SUMMARY OF 2012 ATLANTIC TROPICAL CYCLONE ACTIVITY AND VERIFICATION OF AUTHORS' SEASONAL AND TWO-WEEK FORECASTS

The 2012 hurricane season had more activity than predicted in our seasonal forecasts. It was notable for having a very large number of weak, high latitude tropical cyclones but only one major hurricane. The activity that occurred in 2012 was anomalously concentrated in the northeast subtropical Atlantic. While Superstorm Sandy caused massive devastation along parts of the mid-Atlantic and Northeast coast, its destruction was viewed to be within the realm of natural variability.

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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

Emily Wilmsen, Colorado State University Media Representative, (970-491-6432) is available to answer various questions about this verification.

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ATLANTIC BASIN SEASONAL HURRICANE FORECASTS FOR 2012

Forecast Parameter and 1981-2010 Median (in parentheses)	4 April 2012	Update 1 June 2012	Update 3 Aug 2012	Observed 2012 Total	% of 1981-2010 Median
Named Storms (NS) (12.0)	10	13	14	19	158%
Named Storm Days (NSD) (60.1)	40	50	52	99.50	166%
Hurricanes (H) (6.5)	4	5	6	10	154%
Hurricane Days (HD) (21.3)	16	18	20	26.00	122%
Major Hurricanes (MH) (2.0)	2	2	2	1	50%
Major Hurricane Days (MHD) (3.9)	3	4	5	0.25	6%
Accumulated Cyclone Energy (ACE) (92)	70	80	99	129	140%
Net Tropical Cyclone Activity (NTC) (103%)	75	90	105	121	117%

1981-2010 Median (in parentheses)	Observed 2012 ACE Value	% of 1981-2010 Median
ACE South of 25N (37)	36	97%
ACE North of 25N (56)	93	166%
ACE East of 65W (52)	90	173%
ACE West of 65W (39)	39	100%

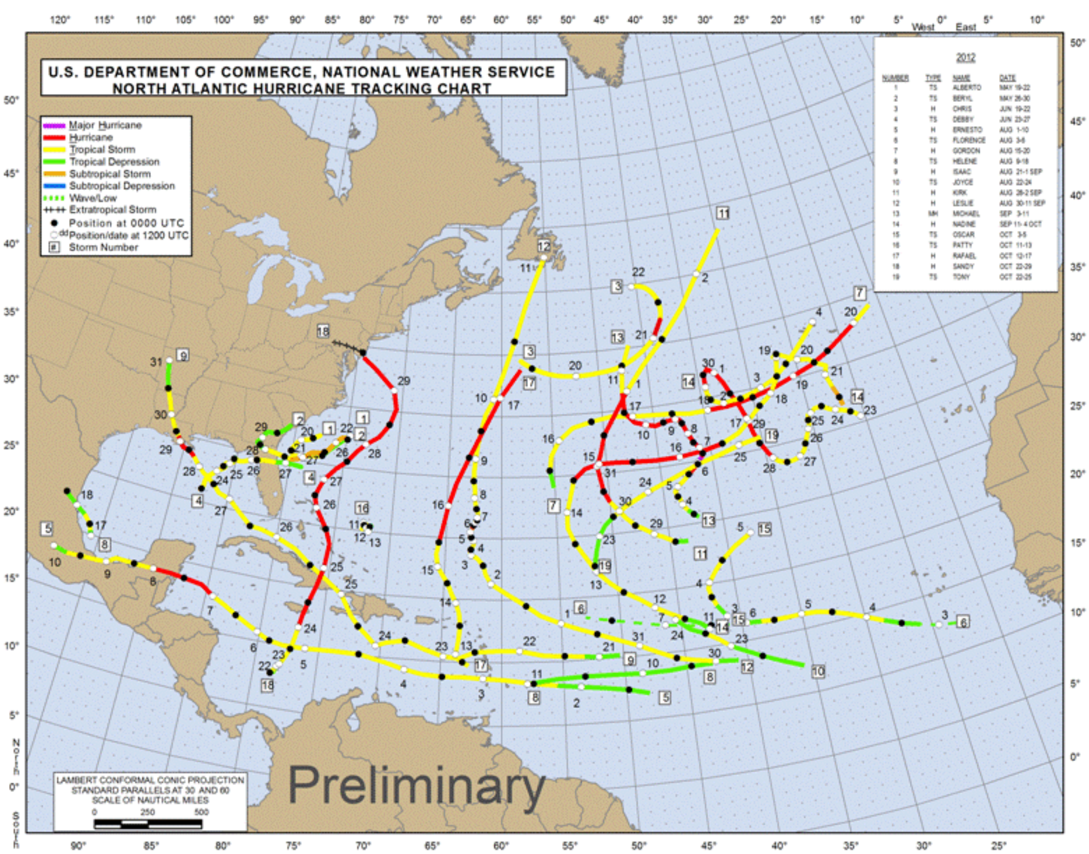

Figure courtesy of the National Hurricane Center (http://www.nhc.noaa.gov)

ABSTRACT

This report summarizes tropical cyclone (TC) activity which occurred in the Atlantic basin during 2012 and verifies the authors' seasonal Atlantic and Caribbean 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 2012 was issued on 4 April with updates following on 1 June and 3 August. These seasonal forecasts also contained estimates of the probability of U.S. and Caribbean hurricane landfall during 2012.

The 2012 hurricane season was one of the most unusual seasons on record in terms of its very high frequency of weaker cyclones in combination with the almost complete lack of major hurricane activity. The formation and tracking of TCs in 2012 was also highly anomalous. Our Atlantic basin seasonal hurricane forecasts predicted an approximately average hurricane season. We significantly under-predicted named storms and named storm days, while we over-predicted more intense hurricane activity for the entire Atlantic basin.

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 were quite accurate this year. Our October-November Caribbean basin-only forecast successfully predicted approximately average activity for the final two months of the season in the Caribbean.

Integrated measures such as Net Tropical Cyclone (NTC) activity and Accumulated Cyclone Energy (ACE) were at above-average levels. Most hurricane activity in 2012 was concentrated in the sub-tropics. It appears that anomalous sinking motion at mid-levels in the atmosphere was the primary reason why 2012 was not more active in the tropics. The anticipated El Niño discussed in the seasonal forecasts did not develop as predicted for a number of reasons.

Superstorm Sandy was a very atypical system that caused some of the most economic damage ever associated with a single storm in US history. Its destruction was the result of a combination of a mid-latitude cyclone and tropical cyclone whose northwesterly track brought major flooding to the New York City and New Jersey coastal areas. Although extremely rare, these types of TCs are well within natural variability, and should not be attributed to increases in human-induced greenhouse gases. This verification contains an extensive write-up of Sandy.

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 Scale – A measurement scale ranging from 1 to 5 of hurricane wind and ocean surge 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 College (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.

Major Highlights of 2012

A. Unusual TC Activity Location

One of the major characteristics of the 2012 Atlantic hurricane season was the highly anomalous tropical cyclone (TC) activity. Figure A displays the tracks of all of the TCs in 2012. The black box indicates an area where six of the ten hurricanes that formed in 2012 had their entire lifespan. This region roughly encompasses the region north of 25°N and east of 65°W. The more traditional Main Development Region (7.5-22.5°N, 75-20°W) had activity at slightly below-average levels.

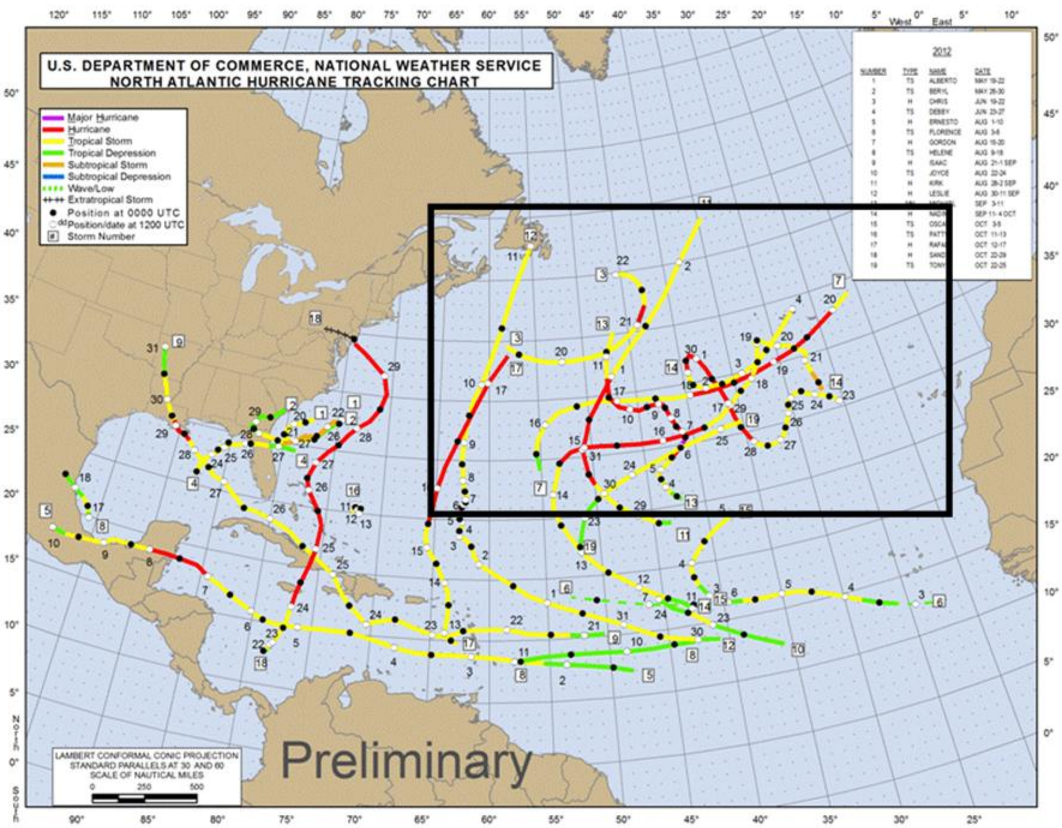

Figure A: Tracks of 2012 Atlantic basin hurricane season TCs, with the subtropical northeast Atlantic highlighted in the black box.

The Accumulated Cyclone Energy (ACE) metric is often used to evaluate total TC activity for the season. In 2012, 71 out of 129 seasonal ACE units (55%) were generated in this region (north of 25°N, east of 65°W). Based on historical data over the period from 1950-2011, about 25% of ACE in a season is typically generated in this region. The only years with a higher percentage of seasonal ACE generated in this region than 2012 were 1986 (63%) and 1976 (73%).

Activity in the northeast subtropical Atlantic was likely to be significantly underestimated prior to the eras of satellite and aircraft reconnaissance. For example, 1933, which was one of the most active seasons on record, had very little observed activity in this region (Figure B), likely due to lack of any satellite measurements at this time.

