ACE | NTC |
|---|---|---|---|---|---|
| Ingrid | 3.50 | 1.75 | 0.00 | 4.8 | 6.9 |

<u>Tropical Storm Jerry (#10):</u> Tropical Storm Jerry formed in the Central Atlantic on September 28 (Figure 10). It remained a weak depression for about 36 hours, before encountering slightly weaker shear and intensifying into a tropical storm on September 30. A brief period of weaker shear late on September 30 allowed Jerry to strengthen to a 45-knot TC, but stronger shear and drier air soon impinged upon the system, and it weakened back to a marginal tropical storm with 35 knot winds on October 1. Jerry drifted slowly northeastward in an area of weak steering currents for the next couple of days. Stronger shear and drier air caused Jerry to weaken back to a depression late on October 2, and it became post-tropical the following day.

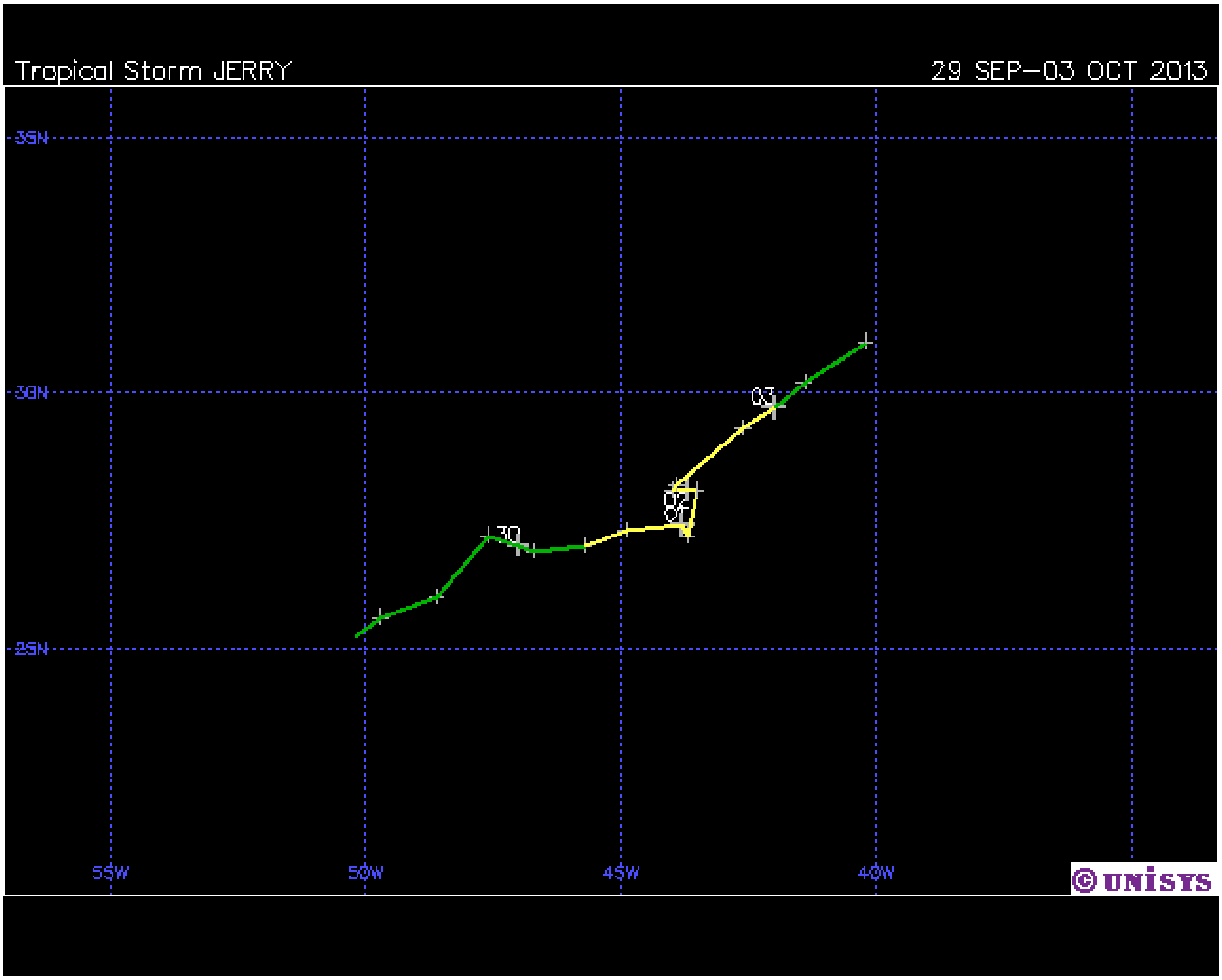


Figure 10: Track of Tropical Storm Jerry. Figure courtesy of Unisys Weather. The yellow line indicates a system at tropical storm strength, while the green line indicates a system at tropical depression strength.

| Name | NSD | HD | MHD | ACE | NTC |
|---|---|---|---|---|---|
| Jerry | 3.00 | 0.00 | 0.00 | 1.7 | 2.8 |

<u>Tropical Storm Karen (#11):</u> Karen developed just north of the Yucatan Peninsula on October 3 (Figure 11). It was classified as a tropical storm at its first advisory. It formed in an area of moderate westerly shear and dry air, and consequently only strengthened slightly as it moved northwestward. Stronger southwesterly shear began to impact Karen the following day, and it began to weaken as it approached the northern Gulf Coast. By late on October 5, Karen was downgraded to a tropical depression as strong shear continued to buffet the storm, and it was declared a remnant low the following day.

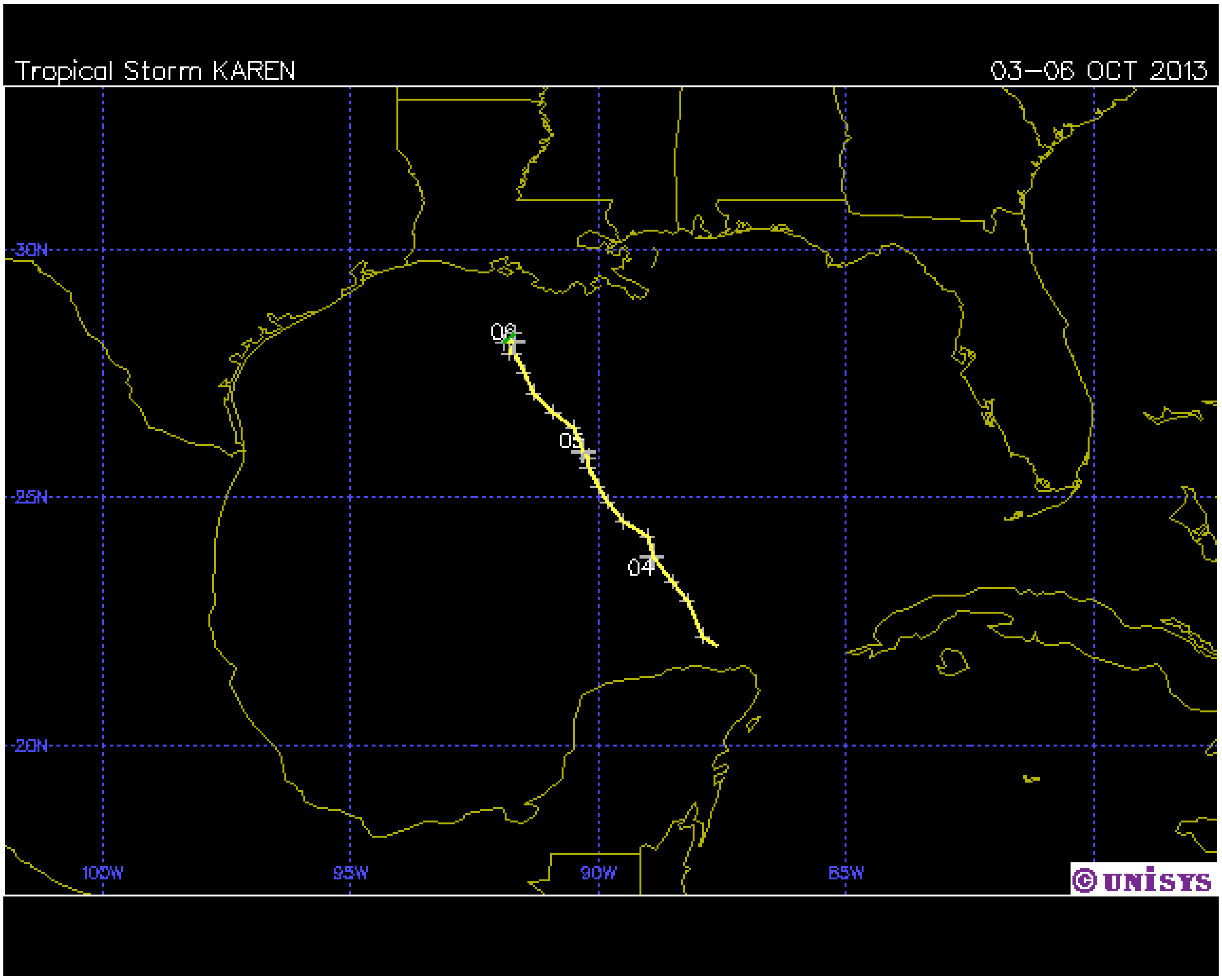


Figure 11: Track of Tropical Storm Karen Figure courtesy of Unisys Weather. The yellow line indicates a system at tropical storm strength, while the green line indicates tropical depression strength.

| Name | NSD | HD | MHD | ACE | NTC |
|---|---|---|---|---|---|
| Karen | 3.00 | 0.00 | 0.00 | 2.4 | 2.8 |

Tropical Storm Lorenzo (#12): Lorenzo formed southeast of Bermuda on October 21 (Figure 12). A mid-level ridge to the northwest of Lorenzo steered the system eastward throughout most of its lifetime. It strengthened into a tropical storm later that day. By the following day, Lorenzo intensified into a 45-knot TC. Lorenzo soon weakened as it encountered very strong northwesterly shear which decimated the system. It was downgraded to a tropical depression late on October 23 and was classified as post-tropical shortly thereafter.

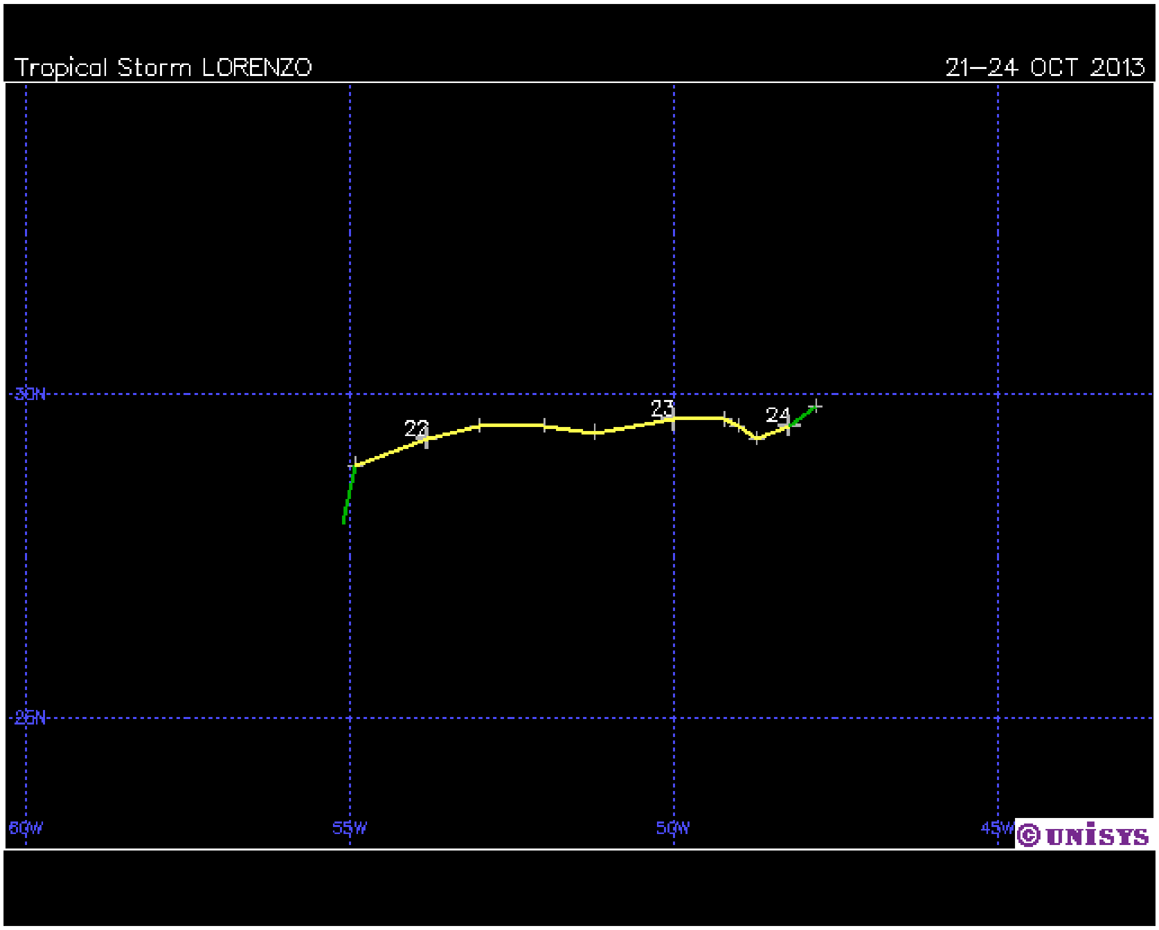


Figure 12: Track of Tropical Storm Lorenzo. Figure courtesy of Unisys Weather. The yellow line indicates a system at tropical storm strength, while the green line indicates a system at tropical depression strength.

| Name | NSD | HD | MHD | ACE | NTC |
|---|---|---|---|---|---|
| Lorenzo | 2.50 | 0.00 | 0.00 | 1.7 | 2.6 |

Subtropical Storm Melissa (#13): Melissa formed well southeast of Bermuda on November 18 from a non-tropical area of low pressure (Figure 13). A trough moving off the US East Coast was forecast to accelerate Melissa towards the northeast in the next few days. Melissa was predicted to intensify somewhat and likely transition from a subtropical to a tropical cyclone in the next couple of days.

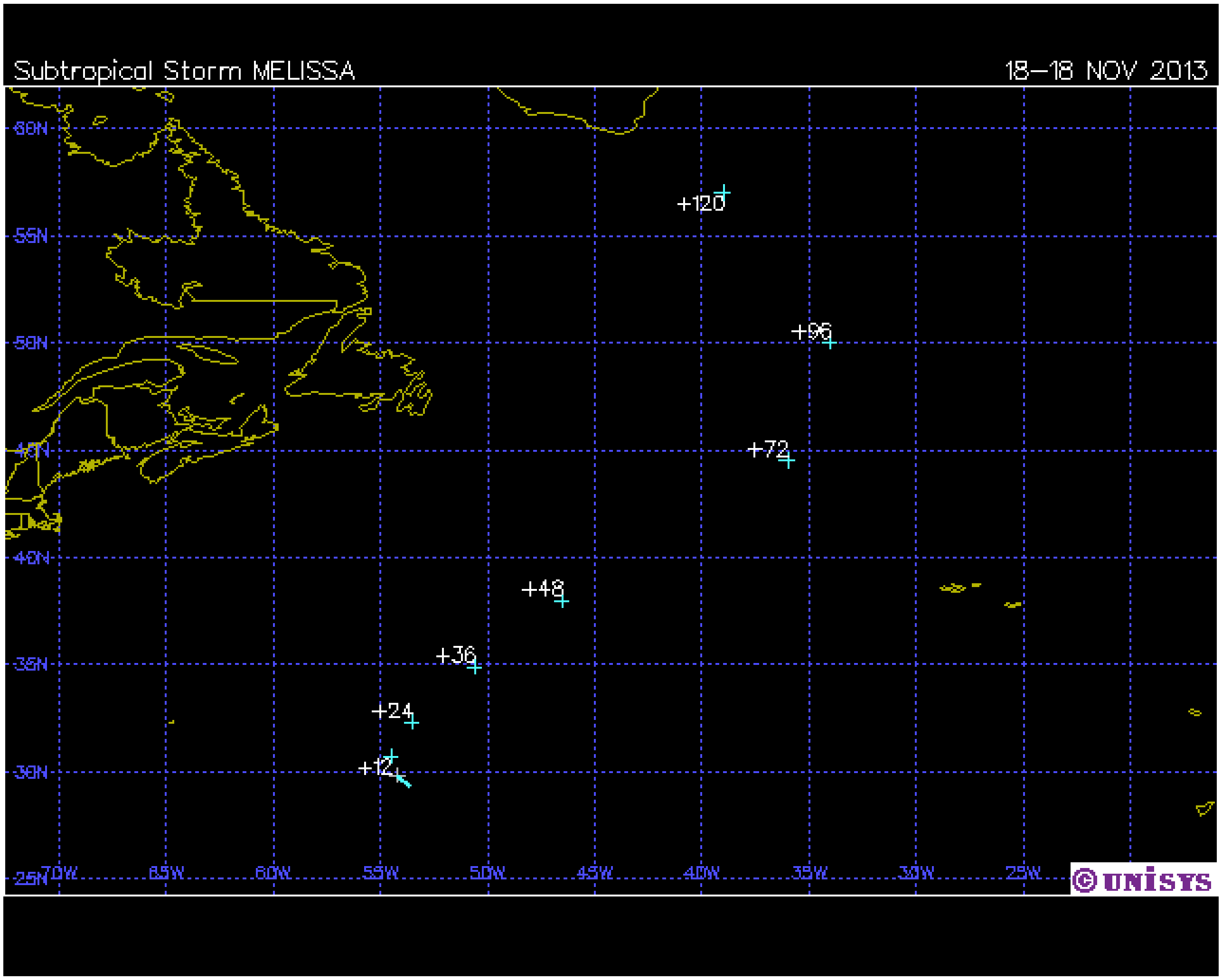


Figure 13: Observed and projected track for Subtropical Storm Melissa. Figure courtesy of Unisys Weather. The blue line indicates a subtropical cyclone, while the blue crosses indicate the projected future track of Melissa.

| Name | NSD* | HD | MHD | ACE | NTC |
|---|---|---|---|---|---|
| Melissa | 0.50 | 0.00 | 0.00 | 0.5 | 1.9 |

*These statistics reflect activity generated by Melissa through November 18 at 18Z. Any TC activity generated by Melissa after November 18 will be included in the December qualitative forecast.

U.S. Landfall. Figure 14 shows the track of Tropical Storm Andrea, which was the only TC to make United States landfall this year. Table 3 summarizes the landfalling statistics for Andrea. Damage and fatality estimates were obtained from Wikipedia.

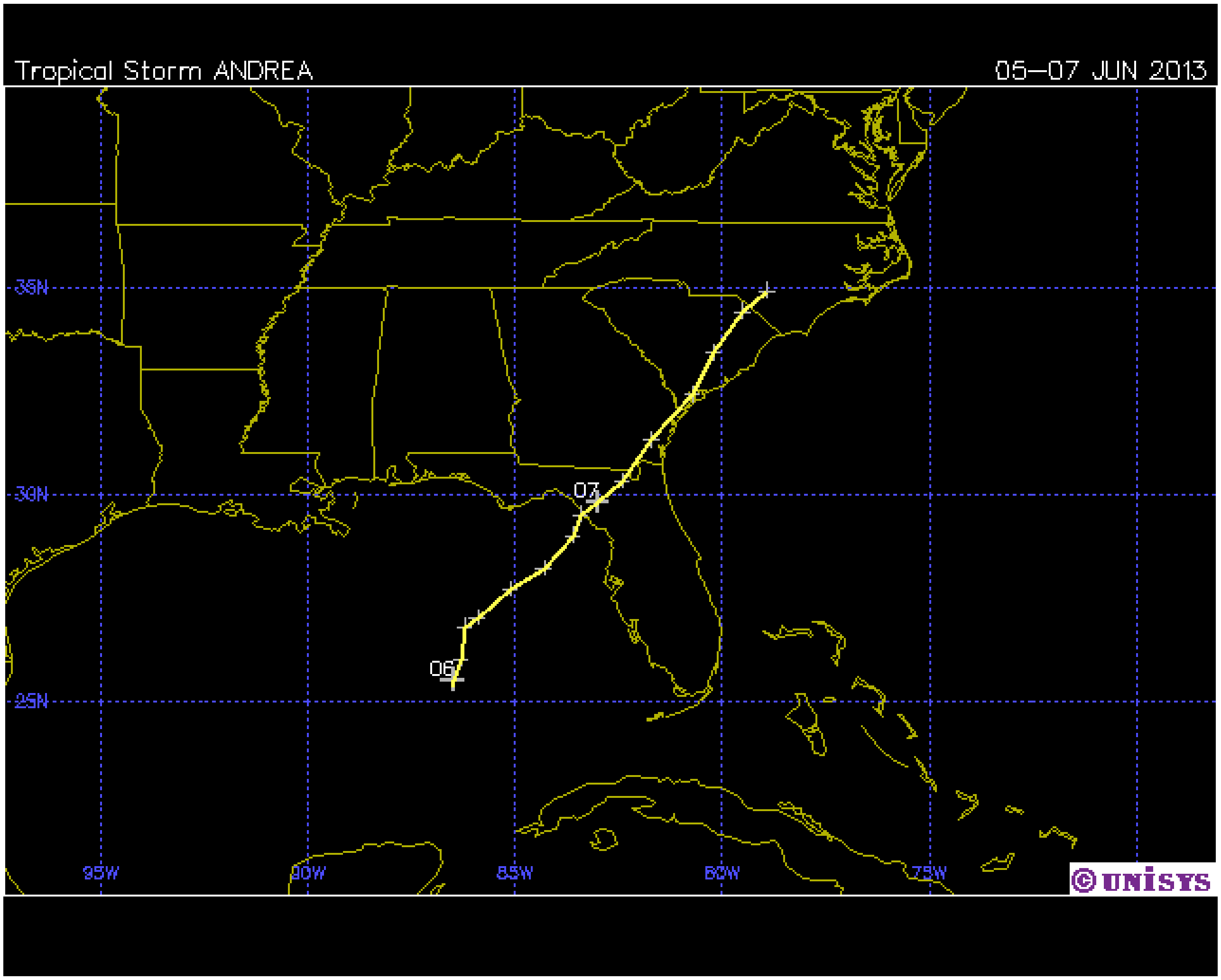


Figure 14: Track of Tropical Storm Andrea - the only TC to make US landfall this year. The yellow line indicates a TC at tropical storm strength. Figure courtesy of Unisys Weather.

Table 3: Summary of US TC landfall statistics for 2013.

| | Landfall Date(s) | Location(s) | Insured Damage (Millions) | Fatalities |
|---|---|---|---|---|
| Tropical Storm Andrea | June 6 | FL | Minimal | 1 |

## 4 Special Characteristics of the 2013 Hurricane Season

The 2013 hurricane season had the following special characteristics:

- Thirteen named storms occurred during 2013. This is the most named storms to occur in a year with two or fewer hurricanes in the historical record. The 1931 hurricane season had thirteen named storms but only three hurricanes.

- 35.75 named storm days (NSD) occurred during 2013. This is the fewest NSD since 2009 (30 NSD).

- Two hurricanes formed in 2013. This is the fewest hurricanes since 1982 - when two hurricanes also formed.

- No major hurricanes formed in 2013. The last year with no major hurricane formations was 1994.

- ACE in 2013 was only 30 units. This is the lowest ACE for an Atlantic hurricane season since 1983 (17 ACE).

- No major hurricanes made US landfall in 2013. The last major hurricane to make US landfall was Wilma (2005), so the US has now gone eight years without a major hurricane landfall. Since 1878 when relatively reliable landfall data became available, the US has never had an eight-year period without a major hurricane landfall.

- The maximum intensity reached by any TC this year was 75 knots (Humberto and Ingrid). This is the weakest maximum intensity achieved by the most intense TC of a season since 1968 (Gladys - 75 knots).

- Humberto reached hurricane strength early on September 11. It became the second latest forming first hurricane of the year, developing into a hurricane just hours before the previous record latest forming first hurricane of the year (Gustav - 2002)

- Two TCs formed in the Main Development Region (south of 23.5°N, east of 75°W) prior to 1 August. The last year with two TCs forming in this region prior to 1 August was 2005. The median ACE of the 10 years with two TCs in the MDR prior to 1 August was 174 ACE units. The 2013 season clearly defied many of the typical pre-season climate signals.

## 5 Verification of Individual 2013 Lead Time Forecasts

Table 4 is a comparison of our forecasts for 2013 for three different lead times along with this year's observations. The 2013 Atlantic hurricane season was characterized by near-average levels of named storm activity but virtually no hurricane activity. Accumulated Cyclone Energy (ACE) was at its lowest levels since 1983.

Table 4: Verification of our 2013 seasonal hurricane predictions.

| Forecast Parameter and 1981-2010 Median (in parentheses) | 10 April 2013 | Update 3 June 2013 | Update 2 Aug 2013 | Observed 2013 Total | % of 1981-2010 Median |
|---|---|---|---|---|---|
| Named Storms (NS) (12.0) | 18 | 18 | 18 | 13 | 100% |
| Named Storm Days (NSD) (60.1) | 95 | 95 | 84.25 | 35.75 | 59% |
| Hurricanes (H) (6.5) | 9 | 9 | 8 | 2 | 31% |
| Hurricane Days (HD) (21.3) | 40 | 40 | 35 | 3.75 | 18% |
| Major Hurricanes (MH) (2.0) | 4 | 4 | 3 | 0 | 0% |
| Major Hurricane Days (MHD) (3.9) | 9 | 9 | 7 | 0 | 0% |
| Accumulated Cyclone Energy (ACE) (92) | 165 | 165 | 142 | 30 | 32% |
| Net Tropical Cyclone Activity (NTC) (103%) | 175 | 175 | 150 | 43 | 40% |

Table 5 provides the same forecasts, with error bars (based on one standard deviation of absolute errors) as calculated from hindcasts over the 1990-2007 period, using equations from the 1950-1989 period. 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. No predictions were within one standard deviation of observed values, and only three of 24 (13%) predictions were within two standard deviations. This year's seasonal forecasts were a large over-prediction.

Table 5: Verification of our 2013 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. Only three of 24 predictions were within two standard deviations of observations, indicative of the large forecast bust that occurred this year. Error bars for storms are rounded to the nearest storm. For example, the hurricane prediction in early April would be 6.8-11.2, which with rounding would be 7-11.

| Forecast Parameter and 1981-2010 Median (in parentheses) | 10 April 2013 | Update 3 June 2013 | Update 2 Aug 2013 | Observed 2013 Total |
|---|---|---|---|---|
| Named Storms (NS) (12.0) | **18** (±4.0) | **18** (±3.8) | **18** (±2.3) | 13 |
| Named Storm Days (NSD) (60.1) | **95** ±(19.4) | **95** (±18.3) | **84.25** (±17.4) | 35.75 |
| Hurricanes (H) (6.5) | **9** (±2.2) | **9** (±2.1) | **8** (±1.6) | 2 |
| Hurricane Days (HD) (21.3) | **40** (±9.5) | **40** (±9.0) | **35** (±8.6) | 3.75 |
| Major Hurricanes (MH) (2.0) | **4** (±1.4) | **4** (±1.2) | **3** (±0.9) | 0 |
| Major Hurricane Days (MHD) (3.9) | **9** (±4.4) | **9** (±4.5) | **7** (±3.5) | 0 |
| Accumulated Cyclone Energy (ACE) (92) | **165** (±39) | **165** (±39) | **142** (±36) | 30 |
| Net Tropical Cyclone Activity (NTC) (103%) | **175** (±41) | **175** (±37) | **150** (±34) | 43 |

## 5.1 Preface: Aggregate Verification of our Last Fifteen 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 fifteen 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 start of the hurricane season.

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 fifteen years (1999-2013).

| Tropical Cyclone Parameter | Early April | Early June | Early August |
|---|---|---|---|
| **NS** | 12/15 | 13/15 | 12/15 |
| **NSD** | 11/15 | 11/15 | 11/15 |
| **H** | 11/15 | 11/15 | 11/15 |
| **HD** | 9/15 | 10/15 | 11/15 |
| **MH** | 10/15 | 11/15 | 12/15 |
| **MHD** | 10/15 | 11/15 | 11/15 |
| **NTC** | 9/15 | 10/15 | 12/15 |
| **Total** | **72/105 (69%)** | **77/105 (73%)** | **80/105 (76%)** |

Of course, there are significant amounts of unexplained variance for a number of the individual parameter forecasts. Even though the skill for some of these parameter forecasts is somewhat low, there is a great curiosity in having some objective measure as to how active the coming hurricane season is likely to be. Therefore, even a forecast that is only modestly skillful is likely of some interest. 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. Despite the large forecast bust this year, in general, our forecasts in recent years have shown significant improvements in skill relative to our earlier predictions. 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 1984-2012.

## 5.2 Verification of Two-Week Forecasts

This is the fifth year that we have issued intraseasonal (e.g. two-week) forecasts of tropical cyclone activity starting in early August. We decided to discontinue our individual monthly forecasts. 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 were judged to be 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 2013 hurricane season and shows their verification. All six two-week periods had below-average activity. In general, we were expecting a much more active hurricane season than what actually occurred, so we had some over-forecasts.

Table 8: Two-week forecast verification for 2013. Forecasts that verified in the correct category are highlighted in blue, forecasts that missed by one category are highlighted in green, while forecasts that missed by two categories are highlighted in red.

| Forecast Period | Predicted ACE | Observed ACE |
|---|---|---|
| **8/2 – 8/15** | **Below-Average (4 or Less)** | **0** |
| **8/16 – 8/29** | **Above-Average (19 or More)** | **2** |
| **8/30 – 9/12** | **Average (20-37)** | **11** |
| **9/13 – 9/26** | **Average (15-28)** | **8** |
| **9/27 – 10/10** | **Below-Average (7 or Less)** | **4** |
| **10/11 – 10/24** | **Below-Average (4 or Less)** | **2** |

The MJO had somewhat coherent eastward propagation during the peak of the 2013 Atlantic hurricane season except during mid to late October when the signal was quite weak (Figure 15).