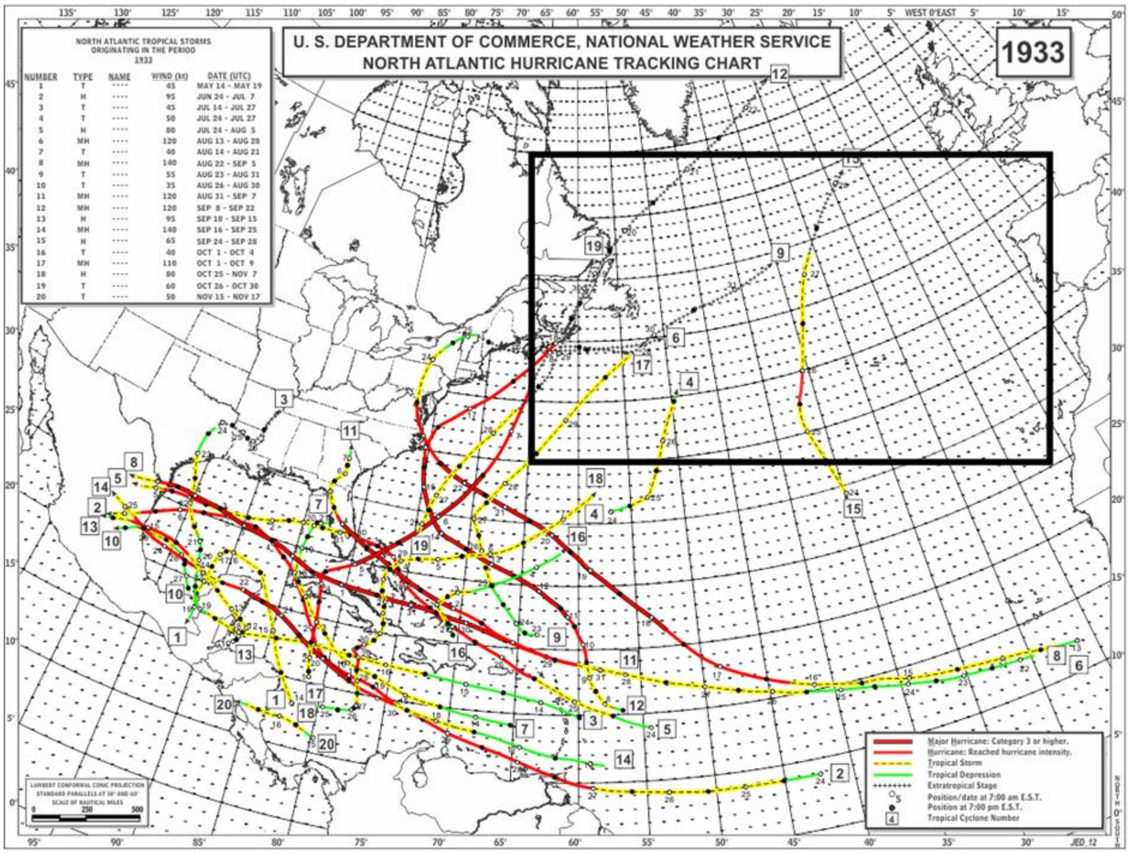

Figure B: Tracks of TCs in 1933. Note that very little activity occurred in the region north of 25°N and east of 65°W in that year.

See Section 8 for a more detailed discussion of why we believe that TC activity occurred in the regions that it did this year.

B. Hurricane/Superstorm Sandy

The most notable TC of the 2012 Atlantic hurricane season was Hurricane/Superstorm Sandy, which devastated parts of the East Coast in late October (Figure C) While damage is still being estimated, this system has the potential to be the most economically destructive storm the United States has ever had, with total economic damage expected to exceed $100 billion dollars. Sandy's path of destruction extended from the Caribbean to the United States, with nearly 200 fatalities blamed on the system.

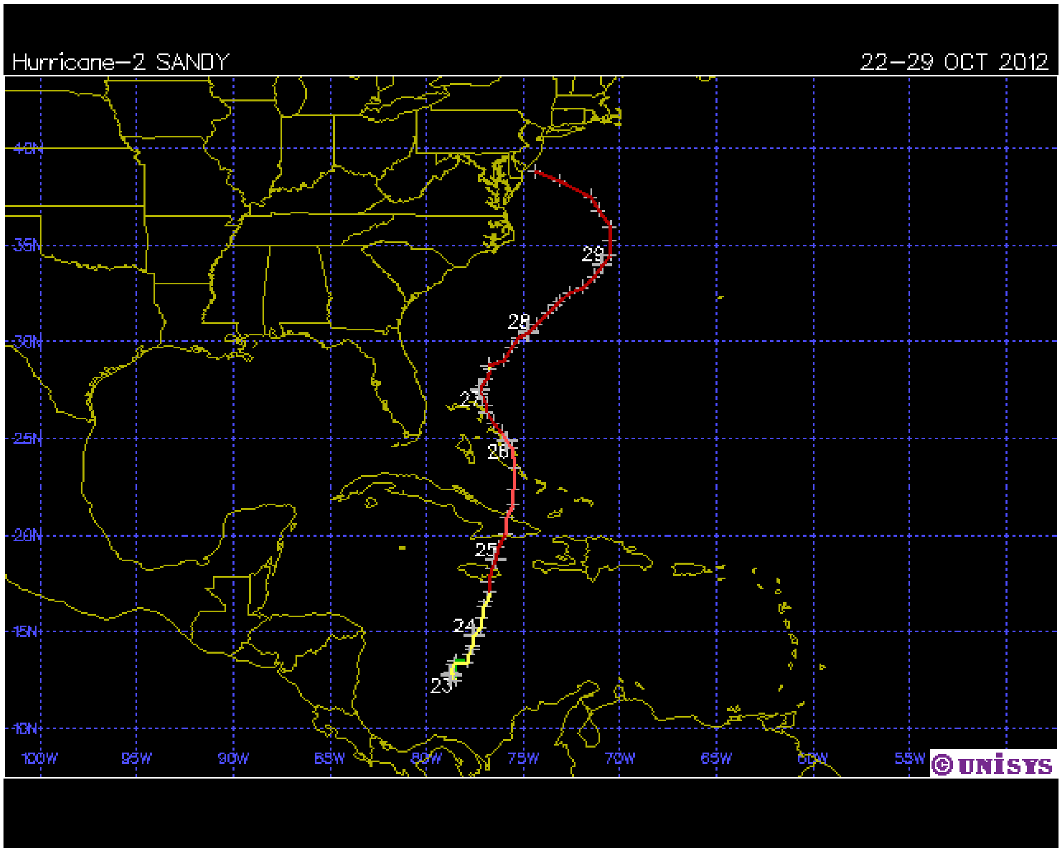

Figure C: Track of Hurricane Sandy. Figure courtesy of Unisys Weather. The red line indicates when Sandy was a hurricane, the yellow line indicates when Sandy was a tropical storm, while the green line indicates the system was a tropical depression.

One of the most impressive features of Hurricane Sandy was the sheer size of the system. While Sandy's landfall intensity of approximately 65 knots was not record-breaking, tropical storm-force wind radii extended out nearly 500 miles from the center. Figure D displays visible satellite imagery near the point of Hurricane Sandy's landfall. Note how large is the area of cloudiness generated by the system.

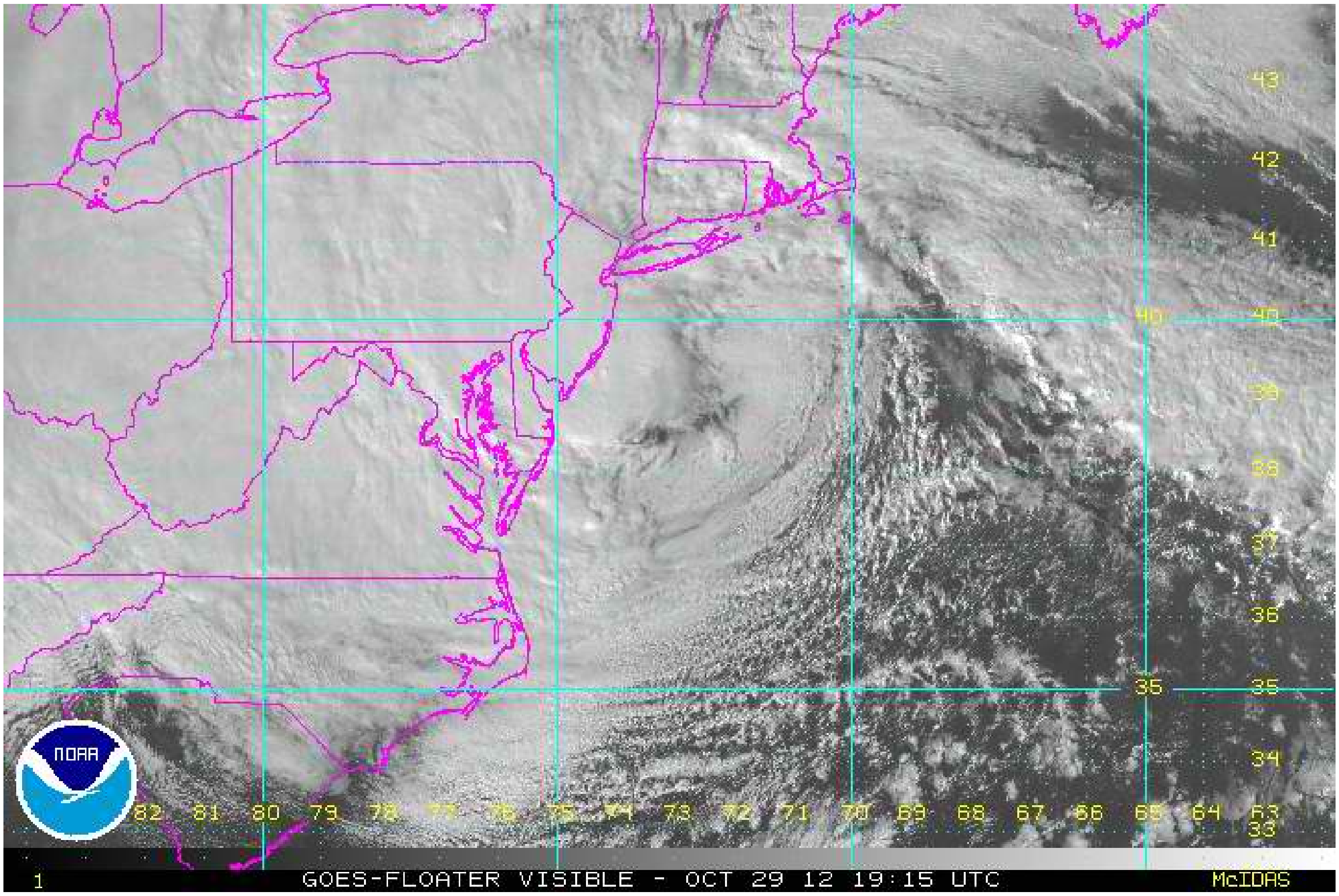

Figure D: Visible satellite image of Hurricane Sandy a few hours before landfall.

Figure E, courtesy of the National Hurricane Center, shows how large the area of tropical storm-force winds associated with Sandy was as it approached the southern New Jersey coast. Tropical storm-force winds extended from South Carolina to Maine!