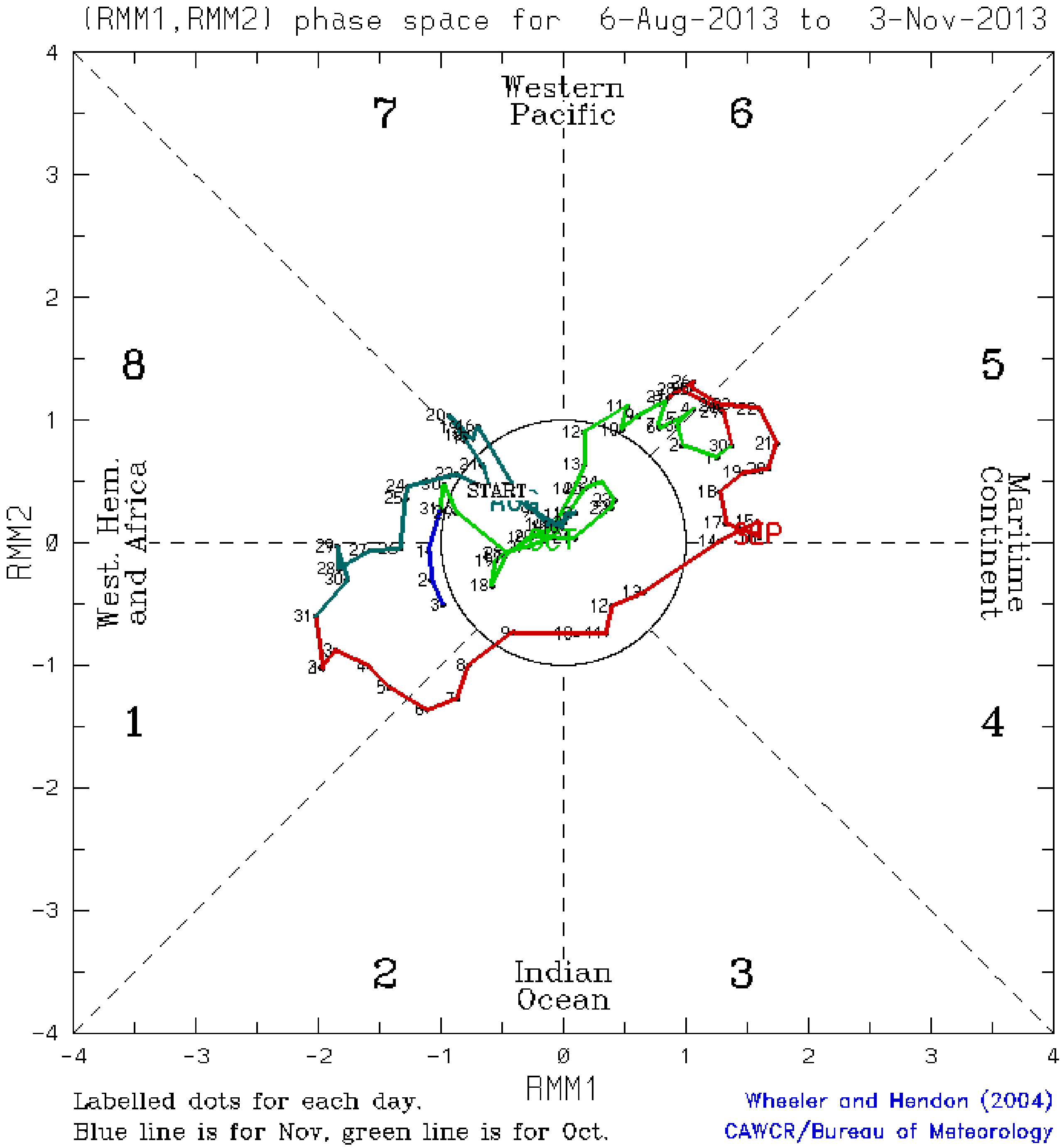


Figure 15: Propagation of the Madden-Julian Oscillation (MJO) based on the Wheeler-Hendon classification scheme over the period from August 6 to November 3. The MJO had somewhat consistent eastward propagation during the three month time period, with a relatively weak signal during most of October. The Maritime Continent refers to Indonesia and the surrounding islands. RMM stands for Real-Time Multivariate MJO.

### 5.3 Verification of October-November Caribbean Basin Forecast

Our October-November Caribbean basin forecast for hurricane days and ACE in the Caribbean did not verify well. This model effectively uses two predictors: 1) the state of ENSO, and 2) the size of the Atlantic Warm Pool. These predictors called for an active end of the season in the Caribbean, and no activity occurred in the Caribbean during the two-month period. Table 9 displays the predicted and observed values of hurricane days and ACE for October-November in the Caribbean.

Table 9: Predicted versus observed October-November Caribbean basin hurricane days and ACE.

| Forecast Parameter and 1981-2010 Climatology (in parentheses) | Forecast | Observed |
|---:|:---:|:---:|
| Hurricane Days (1.25) | 2.5 | 0 |
| Accumulated Cyclone Energy Index (6.3) | 11 | 0 |

# 6 Landfall Probabilities

## 6.1 Landfall Probability Verification

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 10 gives verifications of our landfall probability estimates for the United States and for the Caribbean in 2013.

Landfall probabilities for the 2013 hurricane season were estimated to be well above their long-period averages for all predictions due to the forecasts of an active hurricane season. The 2013 hurricane season was very quiet from a U.S. landfall perspective, with only one tropical storm (Andrea) 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 2013. Both Chantal and Gabrielle 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 16). 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](http://www.e-transit.org/hurricane).

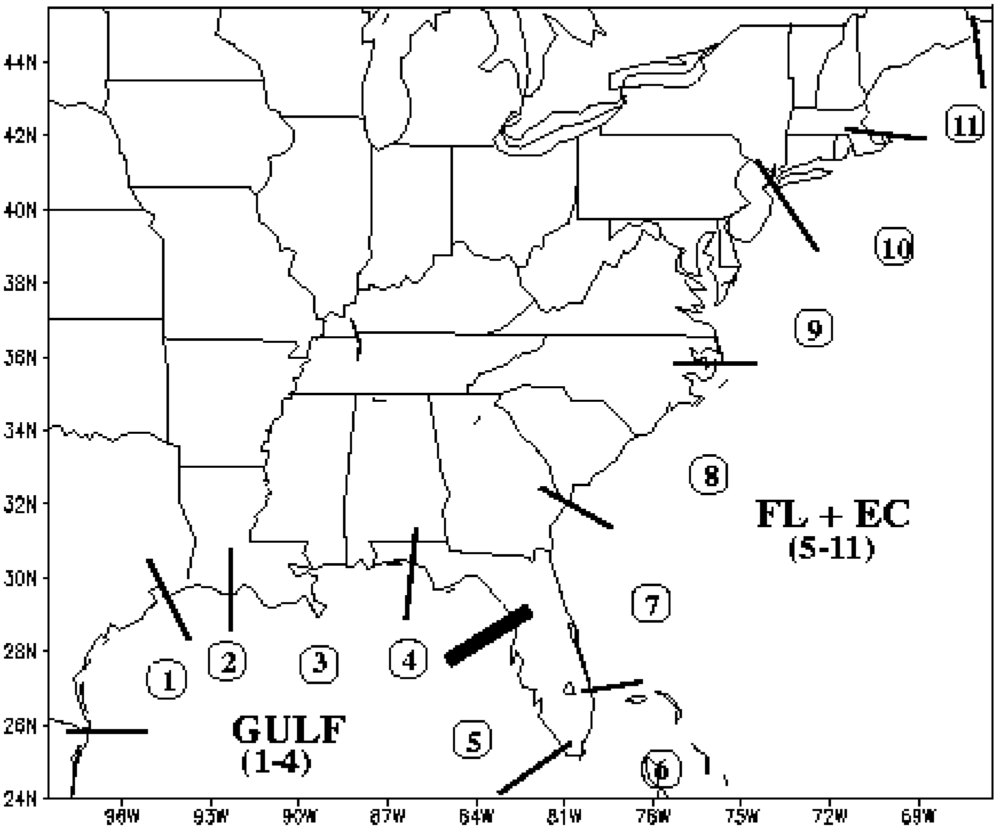


Figure 16: Location of the 11 coastal regions for which separate hurricane landfall probability estimates are made. These subdivisions were determined by the historical frequency of landfalling major hurricanes.

Table 10: 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 2013 at various lead times. The mean annual percentage of one or more landfalling systems during the 20th century is given in parentheses in the 2 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**

| | 10 Apr. | 3 June | 2 August | Observed Number |
|---|---|---|---|---|
| TS | 94% | 94% | 89% (80%) | 1 |
| HUR (Cat 1-2) | 86% | 86% | 79% (68%) | 0 |
| HUR (Cat 3-4-5) | 72% | 72% | 64% (52%) | 0 |
| All HUR | 96% | 96% | 93% (84%) | 0 |
| Named Storms | 99% | 99% | 99% (97%) | 1 |

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

| | 10 Apr. | 3 June | 2 August | Observed Number |
|---|---|---|---|---|
| TS | 79% | 79% | 71% (59%) | 1 |
| HUR (Cat 1-2) | 62% | 62% | 54% (42%) | 0 |
| HUR (Cat 3-4-5) | 47% | 47% | 40% (30%) | 0 |
| All HUR | 80% | 80% | 72% (61%) | 0 |
| Named Storms | 96% | 96% | 92% (83%) | 1 |

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

| | 10 Apr. | 3 June | 2 August | Observed Number |
|---|---|---|---|---|
| TS | 71% | 71% | 62% (51%) | 0 |
| HUR (Cat 1-2) | 64% | 64% | 56% (45%) | 0 |
| HUR (Cat 3-4-5) | 48% | 48% | 40% (31%) | 0 |
| All HUR | 81% | 81% | 74% (62%) | 0 |
| Named Storms | 94% | 94% | 90% (81%) | 0 |

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

|  | 10 Apr. | 3 June | 2 August | Observed Number |
|---|---|---|---|---|
| TS | 95% | 95% | 91% (82%) | 2 |
| HUR (Cat 1-2) | 77% | 77% | 69% (57%) | 0 |
| HUR (Cat 3-4-5) | 61% | 61% | 53% (42%) | 0 |
| All HUR | 91% | 91% | 86% (75%) | 0 |
| Named Storms | 99% | 99% | 99% (96%) | 2 |

## 6.2 Interpretation of Landfall Probabilities

We never intended that our seasonal forecasts be used for individual-year landfall predictions. It is impossible to predict months in advance the mid-latitude ridge-trough patterns that typically dictate the probabilities of U.S. and Caribbean hurricane landfall. We only make predictions of the probability of landfall. Our landfall probability estimates work out very well when we compare 4-5 of our annual forecasts for active seasons versus 4-5 annual forecasts for inactive seasons. This is especially the case for landfalling major hurricanes.

High seasonal forecasts of Net Tropical Cyclone activity (NTC) (see Tables 11 and 12) should be interpreted as a higher probability of U.S. or Caribbean landfall but not necessarily that landfall will occur that year. Low seasonal forecasts of NTC do not mean that landfall will not occur but only that its probability is lower than average during that year. In addition, significant forecast busts can occur like what did this year.

The majority of U.S. landfalling tropical cyclones and Caribbean activity occurs during active Atlantic basin seasons, with below-average Atlantic basin hurricane seasons typically having below-average U.S. and Caribbean hurricane landfall frequency. This is particularly the situation for the Florida Peninsula and the East Coast and the Caribbean.

Table 11 gives observed high to low rankings of NTC for the last 64 (1950-2013) years in association with landfall frequency. Data is broken into numbers of landfalling tropical storms (TS), Cat 1-2 hurricanes (H) and Cat 3-4-5 hurricanes (MH). Note that high Atlantic basin NTC years have substantially increased hurricane landfall numbers, particularly for major hurricanes when compared with low NTC years.

The relationship between Atlantic basin NTC and U.S. landfall is especially strong for major hurricane landfall along Peninsula Florida and the East Coast (Regions 5-11). The Gulf Coast landfall – NTC relationship is weaker except for the most active versus least active seasons. The relationship between NTC and Caribbean major hurricane activity is also quite strong.

Table 11: Observed landfall of named storms (NS), Cat 1-2 hurricanes (H) and Cat 3-4-5 hurricanes (MH) by high versus low observed values of Atlantic basin Net Tropical Cyclone (NTC) activity. Values are separately given for the Gulf Coast, the Florida Peninsula and East Coast, the whole U.S. coastline and the Caribbean for the 64-year period from 1950-2013.

| | Gulf Coast (Regions 1-4) | | | Florida + East Coast (Regions 5-11) | | | Whole US (Regions 1-11) | | | Caribbean (10-20°N, 60-88°W) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| NTC Values | ***NS*** | ***H*** | ***MH*** | ***NS*** | ***H*** | ***MH*** | ***NS*** | ***H*** | ***MH*** | ***NS*** | ***H*** | ***MH*** |
| Top 10 Observed NTC years > 181 | 19 | 11 | 8 | 28 | 19 | 8 | 47 | 30 | 16 | 55 | 35 | 18 |
| Bot 10 Observed NTC years < 52 | 10 | 4 | 1 | 11 | 4 | 0 | 21 | 8 | 1 | 11 | 2 | 1 |
| Top 20 Observed NTC years > 131 | 38 | 18 | 9 | 42 | 24 | 8 | 80 | 42 | 17 | 93 | 57 | 29 |
| Bot 20 Observed NTC years < 83 | 23 | 8 | 3 | 17 | 8 | 3 | 40 | 16 | 6 | 27 | 7 | 3 |
| Top 32 Observed NTC years ≥ 100 | 56 | 30 | 12 | 66 | 36 | 14 | 122 | 66 | 26 | 133 | 74 | 38 |
| Bot 31 Observed NTC years < 100 | 50 | 20 | 8 | 38 | 18 | 7 | 88 | 38 | 15 | 53 | 19 | 9 |

Table 12 shows the number of landfalling tropical cyclones which occurred in our 15 most active forecasts when our real time projects' 1 June prediction of the number of named storms was 12 or more (or eleven named storms and 8 hurricanes) versus those 15 years when our 1 June prediction of the seasonal number of named storms was 11 or less (excluding 1985 when 11 named storms and 8 hurricanes were predicted). Notice the 2 to 1 difference in landfall of major hurricanes for the entire United States. The ratios for the Caribbean are similar, with a greater than 3 to 1 ratio for Caribbean major hurricanes.

Table 12: Number of U.S. and Caribbean landfalling tropical cyclones in the 15 years when our 1 June forecast was for 12 or more named storms (or eleven named storms and 8 hurricanes) versus those 15 years when our 1 June prediction was for 11 or fewer named storms (except 1985).

| Forecast NS | US NS | US H | US MH | Carib NS | Carib H | Carib MH |
|---|---|---|---|---|---|---|
| ≥ 12 & 1985 (15 years) | 66 | 31 | 12 | 64 | 32 | 17 |
| ≤ 11 (15 years) | 43 | 19 | 6 | 37 | 18 | 6 |

Our individual June seasonal forecasts of the last 30 years have been skillful as regards to the multi-year probability of US and Caribbean landfall, and even stronger statistical relationships are found with our real-time forecasts from 1 August.

## 7 Summary of Atmospheric/Oceanic Conditions

In this section, we go into detail discussing large-scale conditions that we believe significantly impacted the 2013 Atlantic basin hurricane season in either a favorable or unfavorable manner.

## 7.1 ENSO

El Niño-Southern Oscillation (ENSO) was relatively well-predicted by the various statistical and dynamical forecast models this year. Our prediction for neutral conditions during the peak months of the Atlantic hurricane season verified quite well. The following are several quotes from our 2013 forecasts regarding ENSO this year:

**(10 April 2013) –**

**"Based on the above information, our best estimate is that we will likely remain in neutral ENSO conditions for the peak of the Atlantic hurricane season. The buildup of the warm pool in the western tropical Pacific has been relatively weak, and trade winds across the central tropical Pacific have generally been somewhat above-normal over the past few weeks."**

**(3 June 2013) –**

**“Our confidence that a significant El Niño event will not develop during this year's hurricane season has grown since early April. Low-level winds near the International Date Line have remained relatively strong out of the east, which helps prevent warming Kelvin waves from propagating eastward across the tropical Pacific. In addition, sea level pressure anomalies have generally been positive across the eastern and central tropical Pacific over the past two months, indicative of a relatively strong Southern Oscillation Index."**

**(2 August 2013) –**

**"Based on this information, our best estimate is that we will likely have cool neutral ENSO conditions during the August-October period."**

In general, neutral ENSO conditions have persisted across the tropical Pacific since late last year. Table 13 displays temperatures in the various Nino regions as observed in January, April, July and October of this year, respectively. The difference from January 2013 anomalies are provided in parentheses.

Table 13: January anomalies, April anomalies, July anomalies, October anomalies for the Nino 1+2, Nino 3, Nino 3.4 and Nino 4 regions. SST anomaly differences from January 2013 are in parentheses.

| Region | January 2013 Anomaly (ºC) | April 2013 Anomaly (ºC) | July 2013 Anomaly (ºC) | October 2013 Anomaly (ºC) |
|---|---|---|---|---|
| Nino 1+2 | -0.5 | -1.3 (-0.8) | -1.7 (-1.2) | -0.8 (-0.3) |
| Nino 3 | -1.0 | -0.2 (+0.8) | -0.6 (+0.4) | -0.3 (+0.7) |
| Nino 3.4 | -0.8 | 0.0 (+0.8) | -0.3 (+0.5) | -0.2 (+0.6) |
| Nino 4 | -0.1 | -0.2 (-0.1) | 0.0 (+0.1) | -0.1 (0.0) |

An index that we have been using more frequently in recent years and generally better represents the atmospheric/oceanic state of the tropical Pacific than simply using SST is the Multivariate ENSO Index (MEI) (Wolter and Timlin 1998). The MEI shows more dramatically the month-by-month fluctuations in the strength of ENSO this year. The MEI is computed as a bi-monthly average, and the bi-monthly averages from December-January 2012/2013 through September-October 2013 are listed in Table 14. The MEI was relatively close to zero throughout the spring months, with a trend towards negative values during the middle of the summer (indicative of a trend towards more La Niña-like atmospheric/oceanic conditions). The index has since rebounded to more neutral conditions over the past couple of months.

Table 14: Bi-monthly values of the MEI from December-January 2012/2013 through September-October 2013. The change from December-January 2012/2013 is also provided.

| MEI Months | MEI Value | Change from Dec-Jan 2012/2013 |
|---|---|---|
| Dec-Jan | 0.0 | |
| Jan-Feb | -0.2 | -0.2 |
| Feb-Mar | -0.2 | -0.2 |
| Mar-Apr | 0.0 | 0.0 |
| Apr-May | 0.1 | +0.1 |
| May-Jun | -0.3 | -0.3 |
| Jun-Jul | -0.5 | -0.5 |
| Jul-Aug | -0.6 | -0.6 |
| Aug-Sep | -0.2 | -0.2 |
| Sep-Oct | +0.1 | +0.1 |

One persistent characteristic of the past year in the tropical Pacific is anomalously positive outgoing longwave radiation (OLR) near the International Date Line (Figure 17). In general, positive OLR anomalies in this area are typical of more La Niña-like conditions.

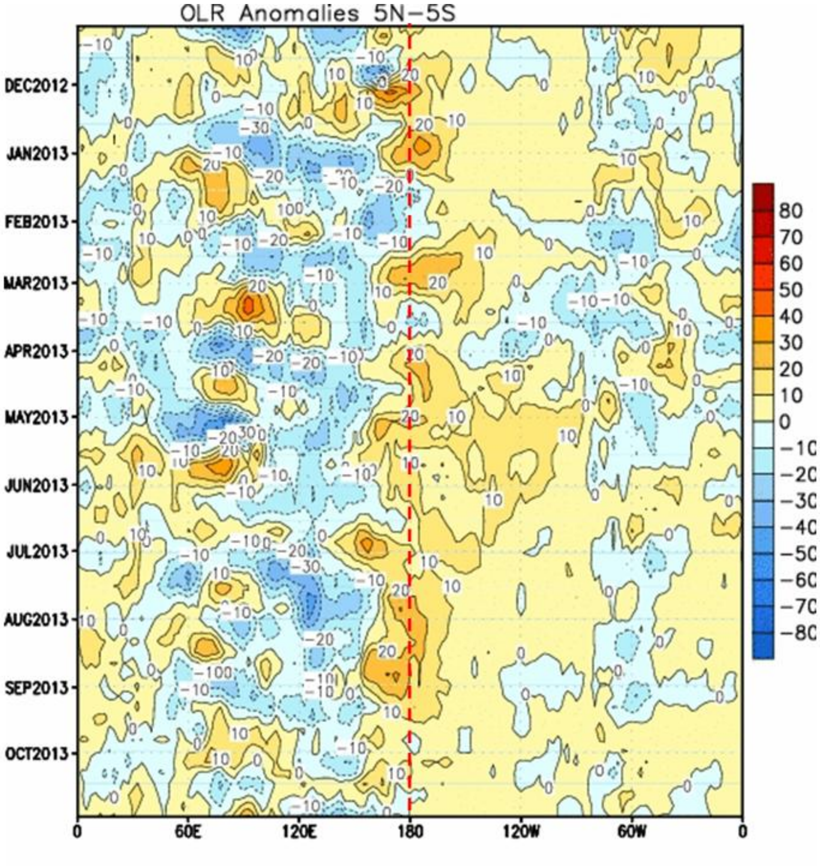


Figure 17: Outgoing longwave radiation (OLR) anomalies across the tropical Pacific. Note the persistence of anomalously positive anomalies near the International Date Line - as highlighted by the dashed red line. Figure courtesy of the Climate Prediction Center.

## 7.2 Intra-Seasonal Variability

Intra-seasonal (MJO) variability was relatively active during the peak months of this year's Atlantic hurricane season. Figure 18 displays the MJO, as calculated from the Wheeler-Hendon (WH) index, over the period from August 4 - November 1. In general, the MJO coherently propagated eastward throughout the period, with the notable exception of mid to late October where the MJO signal was quite weak. Minimal clustering of Atlantic TCs occurred during the 2013 hurricane season, indicating that even when the MJO was favorable (e.g., Phases 1-3), only limited TC formation occurred. Table 15 displays the number of TC formations by MJO phase during the 2013 Atlantic hurricane season. Distinctive differences between MJO phase and TC formations were not observed in 2013.

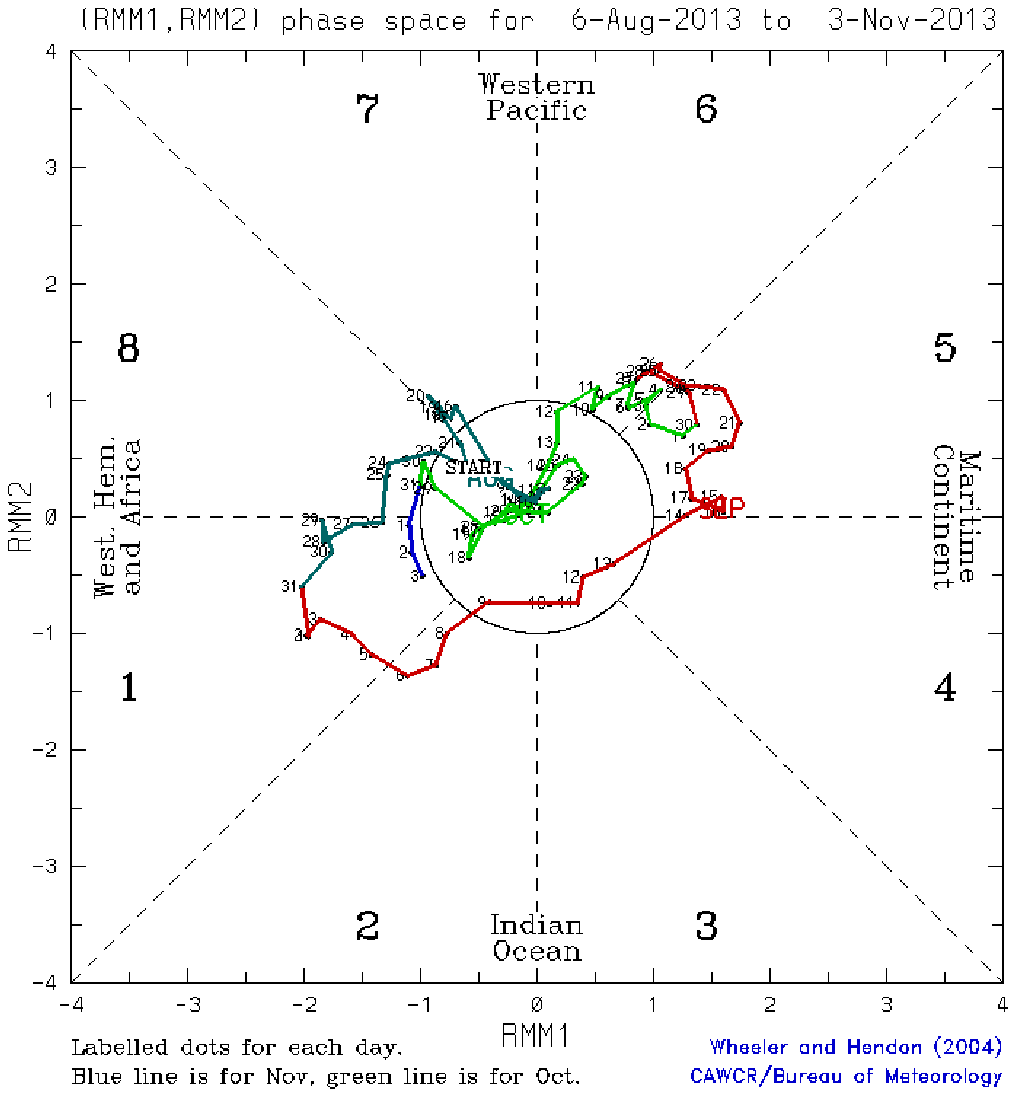


Figure 18: Progression of the MJO, as calculated by the WH index, over the period from August 6 - November 3, 2013.

Table 15: TC formations by MJO phase during the 2013 Atlantic hurricane season.

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

## 7.3 Atlantic SST

The Atlantic was characterized by significant changes in SST over the course of 2013. Positive SST anomalies dominated the far north and tropical Atlantic during the month of March (Figure 19), indicative of a strong thermohaline circulation (THC) and strong Atlantic Multi-decadal Oscillation (AMO) during this time period.

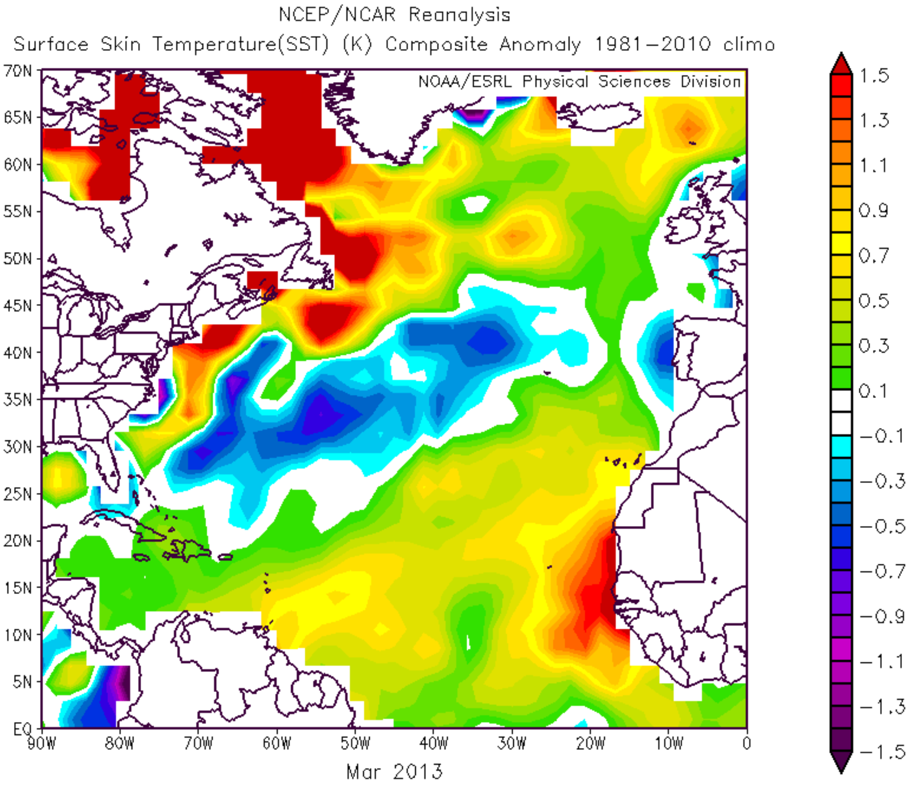


Figure 19: March 2013 SST anomalies across the Atlantic basin. Note the warm anomalies that pervaded both the tropical and far North Atlantic.

However, over the next several months, a very strongly positive North Atlantic Oscillation (NAO) developed (Figure 20). A strong NAO is associated with anomalously strong trade winds which enhance mixing and upwelling in the tropical and subtropical Atlantic, causing cooling. Figure 21 displays the anomalous SST pattern change that took place across the Atlantic from late March to late June. Note the significant anomalous cooling that took place, both in the tropical and far north Atlantic, indicative of a weakening AMO/THC signal.