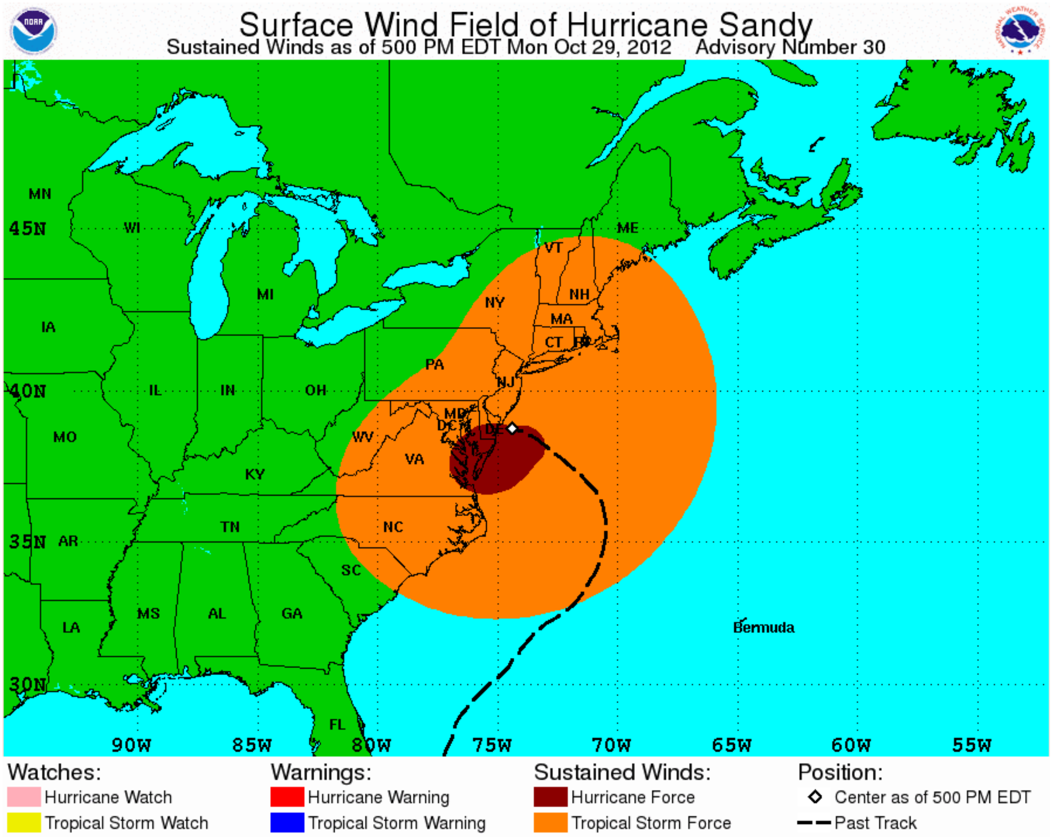

Figure E: Area of tropical storm-force winds associated with Hurricane Sandy as it approached the southern New Jersey coast.

One method of calculating total storm intensity is to evaluate Integrated Kinetic Energy (IKE). Colleague Brian McNoldy has recently made calculations for various United States landfalling systems, and Sandy's IKE is second only to that of Hurricane Isabel (2003) at landfall (Figure F). Isabel made landfall at a much less vulnerable and populated location than Sandy. Full documentation of IKE calculations is available in Powell and Reinhold (2007).

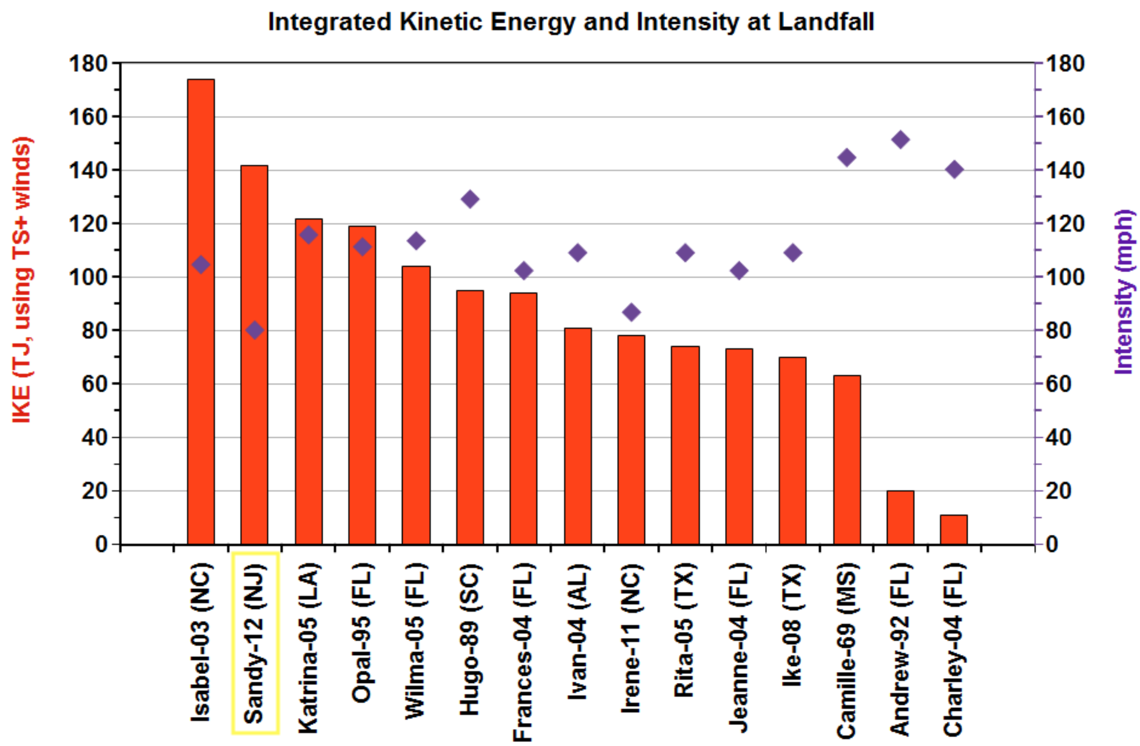

Figure F: Integrated kinetic energy for various TCs at United States landfall. Note the large IKE of Sandy, even larger than that associated with Hurricane Katrina, although Katrina's central pressure was much lower. Figure courtesy of Brian McNoldy.

The forecasts for Hurricane Sandy were remarkably accurate several days in advance. This is especially impressive, given the highly anomalous track that the TC took as it approached the coast. Figure G displays the official forecast from the National Hurricane Center on Thursday, October 25 over four days before it officially made landfall.

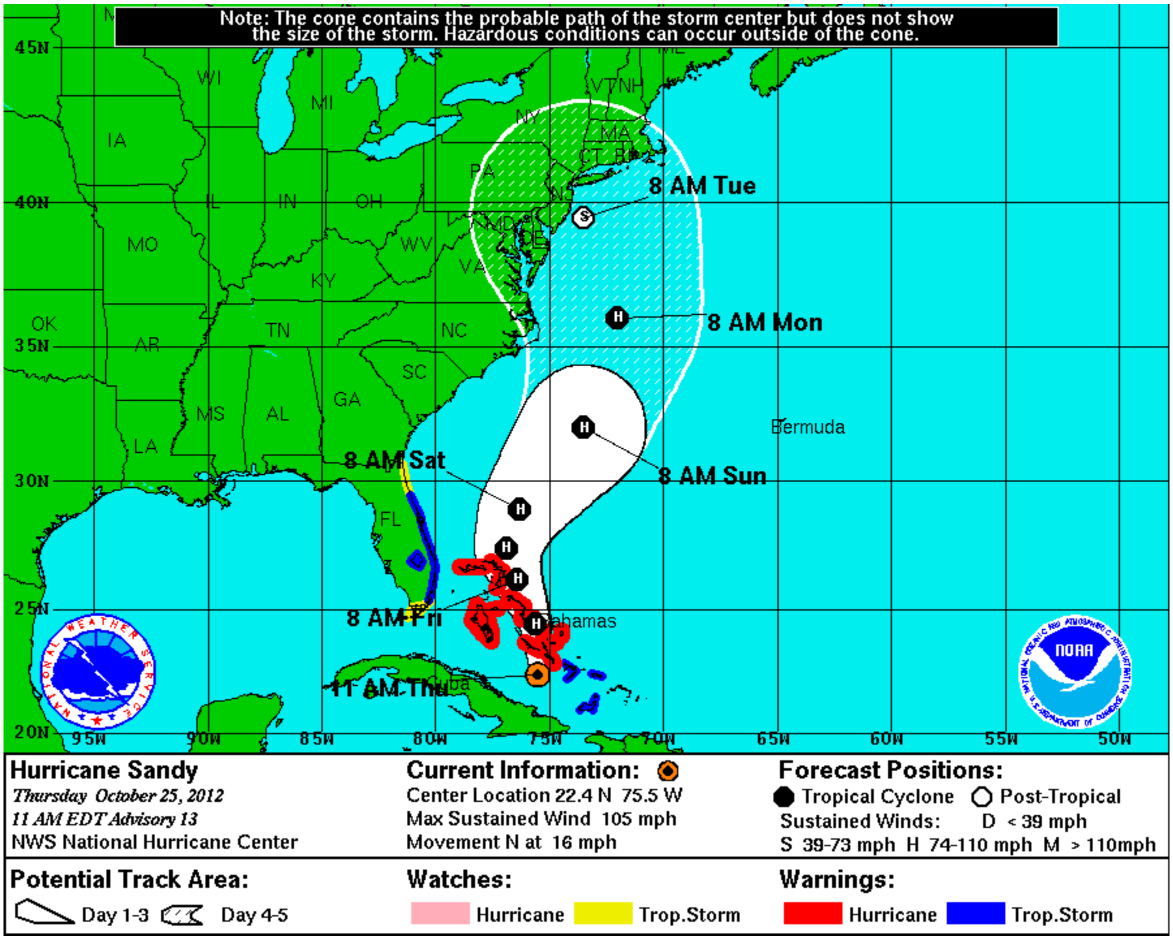

Figure G: National Hurricane Center official forecast of Hurricane Sandy issued on Thursday, October 25, four days before landfall.

The various global model guidance did a very successful job of forecasting Sandy as well. As an example, here is a forecast from the Global Forecast System (GFS) model for Sandy from October 25 for landfall. Note how large the TC is predicted to be (Figure H).