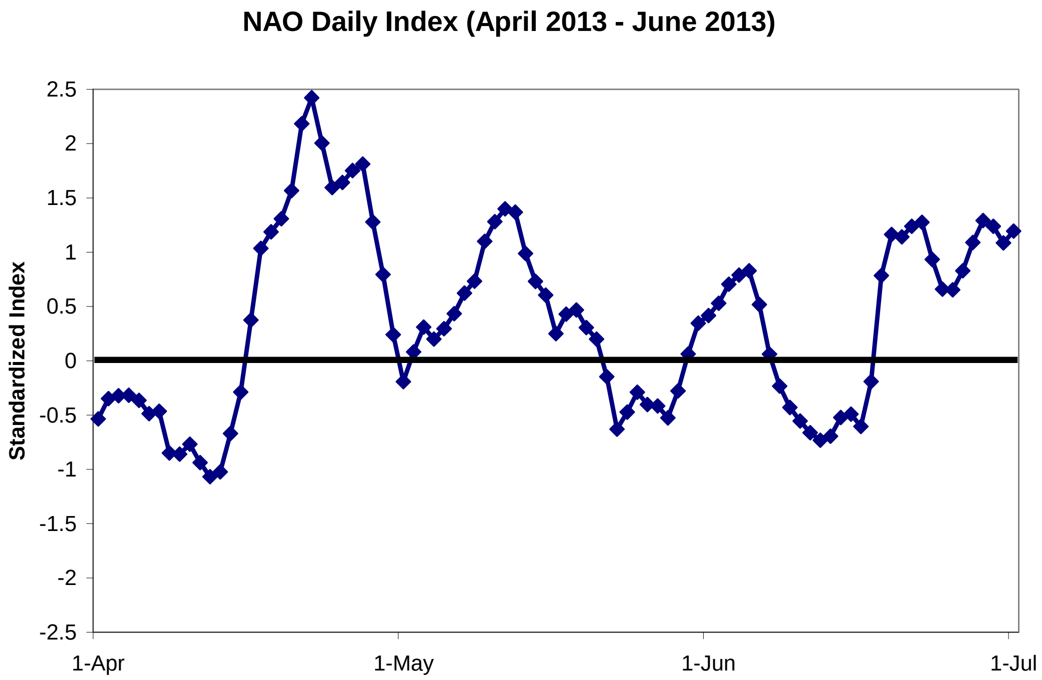
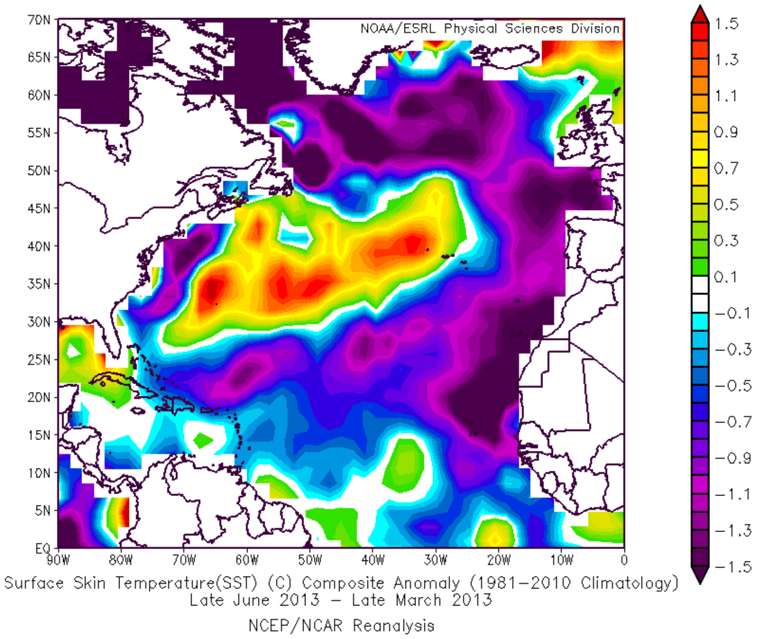

NAO Daily Index (April 2013 - June 2013)

Figure 20: Daily values of the North Atlantic Oscillation (NAO) from April-June 2013. Positive values of the NAO dominated during this three-month period.


NOAA/ESRL Physical Sciences Division

Surface Skin Temperature(SST) (C) Composite Anomaly (1981−2010 Climatology)
Late June 2013 − Late March 2013
NCEP/NCAR Reanalysis

Figure 21: Late June 2013 - late March 2013 anomalous SST change across the Atlantic basin. Note the strong anomalous cooling that occurred throughout most of the Atlantic basin.

However, during July, the trade winds weakened significantly, and most of the Atlantic evidenced a rapid rebound in SSTs (Figure 22). Had the anomalous SST pattern present at the end of June persisted through the end of July, we likely would have forecast a somewhat quieter hurricane season.

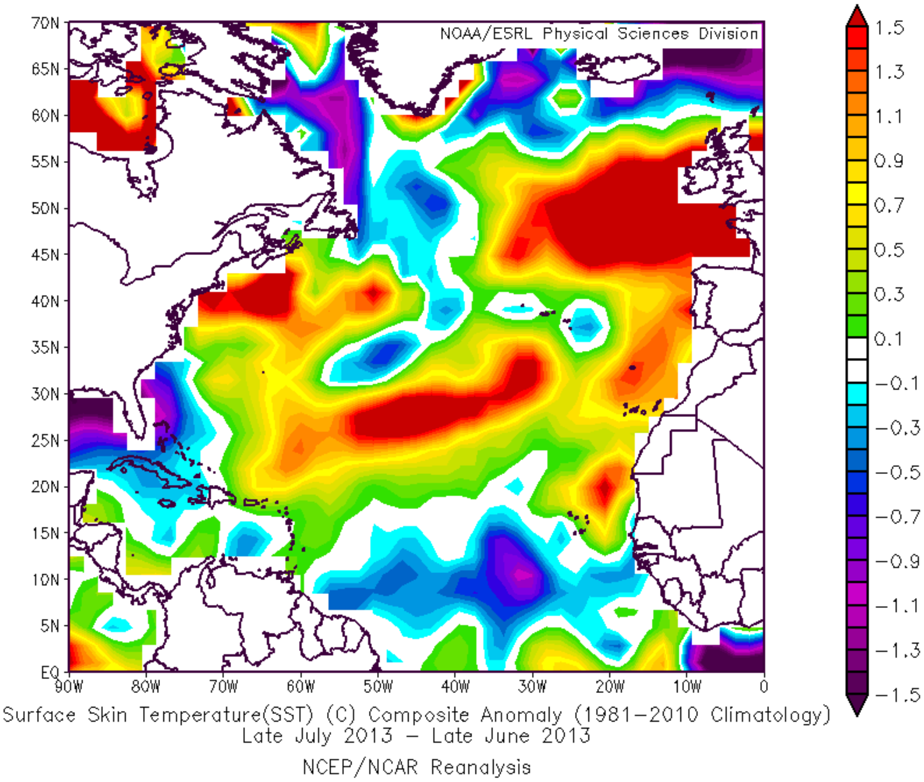


Figure 22: Late July 2013 - late June 2013 anomalous SST change across the Atlantic basin. Most of the basin experienced anomalous warming.

Since the end of July, SSTs in the tropical Atlantic have continued to warm (Figure 23). The current SST anomaly pattern is typically one associated with active Atlantic hurricane seasons (Figure 24).

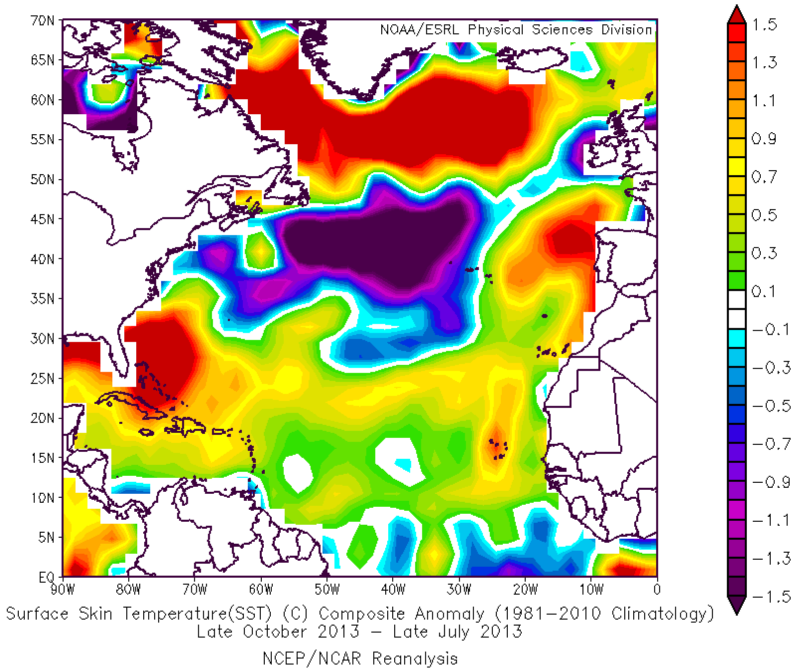


Figure 23: Late October 2013 - late July 2013 anomalous SST change across the Atlantic basin. Most of the basin has continued to experience warming.

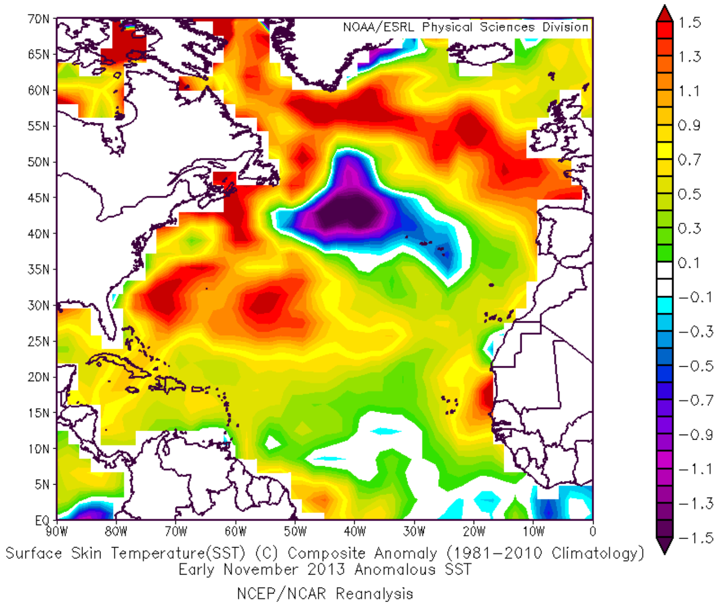


Figure 24: Early November 2013 anomalous SST. Warm anomalies predominate across the basin.

## 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 2013 Atlantic hurricane season was characterized by slightly below-normal sea level pressures throughout the Atlantic basin. Figure 25 displays August-October 2013 tropical and sub-tropical sea level pressure anomalies in the North Atlantic.

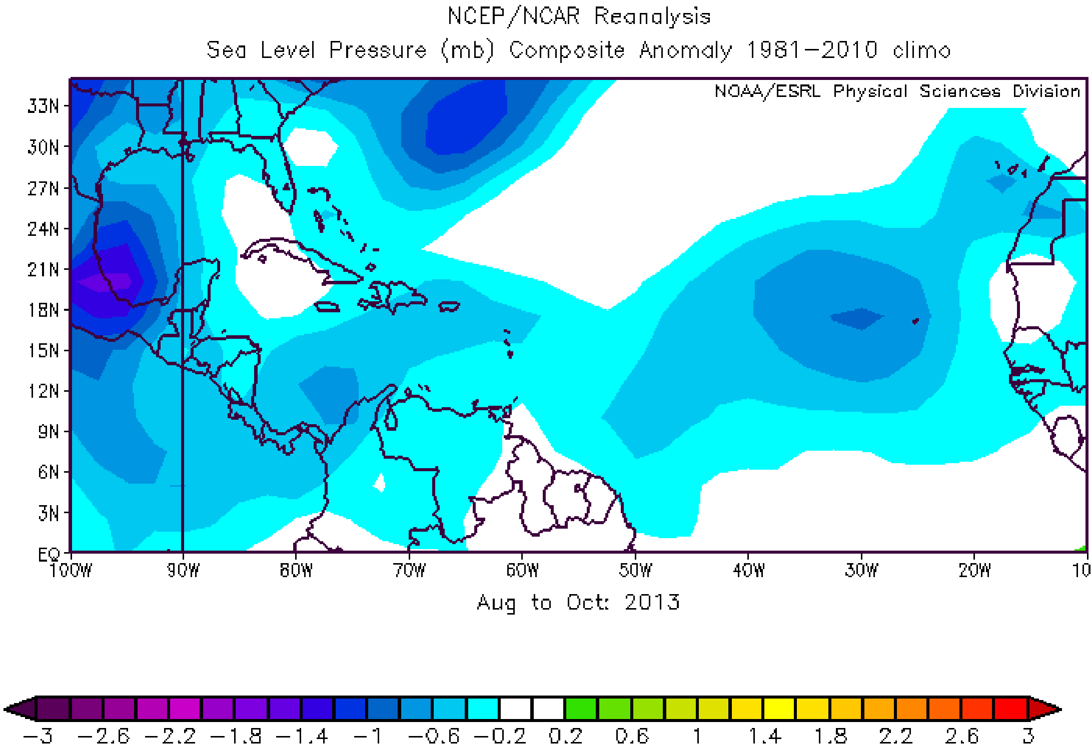
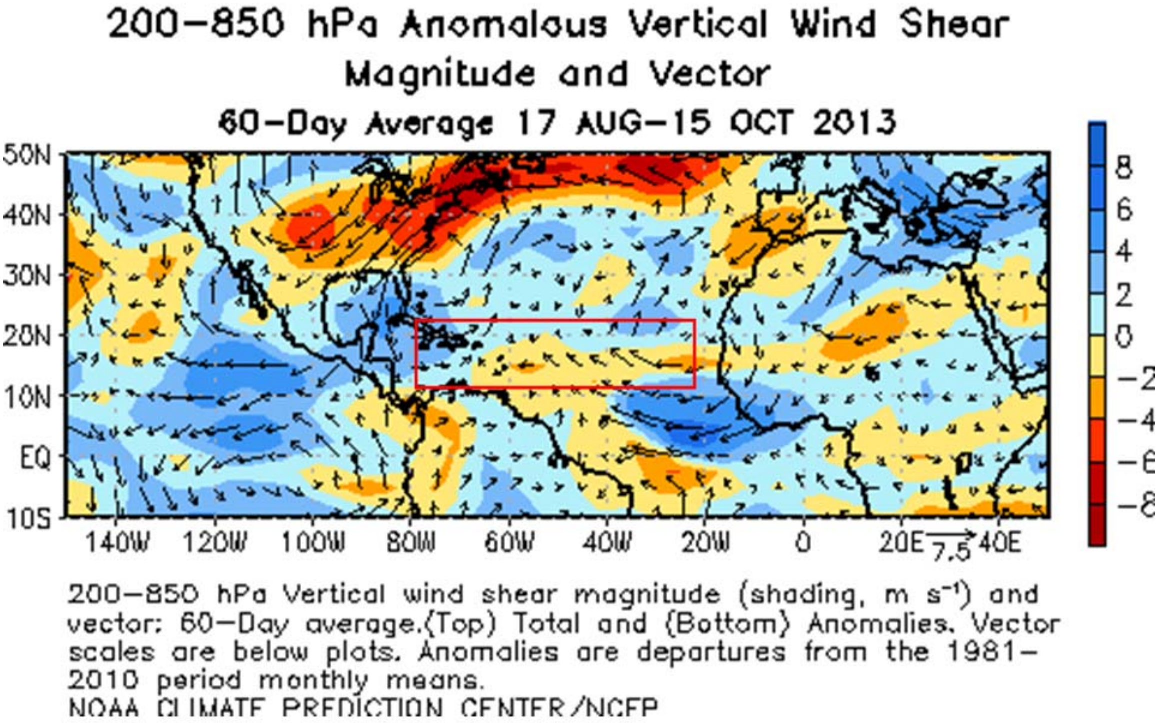


Figure 25: August-October 2013 tropical and sub-tropical North Atlantic sea level pressure anomalies. Sea level pressure anomalies were slightly below average across the tropical Atlantic.

## 7.5 Tropical Atlantic Vertical Wind Shear

Tropical Atlantic vertical wind shear was approximately average when averaged across the entire Main Development Region during the peak two-month period of the Atlantic hurricane season from mid-August to mid-October (Figure 26). Vertical shear anomalies were below-average across the middle portion of the Main Development Region (MDR) (highlighted in the red box) with anomalously strong vertical shear in the far eastern and western portions of the MDR. Relatively strong shear was generally present across the Caribbean and Gulf of Mexico and likely restricted TC formation in these areas. Table 16 displays standardized anomalies of 200-850-mb zonal wind shear for the Gulf of Mexico (20-30°N, 95-80°W) and Caribbean (10-20°N, 88-60°W) for each of three months of the peak of the Atlantic hurricane season from August-October. Shear was generally stronger than normal, more in line with a weak to moderate El Niño year than a cool neutral ENSO year like we observed this year.



200-850 hPa Anomalous Vertical Wind Shear
Magnitude and Vector
60-Day Average 17 AUG-15 OCT 2013

200-850 hPa Vertical wind shear magnitude (shading, m s$^{-1}$) and vector: 60-Day average.(Top) Total and (Bottom) Anomalies. Vector scales are below plots. Anomalies are departures from the 1981-2010 period monthly means.
NOAA CLIMATE PREDICTION CENTER/NCEP

Figure 26: Anomalous vertical wind shear as observed across the Atlantic from August 17 – October 15, 2013.

Table 16: Anomalous vertical shear (in standard deviations) during August, September and October for the Gulf of Mexico (20-30°N, 95-80°W) and Caribbean (10-20°N, 88-60°W), respectively.

| Region/Month | Standardized Vertical Shear |
|---|---|
| GOM - August | +0.6 SD |
| GOM - September | +0.8 SD |
| GOM - October | 0.0 SD |
| Caribbean - August | +1.0 SD |
| Caribbean - September | +0.1 SD |
| Caribbean - October | +0.5 SD |

## 7.6 Tropical Atlantic Moisture

One of the primary reasons why TC activity was not as active in the MDR as would be expected given the reasonably favorable vertical shear and SST conditions was the anomalous dryness that persisted across the tropical Atlantic throughout the peak months of MDR formation from July-September. By October, TC formation tends to shift westward towards the Caribbean. NCEP/NCAR Reanalysis moisture values seem reasonable since the late 1970s (e.g., no unusual trends). Table 17 displays relative humidity and specific humidity compared with other years from 1979-2012. A ranking of one indicates the driest during the time period. Note the anomalous dryness that occurred throughout the three-month period. It seems like this dry air was one of the critical reasons why the season was very quiet.

Table 17: Specific humidity, relative humidity and omega rankings for July 2013, August 2013 and September 2013 at 300-mb, 500-mb and 700-mb across the MDR (7.5-22.5°N, 20-75°W). Note that a ranking of one implies the driest (or most enhanced downward motion) across the MDR, while a ranking of 35 would imply the wettest (or most enhanced vertical motion) month of the last 35 years across the MDR.

**Specific Humidity**

| | 300-mb | 500-mb | 700-mb |
|---|---|---|---|
| July 2013 | 5 | 9 | 16 |
| August 2013 | 12 | 2 | 6 |
| September 2013 | 2 | 2 | 14 |

**Relative Humidity**

| | 300-mb | 500-mb | 700-mb |
|---|---|---|---|
| July 2013 | 5 | 8 | 11 |
| August 2013 | 7 | 14 | 1 |
| September 2013 | 2 | 2 | 8 |

Figure 27 displays anomalous 500-mb relative humidity during the three-month period from July-September 2013. RH was quite low across the MDR, with even drier anomalies noted to the south of MDR. As noted in the storm reports at the start of this verification, dry air was responsible for the death of many of the TCs that formed this year.

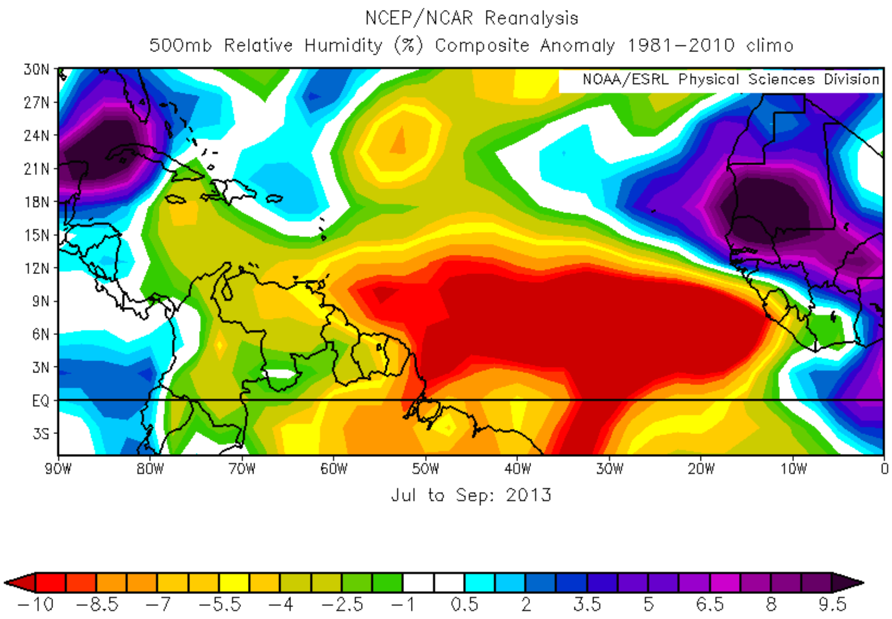


Figure 27: July-September 2013 500-mb RH anomalies. Note the anomalous dryness across the Atlantic MDR this year.

## 7.7 Tropical Atlantic Subsidence

Another reason why the tropical Atlantic was likely very quiet this year was due to anomalous subsidence across the MDR. Table 18 displays omega rankings for July-September 2013 at 300-mb, 500-mb and 700-mb as averaged across the MDR. The peak MDR formation months of July, August and September were characterized by significant anomalous sinking motion, thereby suppressing deep convective development necessary for TC formation and maintenance.

Table 18: Omega rankings for July 2013, August 2013 and September 2013 at 300-mb, 500-mb and 700-mb across the MDR (7.5-22.5°N, 20-75°W). Note that a ranking of one implies the most enhanced downward motion across the MDR, while a ranking of 35 would imply the or most enhanced vertical motion month of the last 35 years across the MDR.

**Omega**

| | 300-mb | 500-mb | 700-mb |
|---|---|---|---|
| July 2013 | 3 | 2 | 1 |
| August 2013 | 4 | 1 | 2 |
| September 2013 | 4 | 3 | 2 |

Another way to view the anomalous subsidence that occurred over the tropical Atlantic is to look at upper-level velocity potential anomalies. Positive velocity potential at upper levels indicates upper-level convergence and sinking motion. Figure 28 displays velocity potential anomalies across the Atlantic MDR during July-September.

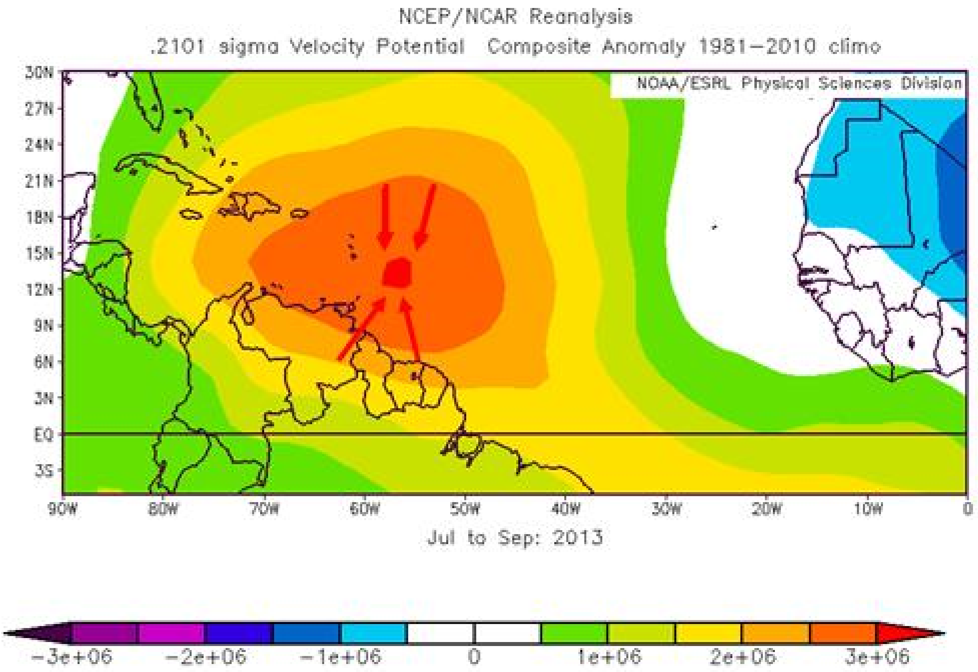


Figure 28: Upper-level velocity potential anomalies in July-September 2013. Note the positive velocity potential anomalies that occurred during the month, indicating upper-level convergence (as demarked by the red arrows) and sinking motion.

## 7.8 Tropical Atlantic Meridional Flow

One of the primary reasons why we believe several of the seasons since 1995 have been very active was due to a pronounced and northward shifted Intertropical Convergence Zone (ITCZ) in the eastern tropical Atlantic (Klotzbach and Gray 2006). A stronger than normal ITCZ is associated with strong cross-equatorial flow which provides increased moisture flux into the tropical Atlantic and provides pre-existing cyclonic vorticity that helps spin up easterly waves. Anomalous meridional flow in July-September 2013 in the eastern tropical Atlantic was strongly out of the north, indicating a suppressed ITCZ and anomalous moisture divergence out of the tropical Atlantic (Figure 29).

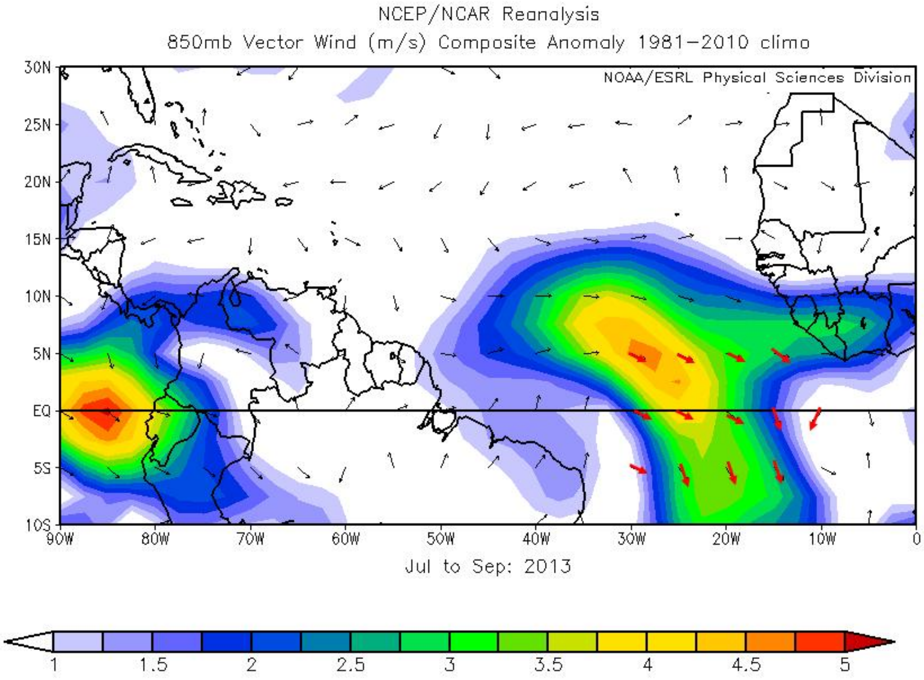


Figure 29: Anomalous vector wind anomaly from July-September 2013. Note the anomalous northerly flow in the tropical Atlantic which likely was one of the reasons why there was such significant dryness in the tropical Atlantic this year.

## 7.8 Tropical Atlantic Moisture Flux Divergence

Unfortunately, moisture flux divergence is not a diagnostic field in the NCEP/NCAR Reanalysis, but it is a diagnostic field in the ERA-Interim Reanalysis. The ERA-Interim Reanalysis is available at a two to three month lag from real-time. We currently have values available through August 2013. When averaged over the tropical Atlantic MDR (7.5-22.5°N, 75-20°W), moisture flux divergence anomalies were strongly positive (e.g., drying in the MDR). The values in both June and July 2013 were the third highest over the period from 1979-2013, while values in August 2013 were near average. It seems that a large portion of the reason why 2013 was so quiet was due to very unfavorable thermodynamic conditions associated with the aforementioned subsidence and dry air.

## 7.9 Tropical Atlantic Rainfall

Given the paucity of moisture in the Main Development Region this year, it is not surprising that rainfall during August-September was significantly below average, especially across the southern part of the domain (Figure 30). Dry anomalies also prevailed across the Caribbean, which is likely one of the reasons why very little TC activity was observed there this year.

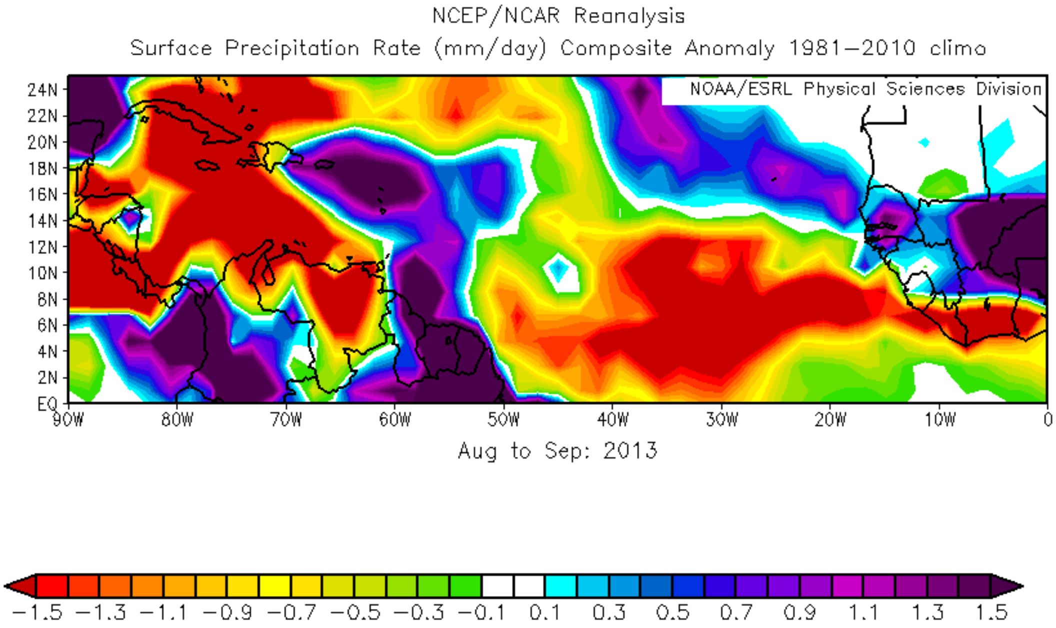


Figure 30: August-September 2013 precipitation anomalies across the tropical and subtropical Atlantic. Note the significant dry anomalies across the southern part of the MDR, as well as the Caribbean.

## 7.10 Northeast Subtropical Atlantic SSTs

One area of concern with our early August forecast was the anomalously cool subtropical Atlantic SSTs that were observed at that point. However, there had been significant anomalous warming in that area during July, and we thought the warming might continue. The warming soon abated, however, and anomalous cooling began anew. Figure 31 displays the anomalous SST pattern across the tropical and subtropical Atlantic during August-September 2013. Cold anomalies in the eastern subtropical Atlantic cause increased baroclinicity and upper-level cold low intrusions into the tropics, thereby causing early recurvature of many tropical waves. A similar phenomenon was observed during the second half of the 2007 Atlantic hurricane season.