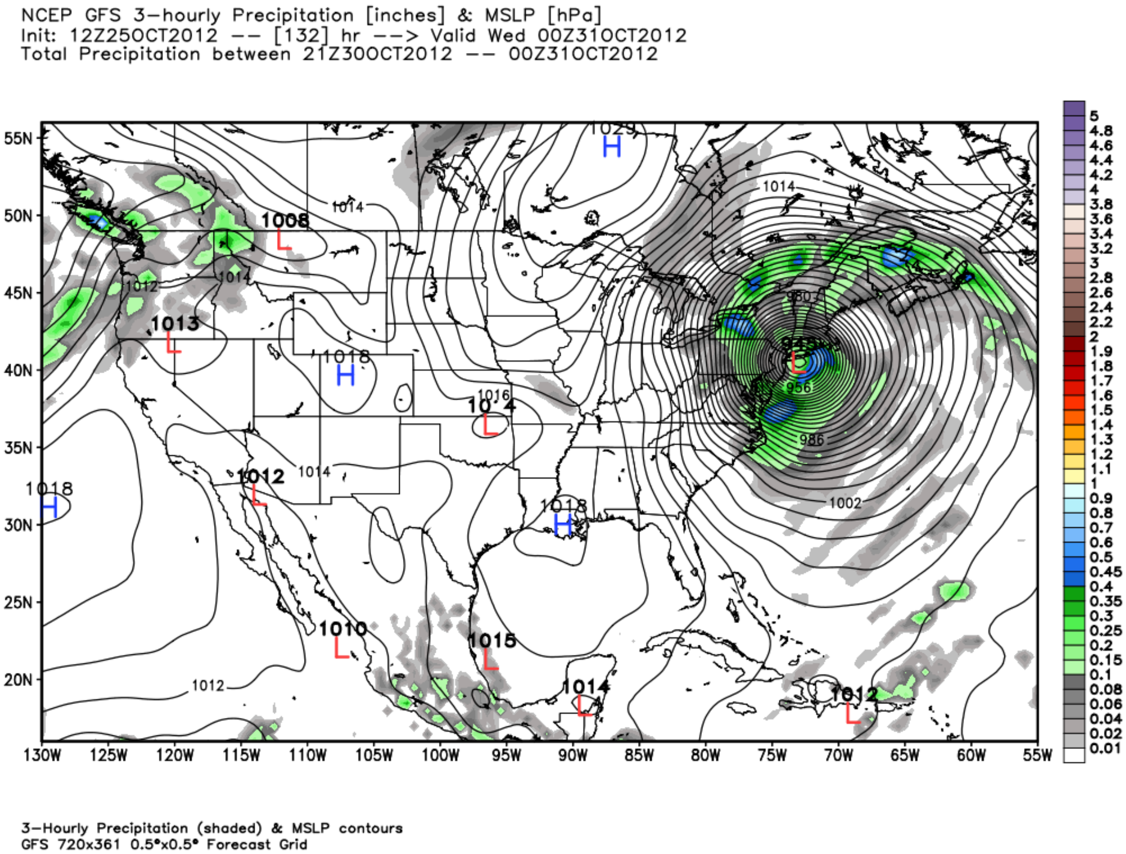

Figure H: Numerical forecast from the GFS model from Thursday, October 25, indicating a large hybrid TC approaching the mid-Atlantic/Northeast United States five days in the future. This was a remarkably accurate forecast.

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 2012

Figure I and Table 2 summarize Atlantic basin TC activity which occurred in 2012. The season was characterized by a very high amount of named storm activity, with well below-average activity experienced for major hurricanes.

3 Individual 2012 Tropical Cyclone Characteristics

The following is a brief summary of each of the named tropical cyclones in the Atlantic basin for the 2012 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.

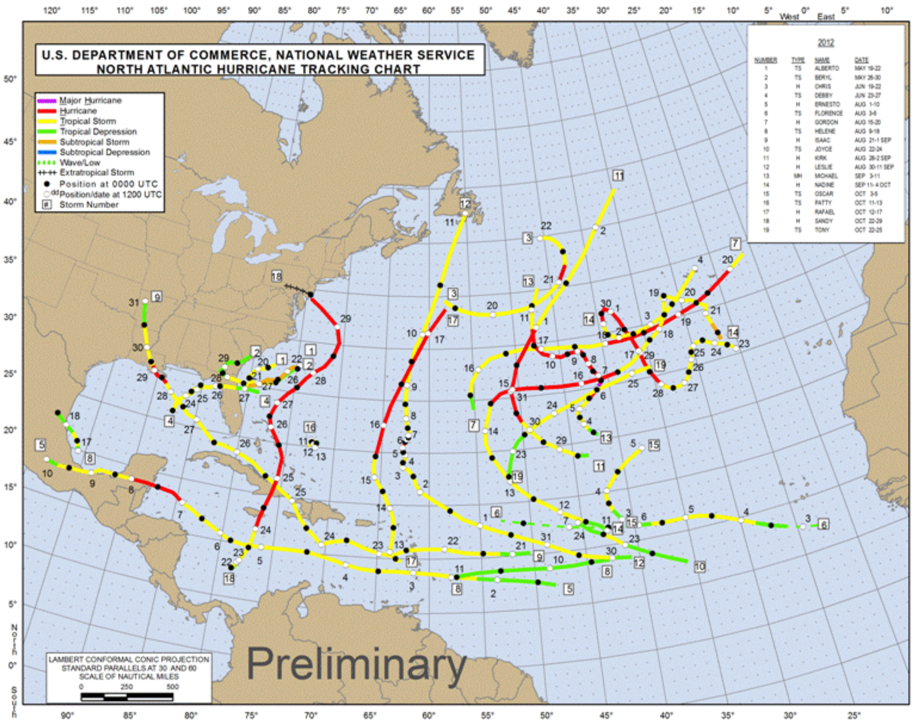

Figure I: Tracks of 2012 Atlantic Basin tropical cyclones. Figure courtesy of the National Hurricane Center (http://www.nhc.noaa.gov).

Table 2: Observed 2012 Atlantic basin tropical cyclone activity.

Highest Category	Name	Dates	Peak Sustained Winds (kts)/lowest SLP (mb)	NSD	HD	MHD	ACE	NTC
TS	Alberto (1)	May 19 - 21	50 kt/995 mb	2.50			1.7	2.6
TS	Beryl (2)	May 26 - 28	60 kt/993 mb	3.50			3.4	2.9
H-1	Chris (3)	June 19 - 22	65 kt/987 mb	3.00	0.25		2.9	5.7
TS	Debby (4)	June 23 - 26	50 kt/990 mb	4.00			3.2	3.1
H-1	Ernesto (5)	August 2 - 10	75 kt/979 mb	7.50	1.00		8.1	7.8
TS	Florence (6)	August 4 - 6	50 kt/1000 mb	2.00			1.5	2.4
H-2	Gordon (7)	August 16 - 20	95 kt/965 mb	4.75	2.00		8.4	7.5
TS	Helene (8)	August 17 - 18	35 kt/1005 mb	0.50			0.2	1.9
H-1	Isaac (9)	August 21 - 30	70 kt/968 mb	8.25	1.00		9.6	8.0
TS	Joyce (10)	August 23	35 kt/1006 mb	0.50			0.2	1.9
H-2	Kirk (11)	August 29 - September 2	90 kt/970 mb	4.75	2.00		7.4	7.5
H-1	Leslie (12)	August 30 - September 11	65 kt/980 mb	12.00	1.75		14.7	9.8
MH-3	Michael (13)	September 4 - 11	100 kt/964 mb	7.50	5.25	0.25	17.0	18.8
H-1	Nadine (14)	September 12 - 22, September 23 - October 4	80 kt/978 mb	21.25	5.00		26.1	15.2
TS	Oscar (15)	October 4 - 5	45 kt/997 mb	2.00			1.3	2.4
TS	Patty (16)	October 11 - 12	40 kt/1005 mb	1.25			0.7	2.2
H-1	Rafael (17)	October 12 - 17	80 kt/969 mb	5.25	2.25		7.4	7.9
H-2	Sandy (18)	October 22 - 29	95 kt/940 mb	7.25	5.50		13.6	10.8
TS	Tony (19)	October 24 - 25	45 kt/1000 mb	1.75			1.2	2.3
Totals	19			99.50	26.00	0.25	128.7	120.8

Tropical Storm Alberto (#1): Alberto formed late on May 19 from an area of low pressure off of the South Carolina coast (Figure 1). A blocking pattern over the mid-Atlantic forced Alberto southwestward early in its lifetime. A mid-level trough caused the system to recurve out to sea before it could make landfall along the northeast Florida coastline. Relatively strong vertical shear and dry air prevented Alberto from strengthening beyond a 45-knot tropical storm. It was declared a remnant low on May 22. Since 1980, only two seasons have started earlier than 2012. Ana formed on April 20 in 2003, and Andrea formed on May 9 in 2007.

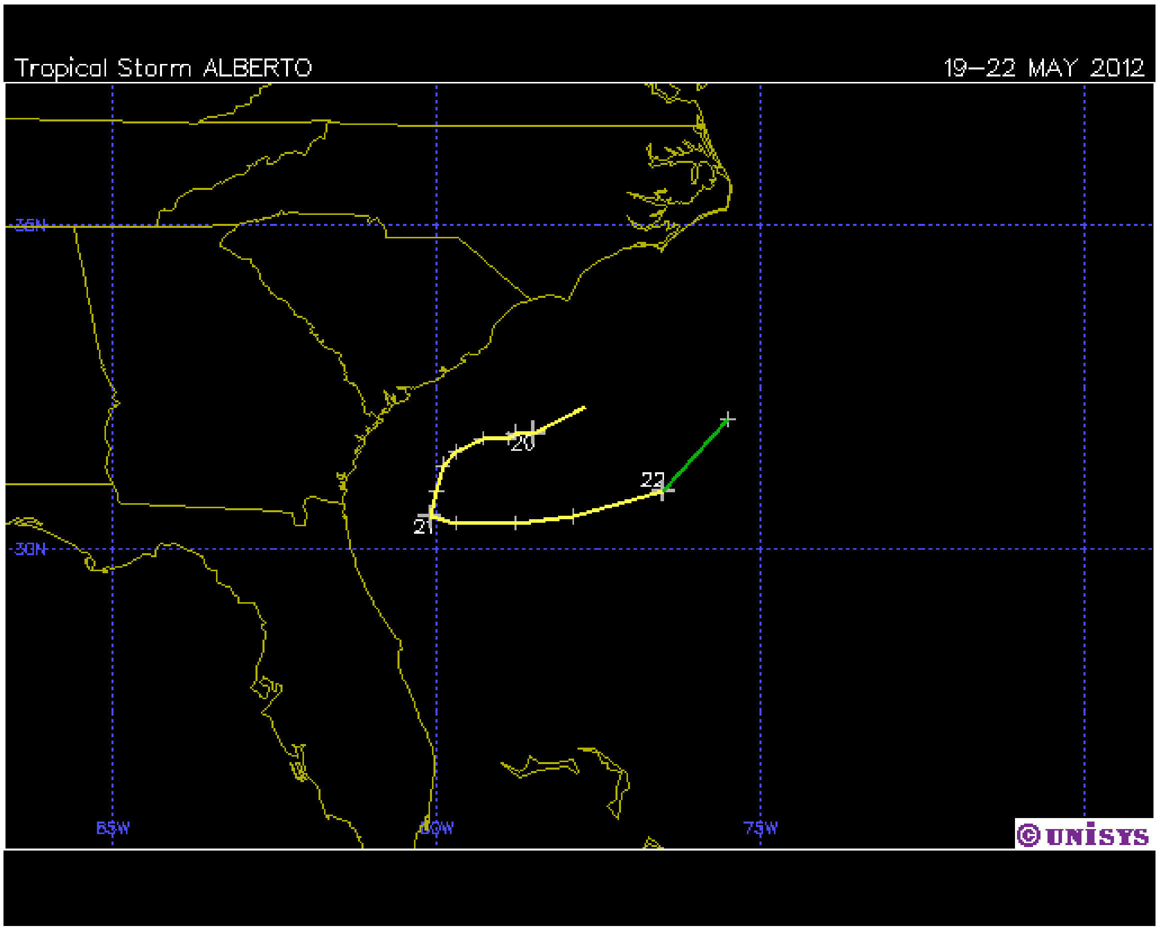

Figure 1: Track of Tropical Storm Alberto. Figure courtesy of Unisys Weather. The yellow line indicates a system at tropical storm strength, while the green line indicates tropical depression strength.