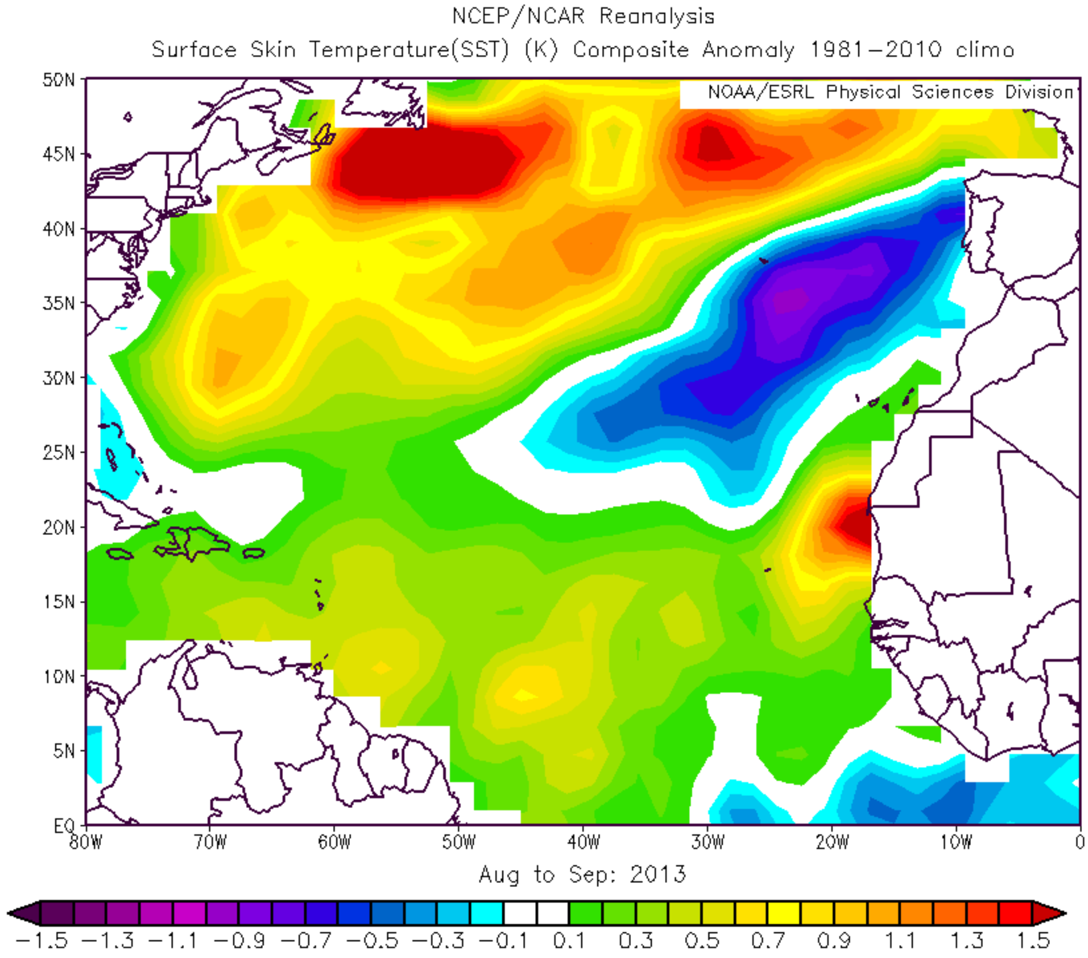


Figure 31: August-September 2013 SST anomaly pattern across the North Atlantic. Note the cold anomalies in the subtropical eastern Atlantic.

## 7.11 Steering Currents

As has been the case for the past several years, anomalous troughing dominated the United States East Coast this year (Figure 32). While there were no hurricane threats of significance to the US mainland this year, the predominant steering flow was such to keep these TCs away from the East Coast. The United States has now gone eight years without a landfalling major hurricane.

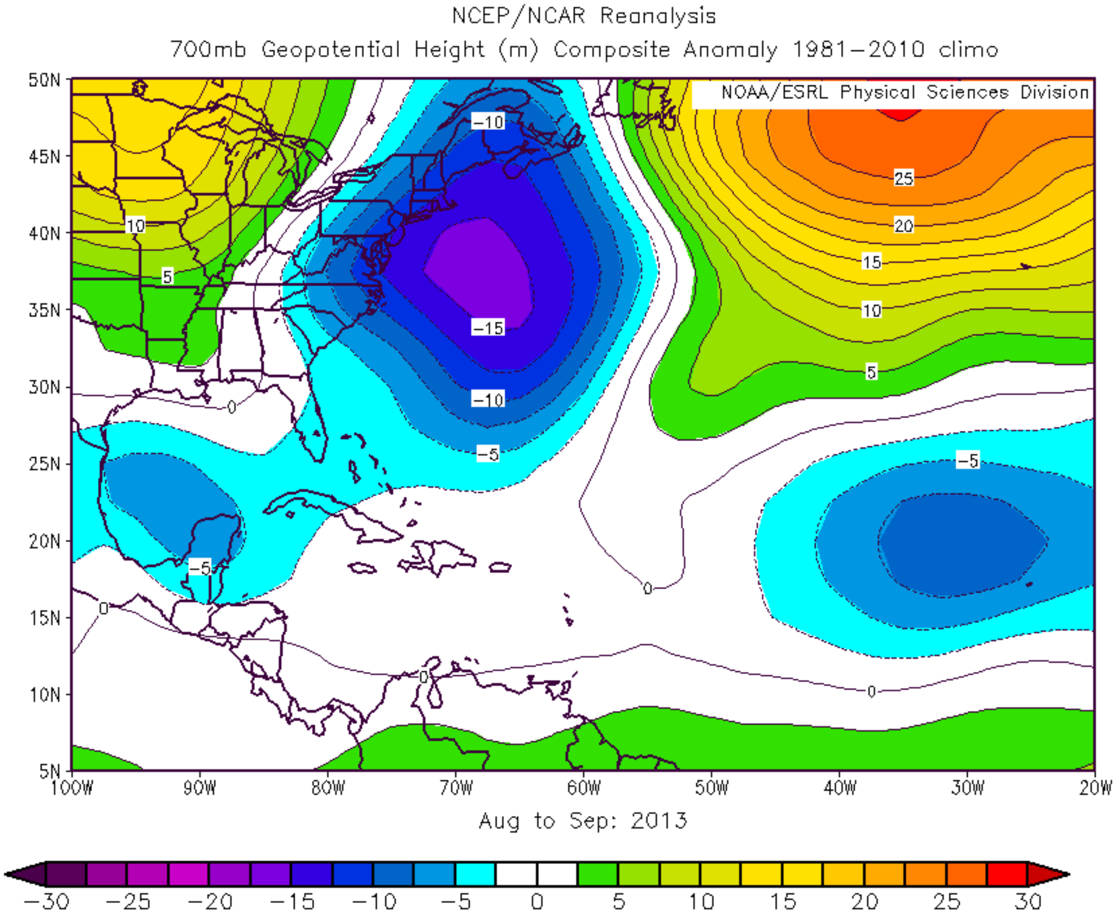


Figure 32: 700-mb height anomalies in the central and western part of the Atlantic in August-September 2013. Anomalous troughing dominated along the East Coast of the United States.

## 8 Physics of the Atlantic Multi-Decadal Oscillation (AMO) or Thermohaline Circulation (THC) on Atlantic Hurricane Activity

One of the primary physical drivers for active versus inactive Atlantic basin hurricane seasons is the strength of the Atlantic Multi-Decadal Oscillation (AMO) or thermohaline circulation (THC) (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 AMO 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. Strong THC or positive AMO conditions are characterized by positive SSTA and salinity content in the North Atlantic, increased rainfall in the Sahel region of Africa, warmer tropical Atlantic SST, reduced sea level pressure in the tropical Atlantic, reduced ENSO frequency and a wide variety of other physical processes (Figure 33). It is not specifically one parameter, such as tropical Atlantic SST, which is dominant but rather the combination of 4-5 parameters which all change sign together in a manner acting to either enhance or reduce Atlantic major hurricane activity.

Through a progression of associations the strength of the THC 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). The favorable changes of SST in the MDR are a consequence of a combination of the ocean's THC influences on a variety of parameters in the Atlantic's MDR (Figure 33). 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 33 to bring about more favorable parameters in the MDR for TC formation and intensification. This figure illustrates how the changing rate of southward advection of colder 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 follow (8). These changing conditions bring about weaker trade winds and reduced evaporation which typically acts to increase SST. It is also found that in periods with a strong THC, El Niño frequency and intensity is typically reduced (9) and Atlantic hurricane activity, particularly major hurricane activity, is enhanced.

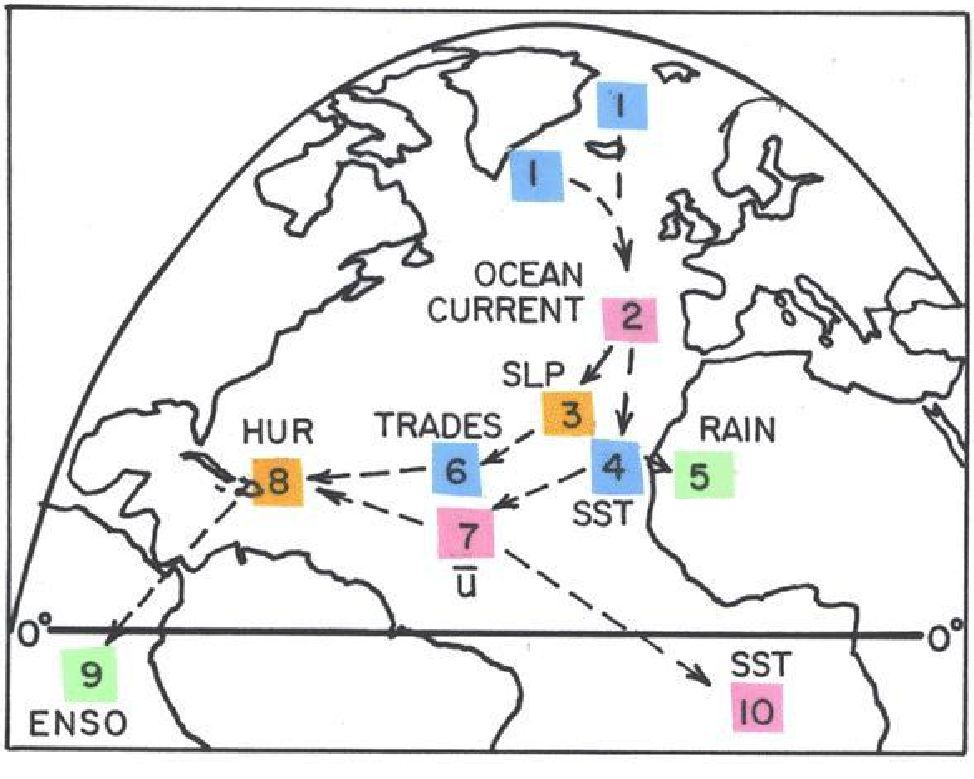


Figure 33: Schematic showing the large number of parameters that are closely related to the AMO or THC.

## 8.1 The Atlantic Ocean Thermohaline Circulation (THC)

Years of study of Atlantic seasonal hurricane variability has lead us to an ever deepening appreciation of the importance of the THC or AMO to Atlantic seasonal hurricane variability. There are few direct measures of the amount of North Atlantic deep sinking which determines the strength of the THC, but we have developed proxy signals which we believe give a reasonable approximation of the THC's intensity.

Our original proxy for the THC consisted of the measurement of the North Atlantic sea surface temperature anomaly (SSTA of 50-65°N; 50°W-10°W) minus the broad Atlantic sea level pressure anomaly (SLPA of 0-50°N; 70°W-10°E). This measurement clearly defines the multi-decadal periods when there are large differences in the frequency and intensity of major (Cat 3-4-5) hurricanes. There are, however, individual year periods within these enhanced and suppressed multi-decadal periods when hurricane activity goes opposite to the longer-period multi-decadal signal. Also, there are multi-monthly periods when our seasonal THC proxy representations are not typical of their yearly average – 2013 was one of these years.

## 8.2 Suggested Physics of Thermohaline Influence

The stronger the THC is, in general, the weaker becomes the Bermuda-Azores high pressure atmosphere and ocean gyre. A weaker gyre reduces low-level eastern Atlantic northerly winds and ocean currents from the north. In response, the tropical Atlantic becomes warmer, sea level pressures are reduced, more precipitation occurs and TC activity is enhanced. By contrast, when the THC is weak, there is less warm tropical Atlantic water advected to high latitudes and lost to subsidence at deep levels.

The extra water that would otherwise sink at high latitudes stays in the sub-tropics and is advected to the east and then the southeast side of the gyre. This acts to enhance advection of cold temperatures from the north. The process brings about enhanced cold water upwelling, higher surface pressure, stronger meridional flow from the north, more dry air advection from Africa, and greater north-south temperature gradients (with greater tropospheric vertical wind shear) over the MDR. All these features inhibit TC formation in the MDR. It is likely not a single specific negative parameter which plays an overly dominant role in TC enhancement or suppression but rather a combination of a number of negative or positive factors which act together to bring about enhanced or suppressed Atlantic TC activity.

## 8.3 New Thermohaline Proxy

We have developed a new proxy representation for the strength of the Atlantic Ocean THC which uses three eastern Atlantic parameters in the area of 20°N-50°N; 30°W-10°W (see Figure 34). This proxy is a sum of three parameters. The parameters are the standard deviations of the surface meridional wind ($V_{sfc}$), the sea surface temperature anomaly (SSTA) and the negative of the sea level pressure anomaly (SLPA). We find that the THC is strongest when the standard deviation of the sum of these parameters in the above area give a maximum values of [$V_{sfc}$ + SSTA – SLPA]. That is, the subtropical East Atlantic is characterized by southerly surface wind anomalies, warm SSTA and low SLPA. Table 19 lists multi-decadal averages of this East Atlantic (E. ATL) THC proxy parameter and a special parameter which utilizes only the first 6-months of this (E. ATL) proxy parameter. We call this the Pre-E. ATL proxy. We define the Pre-E. ATL as the sum of the standard deviation of [$V_{sfc}$ + SSTA – SLPA] for the period of (April-June) plus [(April-June) minus (January-March)] or [2(April-June) minus (January-March)]. The table also includes measurements of our earlier developed whole Atlantic THC proxy (W. ATL).

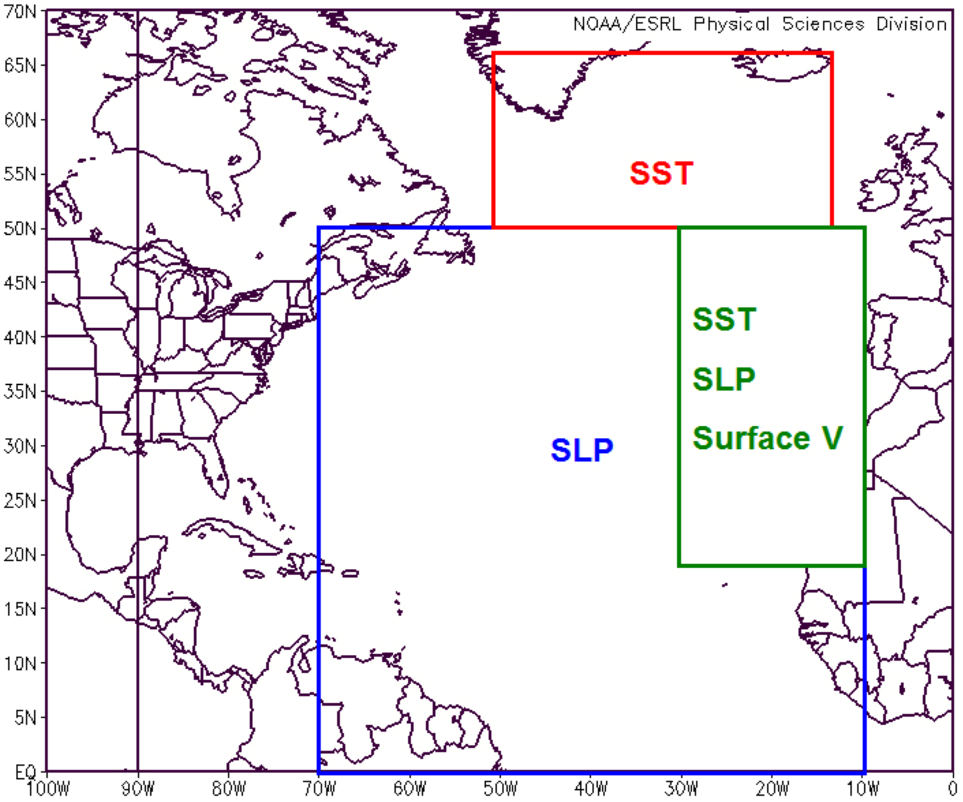


Figure 34: Areas for which SLP and SST are calculated to approximate the real-time strength of the THC.