Name	NSD	HD	MHD	ACE	NTC
Alberto	2.50	0.00	0.00	1.7	2.6

Tropical Storm Beryl (#2): Beryl formed off of the South Carolina coast as a sub-tropical cyclone on May 26 (Figure 2). A ridge built near Beryl which drove the system southwestward towards the Florida coast. By the following day, Beryl began to intensify as it moved over warmer water, and it completed its transition to a tropical cyclone. The system made landfall as a 60-knot tropical cyclone near Jacksonville Beach, FL on May 28. It maintained tropical depression status as it began to recurve into the mid-latitudes, eventually being declared extra-tropical on May 30. Beryl was the strongest tropical cyclone on record to make US landfall before the official start of the Atlantic hurricane season on 1 June. The last TC to approach Jacksonville from the due east was Dora (1964).

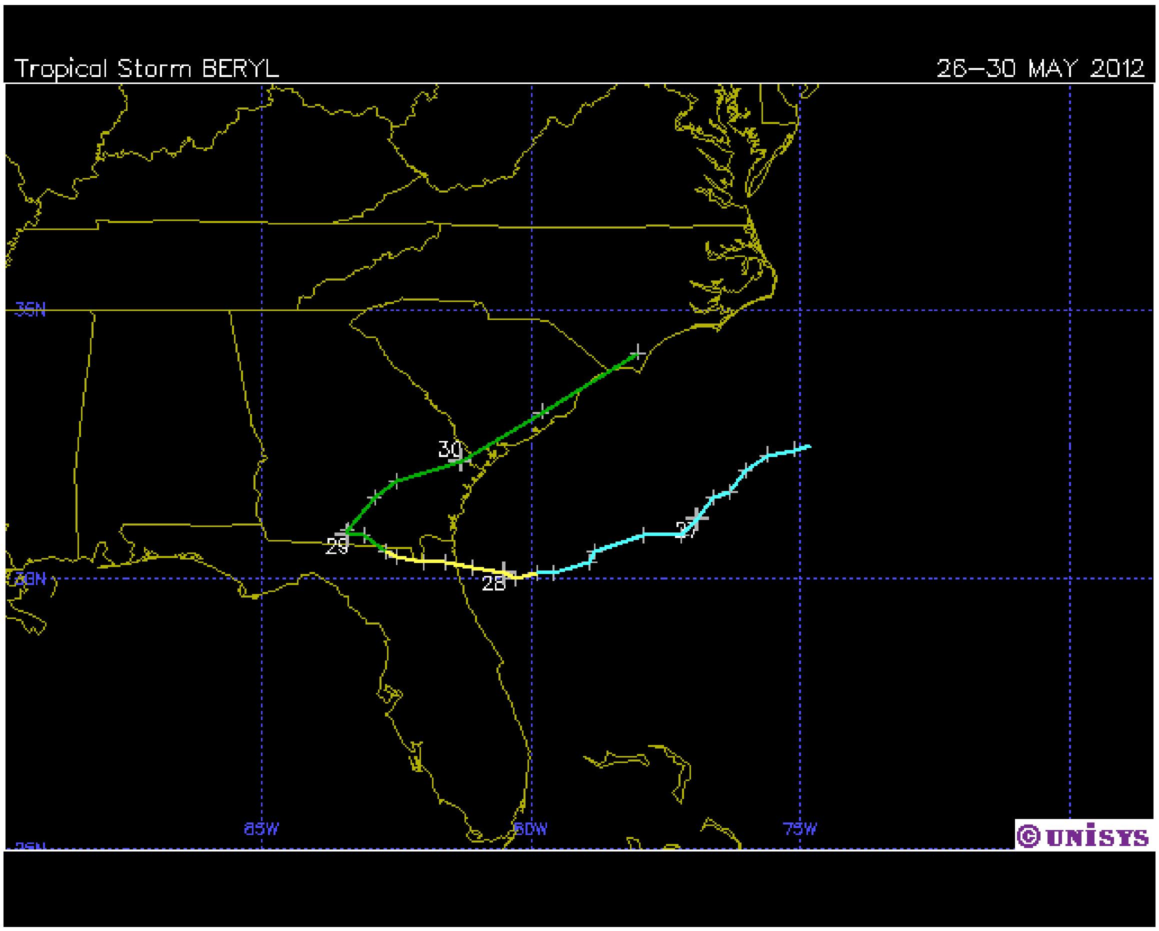

Figure 2: Track of Tropical Storm Beryl. Figure courtesy of Unisys Weather. The yellow line indicates a system at tropical storm strength, the blue indicates a sub-tropical system, while the green line indicates tropical depression strength.

Name	NSD	HD	MHD	ACE	NTC
Beryl	3.50	0.00	0.00	3.4	2.9

Hurricane Chris (#3): Chris developed from a low pressure area while moving northeast away from Bermuda (Figure 3). Low wind shear and relatively warm SSTs allowed for Chris to become a tropical cyclone on June 19. Despite moving over progressively cooler water, Chris surprisingly intensified briefly into a hurricane before weakening to a tropical storm again on June 21. It transitioned into an extra-tropical cyclone the following day.

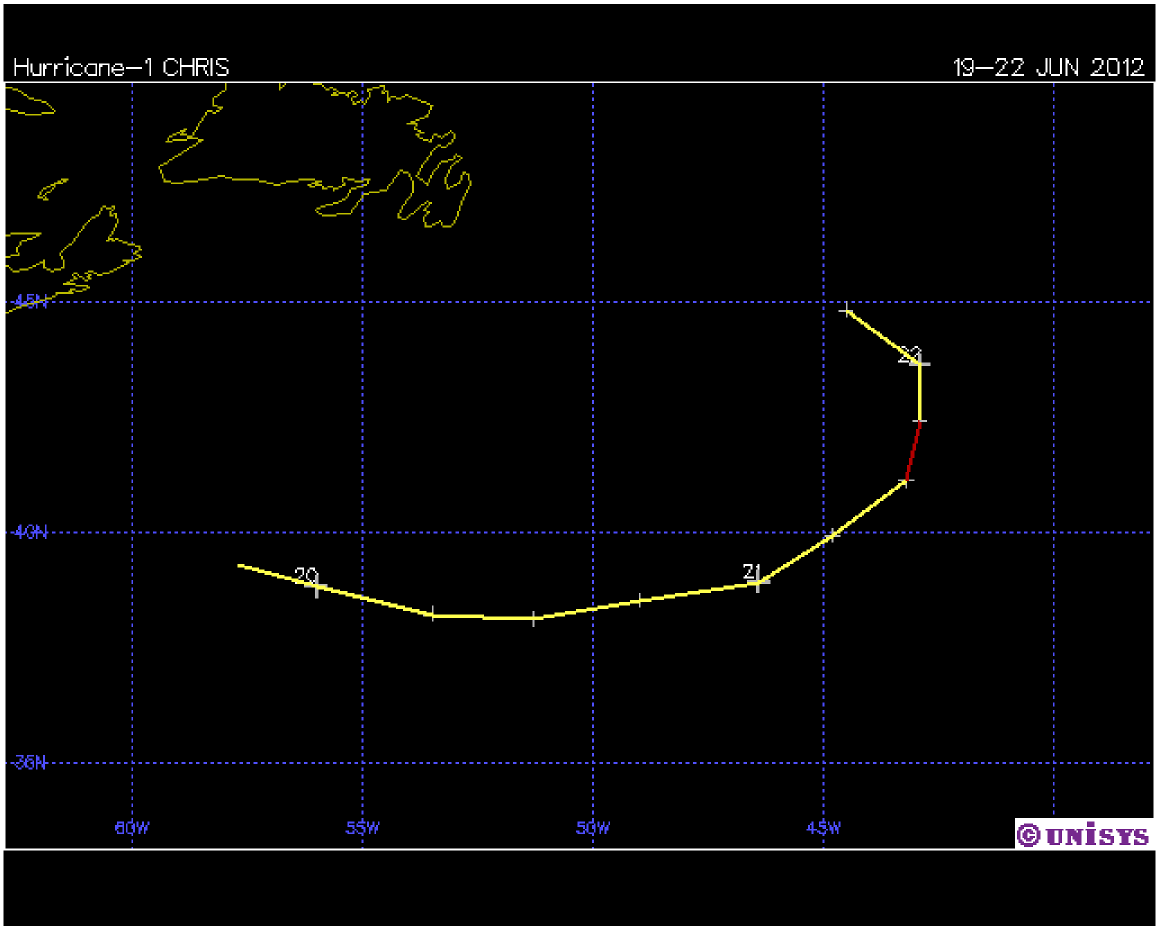

Figure 3: Track of Hurricane Chris. Figure courtesy of Unisys Weather. The red line indicates a system at hurricane strength, while the yellow line indicates a system at tropical storm strength.

Name	NSD	HD	MHD	ACE	NTC
Chris	3.00	0.25	0.00	2.9	5.7

Tropical Storm Debby (#4): Debby developed in the northern Gulf of Mexico from a low pressure area on June 23 (Figure 4). It intensified briefly before encountering relatively strong vertical shear and dry air which caused it to weaken to a marginal tropical storm before making landfall near Steinhatchee, Florida on June 26. It dissipated soon thereafter. Debby caused significant flooding in north Florida while transiting the state. It soon recurved and was declared post-tropical on June 27.

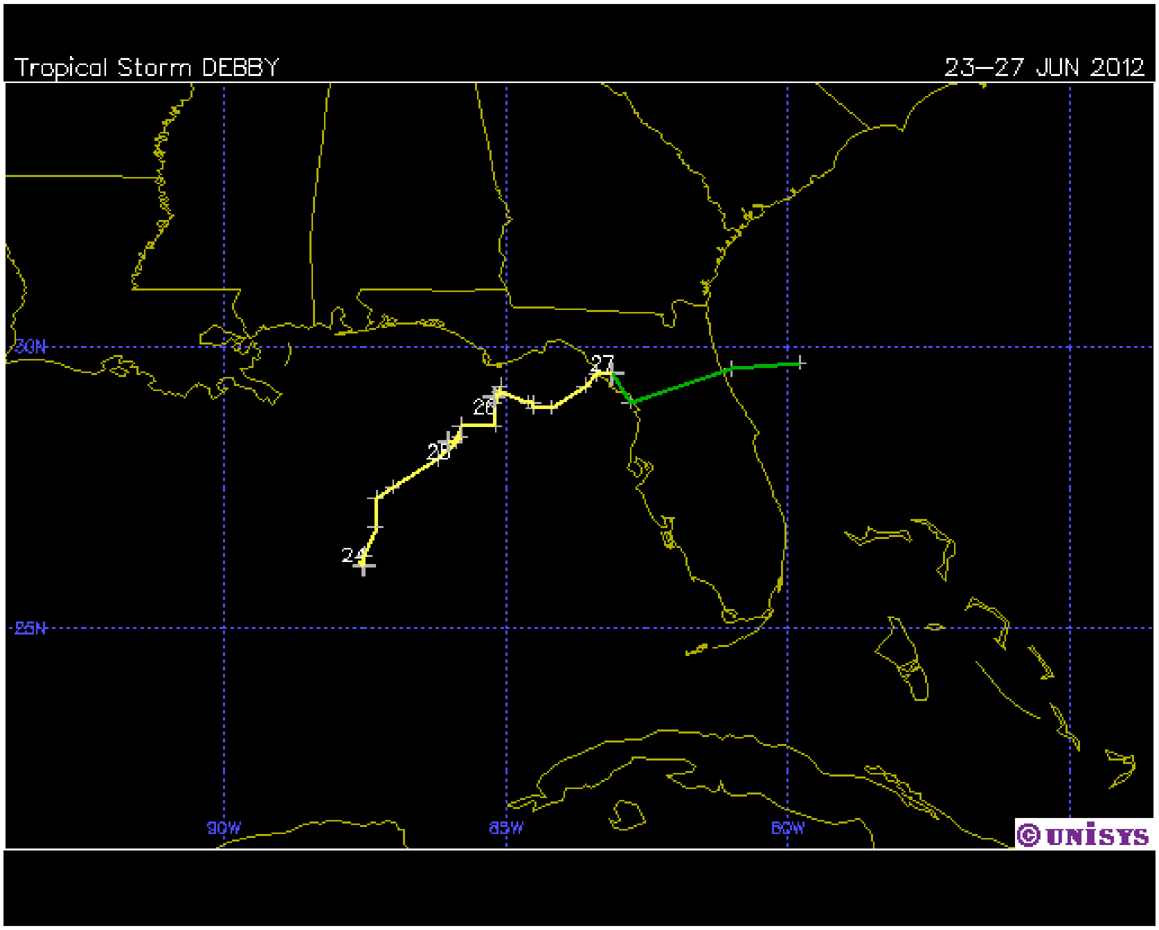

Figure 4: Track of Tropical Storm Debby. The yellow line indicates a system at tropical storm strength, while the green line indicates a system at tropical depression strength.

Name	NSD	HD	MHD	ACE	NTC
Debby	4.00	0.00	0.00	3.2	3.1

Hurricane Ernesto (#5): Ernesto formed from a tropical wave on August 1 in the central tropical Atlantic. It intensified into a tropical storm the following day. It moved rapidly westward through the northern Windward Islands, bringing tropical storm-force winds to Saint Lucia. Ernesto slowly intensified as it continued its brisk trek through the Caribbean. Dry air prevented rapid intensification, despite Ernesto being in area of warm sea surface temperatures and low vertical wind shear. As Ernesto moved into the western Caribbean, it encountered a more favorable moisture environment, and it became a hurricane on August 7. It made landfall in the southern part of the Yucatan Peninsula early on August 8 as a Category 1 hurricane. It weakened significantly the following day as it traversed the Yucatan. Ernesto briefly re-strengthened as it emerged over the southern Bay of Campeche, before making a second landfall in southern Mexico as a strong tropical storm. It dissipated on August 10 as it tracked over the high terrain of southern Mexico. Seven fatalities in southern Mexico were attributed to Ernesto.

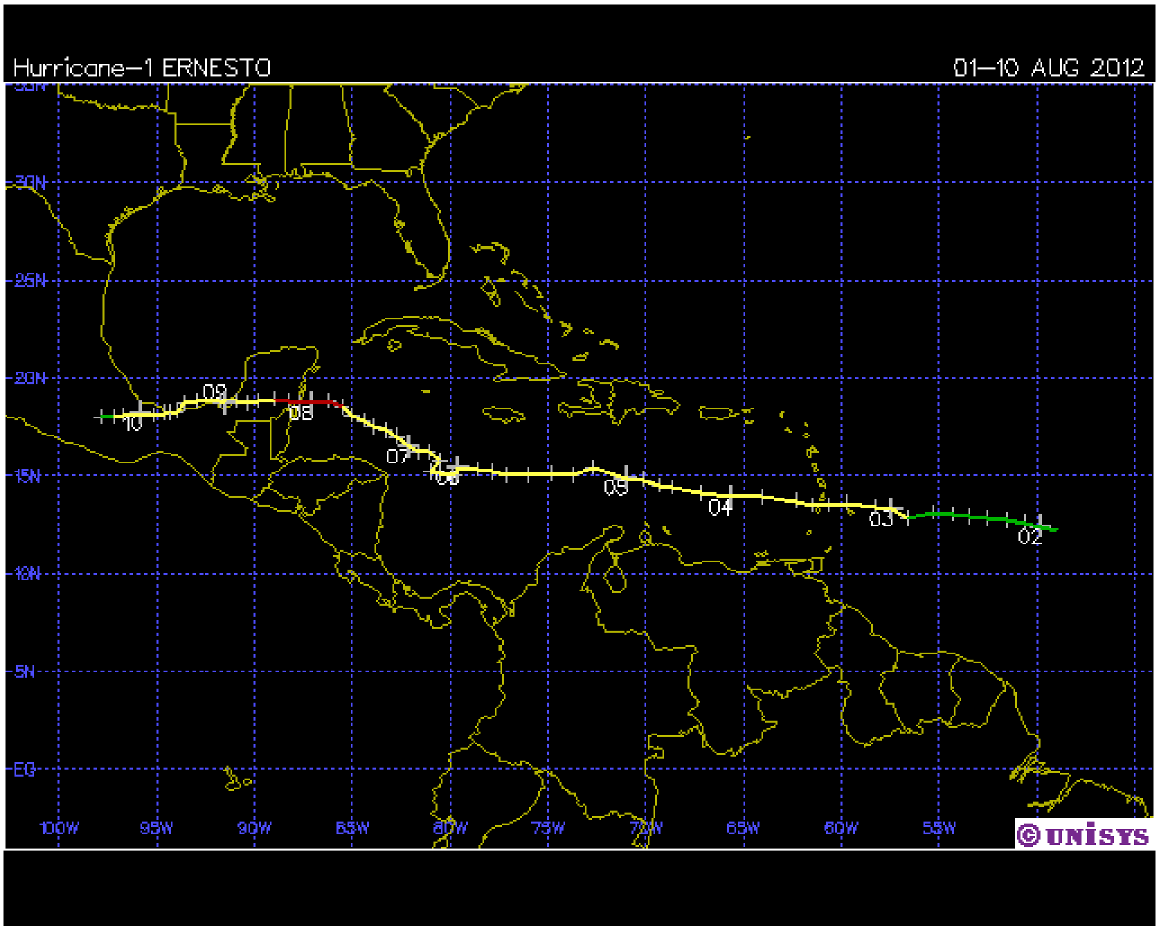

Figure 5: Track of Hurricane Ernesto. Figure courtesy of Unisys Weather. The red line indicates a system at hurricane strength, the yellow line indicates a system at tropical storm strength, while the green line indicates tropical depression strength.

Name	NSD	HD	MHD	ACE	NTC
Ernesto	7.50	1.00	0.00	8.1	7.8

Tropical Storm Florence (#6): Florence developed from a tropical wave in the eastern part of the Atlantic early on August 4. It became a tropical storm later that day as it moved northwestward. It strengthened to reach its maximum intensity of 50 knots early on August 5, before encountering cooler waters, drier air and increased vertical wind shear. All three of these factors caused the system to weaken. By early on August 6, Florence was downgraded to a tropical depression and a remnant low later that day.

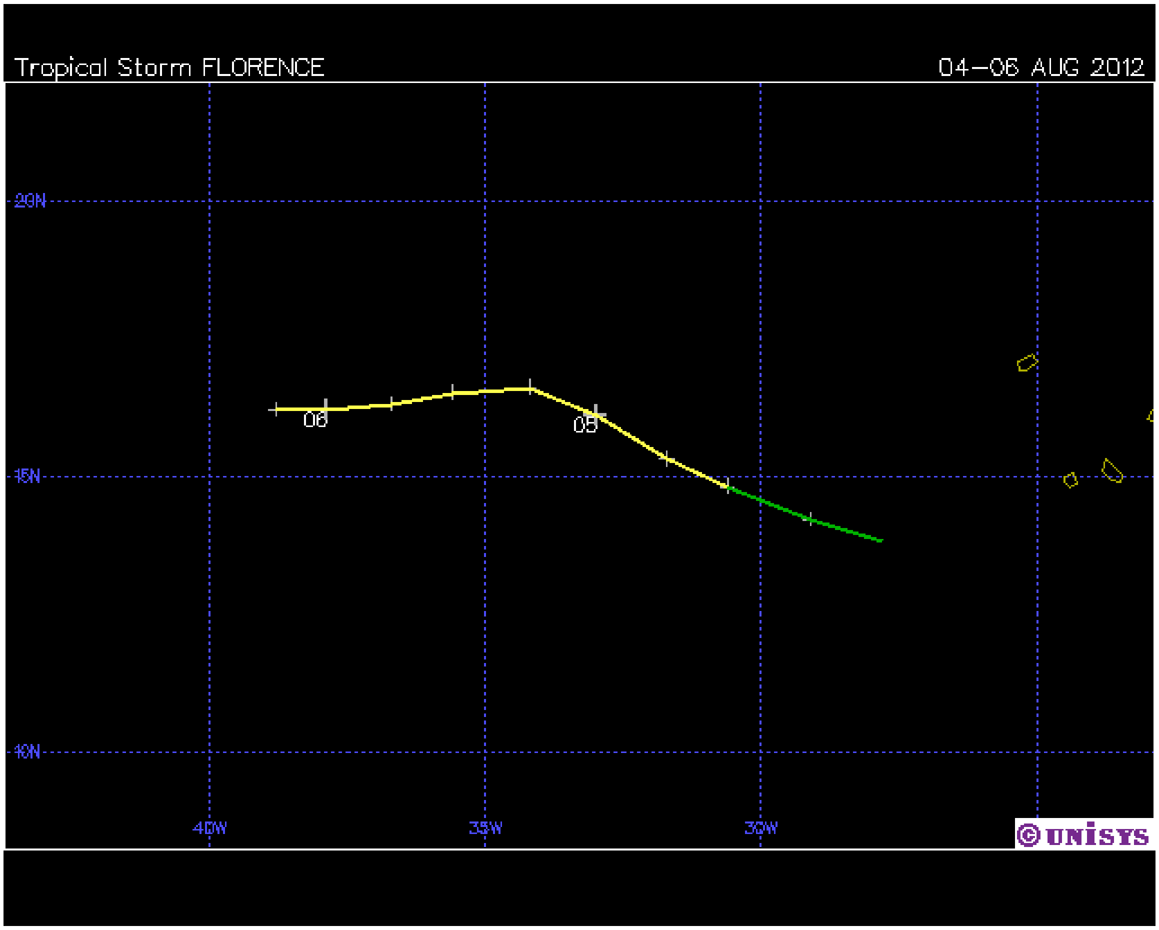

Figure 6: Track of Tropical Storm Florence. Figure courtesy of Unisys Weather. The yellow line indicates a system at tropical storm strength, while the green line indicates tropical depression strength.