Table 19: Comparison of the decadal average differences of our two Atlantic Ocean THC strength proxy signals. This includes our whole Atlantic (W. ATL) proxy and our East Atlantic (E. ATL) proxy – the sum is our total proxy.

| | **W. ATL + E. ATL Proxy (January – December)** | | | **Pre-W. ATL + E. ATL Proxy [2(Apr-June) – (Jan-Mar)]** | | |
|---|---|---|---|---|---|---|
| | *W. ATL* | *E. ATL* | *Total Proxy* | *Pre-W. ATL* | *Pre-E. ATL* | *Total Pre-Proxy* |
| 1950-1969 | .94 | .50 | 1.44 | 1.36 | 1.15 | 2.51 |
| 1970-1994 | -.99 | -.84 | -1.83 | -.68 | -1.07 | -1.75 |
| 1995-2012 | .52 | .96 | 1.48 | .55 | 1.12 | 1.67 |
| 2013 (Jan-Oct) | -.09 | .17 | .08 | -5.40 | -3.65 | -9.05 |

## 8.4 Rapid Changes in the AMO/THC in 2013

While the AMO typically remains in an above-average or in a below-average stage for periods of 25-35 years, there can be monthly, seasonal or longer breaks up to a year or two within these longer periods when the AMO (or THC) conditions of features such as SST, salinity, pressure, wind, and moisture become substantially weaker in positive phases or stronger during negative phases. During these periods where the multi-decadal signal is interrupted, we sometimes observe below-average TC activity during a positive phase (e.g., 1962 and 1968) or above-average TC activity during a negative phase (e.g., 1988 and 1989).

The AMO/THC appears to have undergone a significant weakening followed by a re-strengthening over the past several months. The AMO/THC was quite strong during the first three months of 2013 according to our E. ATL metric, then weakened dramatically during the spring (Figure 35). Values in May/June were the lowest observed in the Atlantic basin since 1950. However, these values soon rebounded and were back above normal by July. Despite the rapid re-strengthening of the AMO/THC during the summer of 2013, it appears that the lagged impact of the sudden weakening during the spring months was partially responsible for the much weaker than anticipated Atlantic hurricane season this year.

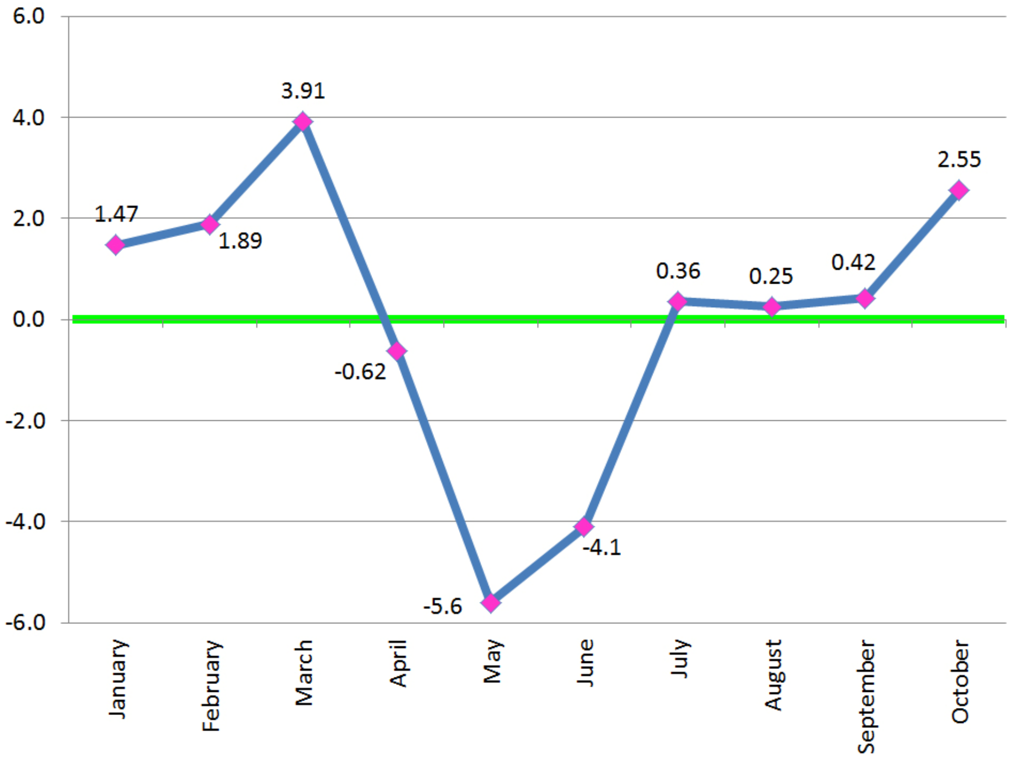


Figure 35: Changes in the strength of the new proxy for the THC/AMO from January-October 2013. Note the dramatic spring collapse. The combined May-June 2013 value was the lowest of any year since 1950.

**Why was the 2013 hurricane season so weak?** The majority of Atlantic basin hurricane seasons with the least amount of activity occur in El Nino years. The average amount of hurricane activity as expressed by ACE in 12 (or 20%) of the last 64 years in which moderate or strong El Nino have occurred was only 50. The average ACE of the other 48 (or 80% of years since 1950) years in which El Nino activity was not present was 120 or 240 percent greater.

The 2013 Atlantic hurricane season had an ACE value of only 30. This low hurricane season is only rivaled for low activity since 1950 during non-El Nino years by 1962 (ACE = 36), 1968 (ACE = 45), 1977 (ACE = 25), 1993 (ACE = 39), and 1994 (ACE = 32).

Why did this non-El Nino year of 2013 have such a great reduction in Atlantic hurricane activity? Recent research has led us to attribute a sizable portion of the reduction in the 2013 hurricane activity to the unusual springtime weakening of the THC (Figure 35). We failed to realize the importance of this first half of the year reduction in the strength of the THC. Part of our failure to predict an inactive season was due to the rapid THC reversal in July and general THC recovery in the second half of the year.

There are large observed multi-decadal differences in Atlantic basin seasonal hurricane activity, particularly with major (Cat 3-4-5) hurricane activity. These multi-decadal variations of major hurricane activity occur during periods when we estimate, from proxy information, that the strength of the THC is above the long period average. During periods when we estimate from proxy data that the Atlantic THC is, by contrast weak, we see a great reduction in major hurricane activity. Table 20 shows the strong influence of THC variability in comparison with the frequency of seasonal hurricane intensity.

Table 20: Comparison of the ratio of 1995-2012 seasonal average hurricane activity when our proxy for the THC was strong (right column) versus the seasonal hurricane activity during the 25-year period of 1970-1994 when our proxy for the THC was weak (left column). Note that the largest differences occur with the most intense TC activity.

| | 1970-1994 | 1995-2012 |
|---|---|---|
| Hurricanes (H) | 1.00 | 1.65 |
| Hurricane Days (HD) | 1.00 | 1.95 |
| Major Hurricanes (MH) | 1.00 | 2.47 |
| Major Hurricane Days (MHD) | 1.00 | 3.25 |
| Accumulative Cyclone Energy (ACE) | 1.00 | 2.06 |
| Category 4-5 Hurricanes | 1.00 | 2.92 |

The THC proxy we have been using clearly demarked the strong from the weak multi-decadal periods (see Figure 36). But up to now, we had not yet attempted to measure the strength of the changes of the THC on shorter-period time scales. We have yet to investigate how these smaller time-scale THC changes might be related to year-to-year hurricane activity variations. For instance, during the 1970-94 weak THC period, we observed an apparent 2-year increase in TC activity in 1988-1989 when we had three Category 4 hurricanes form, and two hurricanes reached Category 5 strength. At that time we thought the THC may have begun to come out of its weak phase. But this was not the case, and for the next five years from 1990-1994 the THC remained quite weak. We had an unprecedented decrease in the 5-year running mean of hurricane activity (average 5-year 1990-94 yearly ACE values were only 34).

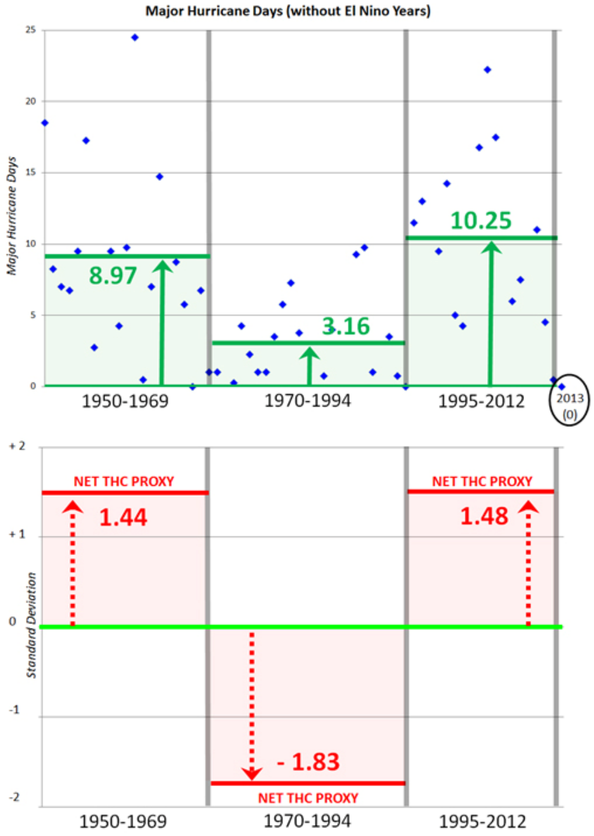


Figure 36: Illustration of the multi-decadal relationship between our proxy for the strength of the Atlantic THC and the average seasonal number of major (Cat 3-4-5) hurricanes per year. THC proxy is a combination of (SSTA 50-65°N; 50°W-10°W) plus E. ATL.

There is no question that the strength of the Atlantic THC plays a direct and fundamental statistical role in specifying the amount of hurricane activity which will occur, especially with major hurricane activity.

It will likely take many future years to sort out the different processes which cause the THC to alternate on a seasonal, yearly, decadal and century time-scale. It is likely that the primary THC variations of the recent few centuries are driven by global ocean salinity changes.

The failure of this year's forecast appears to a large extent to be a result of an unprecedented April to June 2013 weakening of the THC. The sudden rebound of the THC in July complicated matters.

Had we earlier realized the importance of this dramatic decrease in the strength of our THC proxy, we would not have made such a large over forecast. We approached our early June and early August forecasts with the assumption that we remained in the strong phase of the multi-decadal THC which had been in place since 1995. We have since developed a new and second THC proxy signal of the THC strength from three meteorological processes of the Eastern Atlantic. We will use this new THC proxy in conjunction with our older THC proxy to more carefully monitor the smaller-scale changes of the THC in the future.

## 8.5 Summary

The majority of most inactive hurricane seasons are associated with El Nino years. That was not the case this year. There was no El Nino in 2013. There were a number of inhibiting tropical Atlantic parameters which unexpectedly occurred this season such as have been discussed earlier. These negative parameters were responsible for the low hurricane activity which resulted. But the more basic question is why did so many of these negative hurricane genesis parameters occur when most of our large-scale pre-season precursor climate signals appeared similar to those which occur before most of the previous active seasons?

We believe that much of the explanation for the lack of activity this year was due to a significant weakening of our proxy of the Atlantic THC from April through June. Our THC proxy signals of April-June 2013 indicate that the Atlantic THC (from both W. ATL and E. ATL proxy signals) had the strongest drop and was the weakest overall of any year since 1950. We hypothesize that this very large springtime collapse of the THC set up broad-scale conditions that likely related to the unusually dry mid-level air, stronger-than-normal mid-level subsidence and stronger than expected vertical wind shear in the Atlantic MDR, Caribbean and Gulf of Mexico.

Additional discussion of the THC will be included in the December outlook for 2014 issued on December 10.

"The best laid schemes of mice and men sometimes go awry"

-- R. Burns

## 9 Forecasts of 2014 Hurricane Activity

We will be issuing our first outlook for the 2014 hurricane season on Tuesday, 10 December 2013. This forecast will provide a qualitative outlook for factors likely to impact the 2014 hurricane season. This December forecast will include the dates of all of our updated 2014 forecasts. All of these forecasts will be made available online at: http://hurricane.atmos.colostate.edu/Forecasts.

## 10 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 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.

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# 12 Verification of Previous Forecasts

Table 21: Verification of the authors' early August forecasts of Atlantic named storms and hurricanes between 1984-2013. 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 25 of 30 years for named storms and 22 of 30 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 |
| Average | **11.1** | **10.9** | **6.4** | **6.1** |
| 1984-2013 Correlation | | **0.58** | | **0.52** |

Table 22: Summary verification of the authors' five previous years of seasonal forecasts for Atlantic TC activity between 2008-2012. Verifications of all seasonal forecasts back to 1984 are available here: http://tropical.atmos.colostate.edu/Includes/Documents/Publications/forecast_verifications.xls

| 2008 | 7 Dec. 2007 | Update 9 April | Update 3 June | Update 5 August | Obs. |
|---|---|---|---|---|---|
| Hurricanes | 7 | 8 | 8 | 9 | 8 |
| Named Storms | 13 | 15 | 15 | 17 | 16 |
| Hurricane Days | 30 | 40 | 40 | 45 | 30.50 |
| Named Storm Days | 60 | 80 | 80 | 90 | 88.25 |
| Major Hurricanes | 3 | 4 | 4 | 5 | 5 |
| Major Hurricane Days | 6 | 9 | 9 | 11 | 7.50 |
| Accumulated Cyclone Energy | 115 | 150 | 150 | 175 | 146 |
| Net Tropical Cyclone Activity | 125 | 160 | 160 | 190 | 162 |

| 2009 | 10 Dec. 2008 | Update 9 April | Update 2 June | Update 4 August | Obs. |
|---|---|---|---|---|---|
| Hurricanes | 7 | 6 | 5 | 4 | 3 |
| Named Storms | 14 | 12 | 11 | 10 | 9 |
| Hurricane Days | 30 | 25 | 20 | 18 | 12 |
| Named Storm Days | 70 | 55 | 50 | 45 | 30 |
| Major Hurricanes | 3 | 2 | 2 | 2 | 2 |
| Major Hurricane Days | 7 | 5 | 4 | 4 | 3.50 |
| Accumulated Cyclone Energy | 125 | 100 | 85 | 80 | 53 |
| Net Tropical Cyclone Activity | 135 | 105 | 90 | 85 | 69 |

| 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 | 4.5 |
| 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 |
| 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 |