Name	NSD	HD	MHD	ACE	NTC
Florence	2.00	0.00	0.00	1.5	2.4

Hurricane Gordon (#7): Gordon developed in the Central Atlantic from an area of low pressure on August 15 (Figure 7). It intensified to a tropical storm the following day as it moved northward. Gordon continued to develop and nearly reached hurricane strength before weakening slightly. It then re-intensified, reaching hurricane status on August 18. Relatively low vertical wind shear and warm sea surface temperatures allowed Gordon to continue intensifying, reaching a maximum intensity of 95 knots early on August 19. It began to weaken as it encountered cooler waters and stronger shear, although it was still a hurricane when it made landfall near Santa Maria in the Azores Islands. Gordon became a post-tropical cyclone late on August 20. No significant damage or fatalities were reported from Hurricane Gordon.

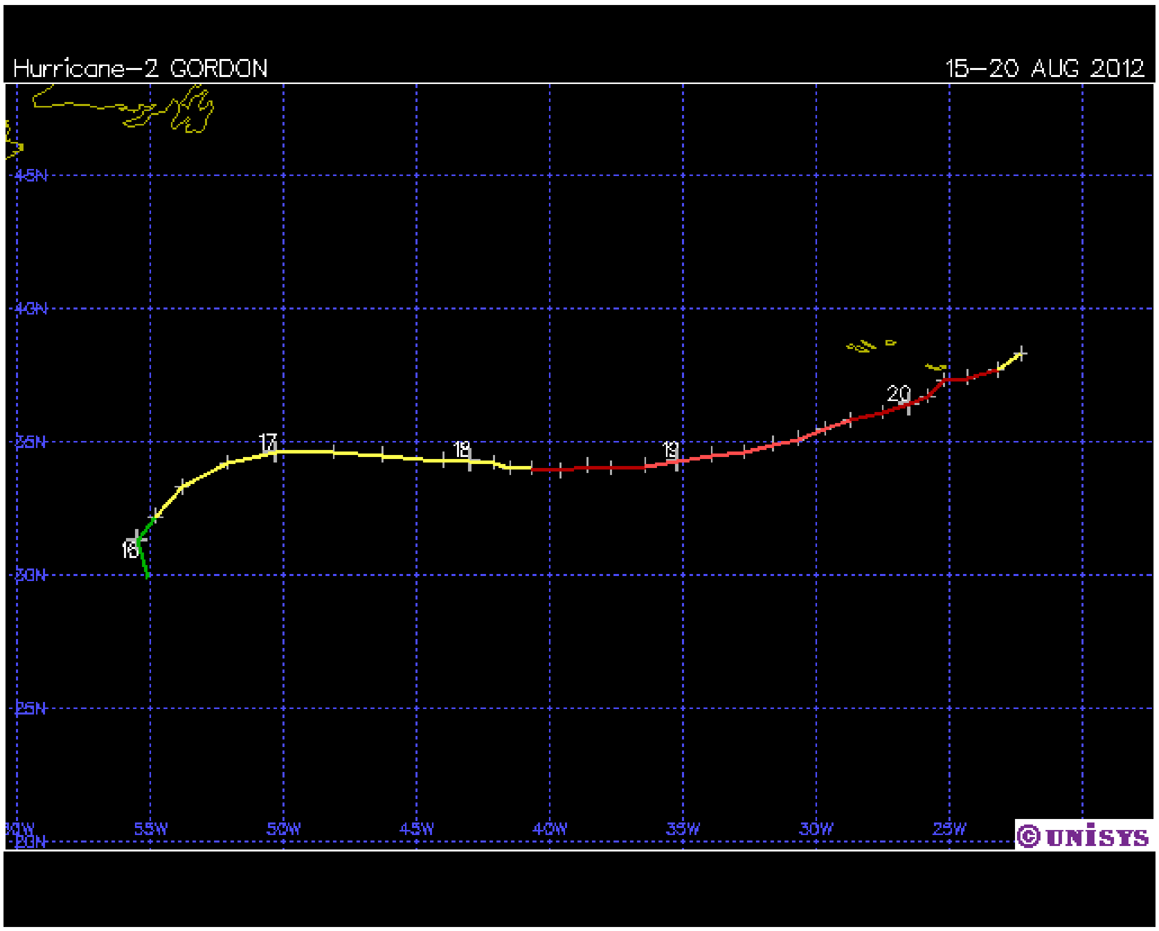

Figure 7: Track of Hurricane Gordon. Figure courtesy of Unisys Weather. The red line indicates a system at hurricane strength, the yellow line indicates a system at tropical storm strength, while the green line indicates tropical depression strength.

Name	NSD	HD	MHD	ACE	NTC
Gordon	4.75	2.00	0.00	8.4	7.5

Tropical Storm Helene (#8): Helene developed from a tropical wave in the central tropical Atlantic on August 9 (Figure 8). While Helene was in an area of relatively warm SSTs and low vertical wind shear, it was hindered by dry air and did not reach tropical storm status. By the time it approached the islands, southwesterly vertical wind shear increased, and Helene degenerated into a tropical wave. It continued as a wave across the Caribbean and as it transited the Yucatan Peninsula. When it reached the Bay of Campeche, it intensified into a tropical storm. It made landfall near Tampico, Mexico, on August 17, bringing heavy rains as it did so. Helene became a remnant low while moving northwestward over northern Mexico the following day. The tropical wave that spawned Helene was responsible for two deaths in Trinidad and Tobago. Relatively little damage occurred in Veracruz, Mexico from Helene.

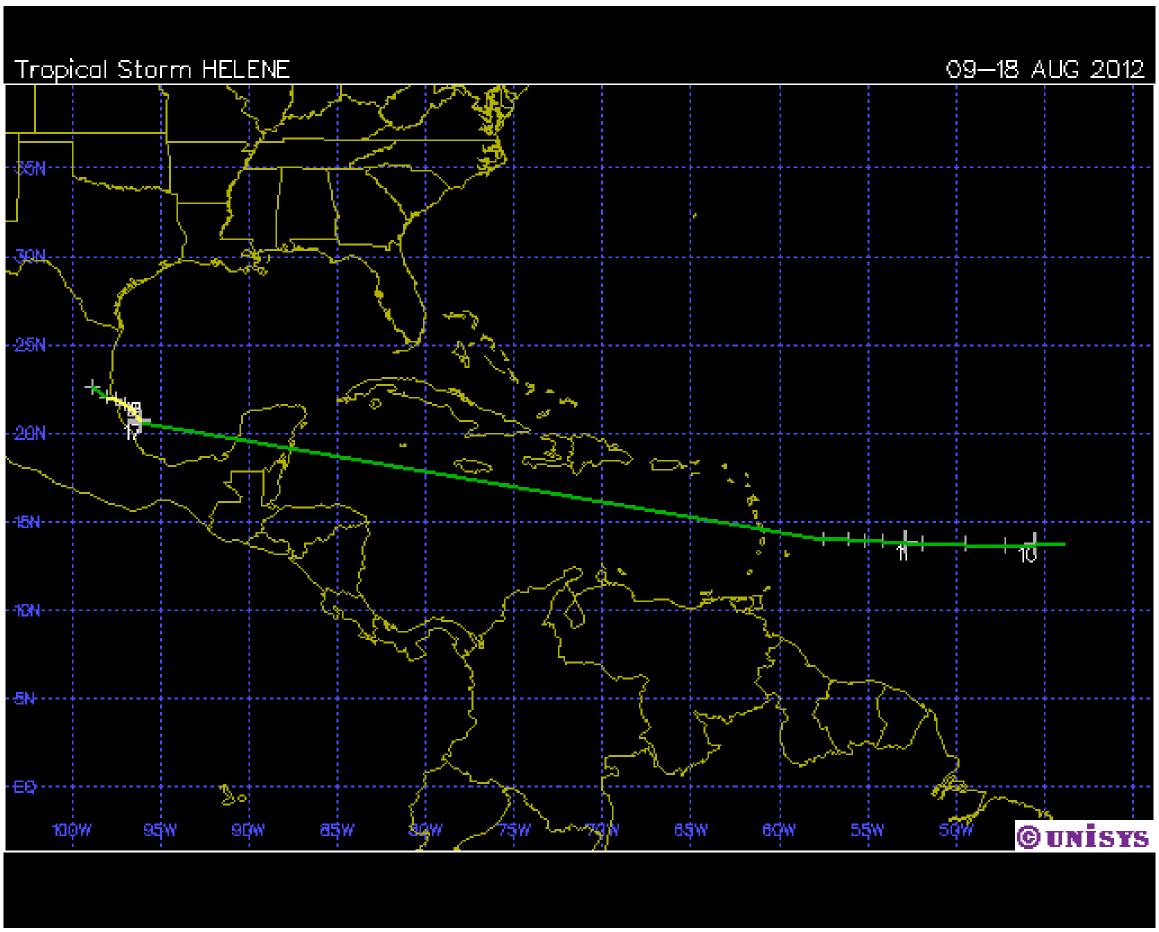

Figure 8: Track of Tropical Storm Helene. Figure courtesy of Unisys Weather. The yellow line indicates a system at tropical storm strength, while the green line indicates tropical depression or tropical wave strength.

Name	NSD	HD	MHD	ACE	NTC
Helene	0.50	0.00	0.00	0.2	1.9

Hurricane Isaac (#9): Isaac formed in the central tropical Atlantic from a tropical wave on August 21 (Figure 9). It was upgraded to a tropical storm later that day. The circulation battled dry air intrusions during the initial portion of its lifetime and did not strengthen much as it passed through the Lesser Antilles. By late on August 23, Isaac began to strengthen. Isaac reached an intensity of 60 knots before making landfall in Haiti on August 25. It weakened somewhat after tracking over Haiti. It made a second landfall in Cuba and then curved northwestward, passing west of the Florida Keys as it emerged into the Gulf of Mexico. Mid-level dry air continued to prevent rapid strengthening of Isaac. It finally achieved hurricane status as it neared the coast of Louisiana on August 28. It made landfall near the Mississippi River Delta late on August 28, wobbled along the coast of Louisiana for several hours, then made a second landfall on August 29 near Port Fourchon, Louisiana. Isaac slowly moved inland, weakening as it did so, and was downgraded to a tropical depression on August 30. It was responsible for a total of 41 deaths, including 21 in Haiti and 7 in the United States. Total damage from Isaac may exceed two billion dollars, mostly due to flooding rains.

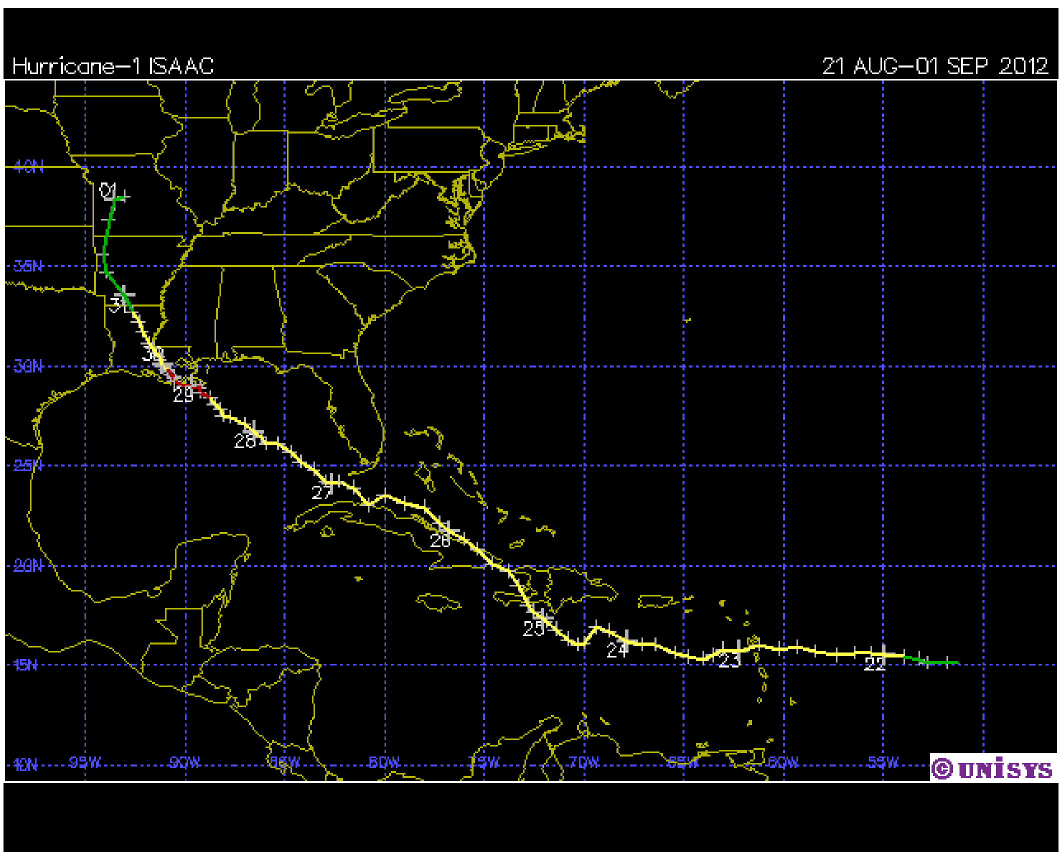

Figure 9: Track of Hurricane Isaac. Figure courtesy of Unisys Weather. The red line indicates a system at hurricane strength, the yellow line indicates a system at tropical storm strength and the green line indicates a system at tropical depression strength.

Name	NSD	HD	MHD	ACE	NTC
Isaac	8.25	1.00	0.00	9.6	8.0

Tropical Storm Joyce (#10): Tropical Storm Joyce was a very short-lived TC (Figure 10). It developed from a tropical wave on August 22 and intensified into a tropical storm the following day. Strong southerly shear displaced the deep convection well north of the center, and it was downgraded to a tropical depression after being a tropical storm for only 12 hours. Continued strong shear and dry air entrainment caused complete dissipation of the system by August 24.

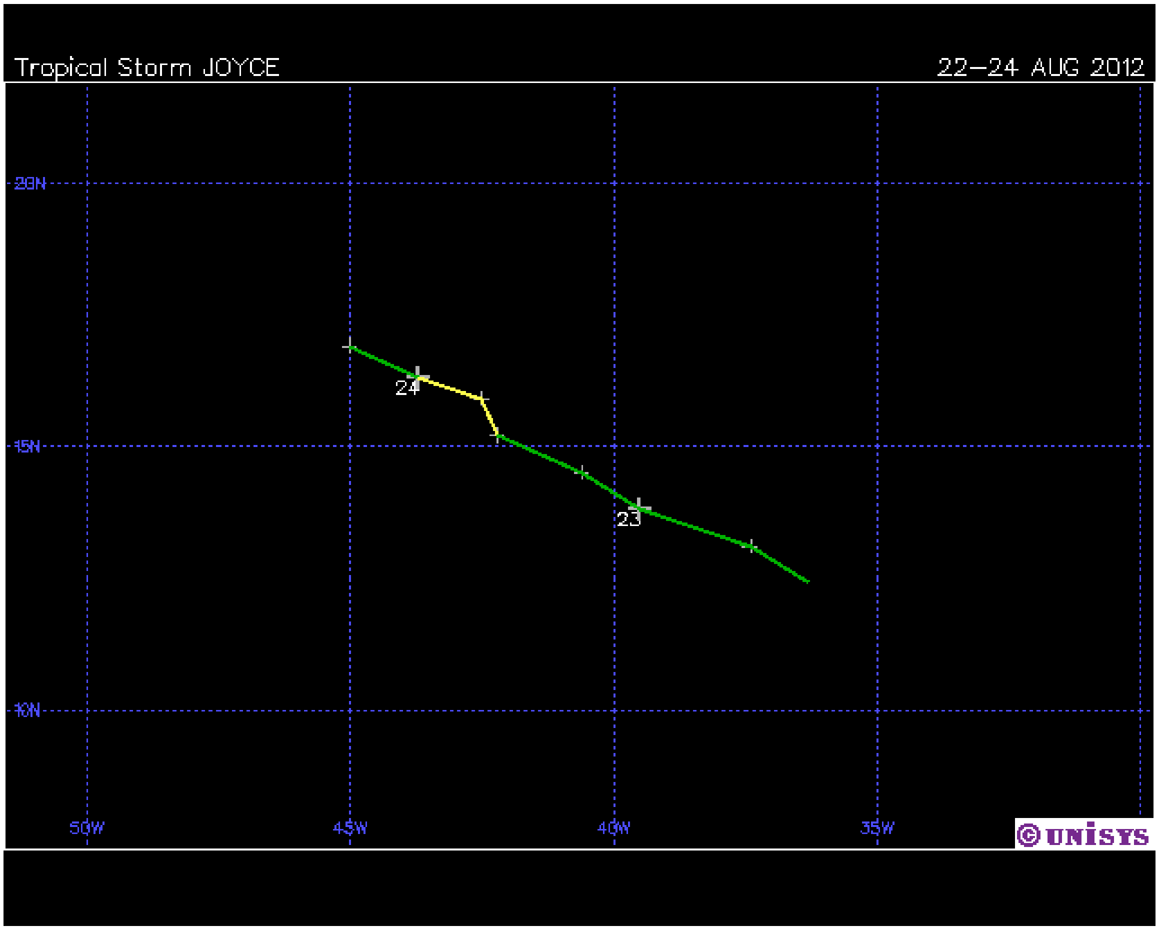

Figure 10: Track of Tropical Storm Joyce. Figure courtesy of Unisys Weather. The yellow line indicates a system at tropical storm strength, while the green line indicates a system at tropical depression strength.

Name	NSD	HD	MHD	ACE	NTC
Joyce	0.50	0.00	0.00	0.2	1.9

Hurricane Kirk (#11): Kirk was first identified as a tropical depression while moving through the Central Atlantic on August 28 (Figure 11). It was upgraded to a tropical storm soon after, as a deep convective burst was generated near the center of the circulation. Moderate southwesterly shear inhibited rapid intensification early in its lifecycle, but Kirk did slowly intensify into a hurricane on August 30. It continued to strengthen to reach its maximum intensity of 90 knots on August 31 in an environment of relatively low vertical shear and warm sea surface temperatures. Cooler water and stronger shear caused Kirk to weaken back to a tropical storm on September 1, and it became extra-tropical the following day.

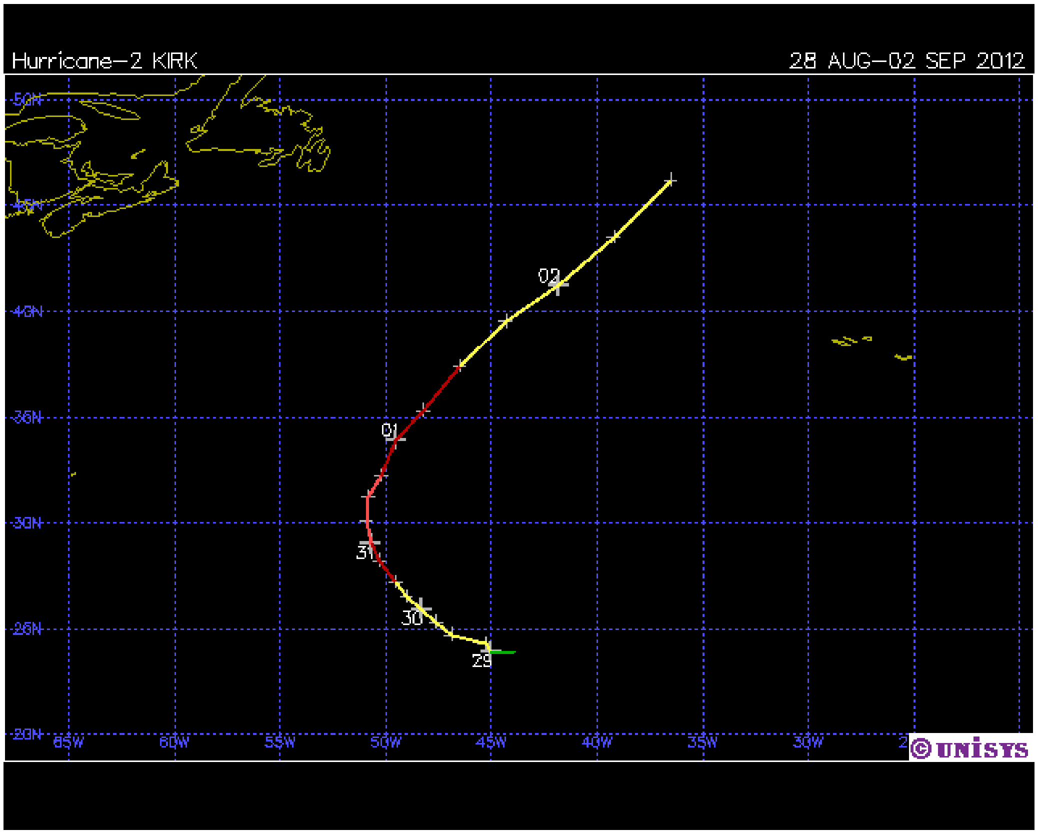

Figure 11: Track of Hurricane Kirk. Figure courtesy of Unisys Weather. The red line indicates a system at hurricane strength, the yellow line indicates a system at tropical storm strength, while the green line indicates tropical depression strength.

Name	NSD	HD	MHD	ACE	NTC
Kirk	4.75	2.00	0.00	7.4	7.5

Hurricane Leslie (#12): Leslie formed from an easterly wave in the central tropical Atlantic on August 30 (Figure 12). It intensified into a tropical storm six hours later and continued to intensify into a strong tropical storm the following day. Strong northwesterly shear prevented Leslie from becoming a hurricane, and it weakened back to a 50-knot TC on September 2. The system moved very slowly northward and eventually reached hurricane strength as the shear relaxed. Leslie also grew in size to become a very large tropical cyclone during this time, with 34-knot wind radii extending to 200 nautical miles away from the center of the TC by late on September 5. By September 7, Leslie weakened back to a tropical storm, primarily due to the fact that the TC drove significant levels of upwelling. The system finally began moving northward on September 8, bringing tropical storm-force winds to Bermuda as it did so. By September 10, Leslie accelerated northeastward and made landfall in Newfoundland. It re-intensified to a 60-knot tropical storm as it underwent extra-tropical transition. By later on September 11, it was absorbed by a cold front. Leslie caused minor damage in Bermuda and in Newfoundland, but no fatalities were reported.

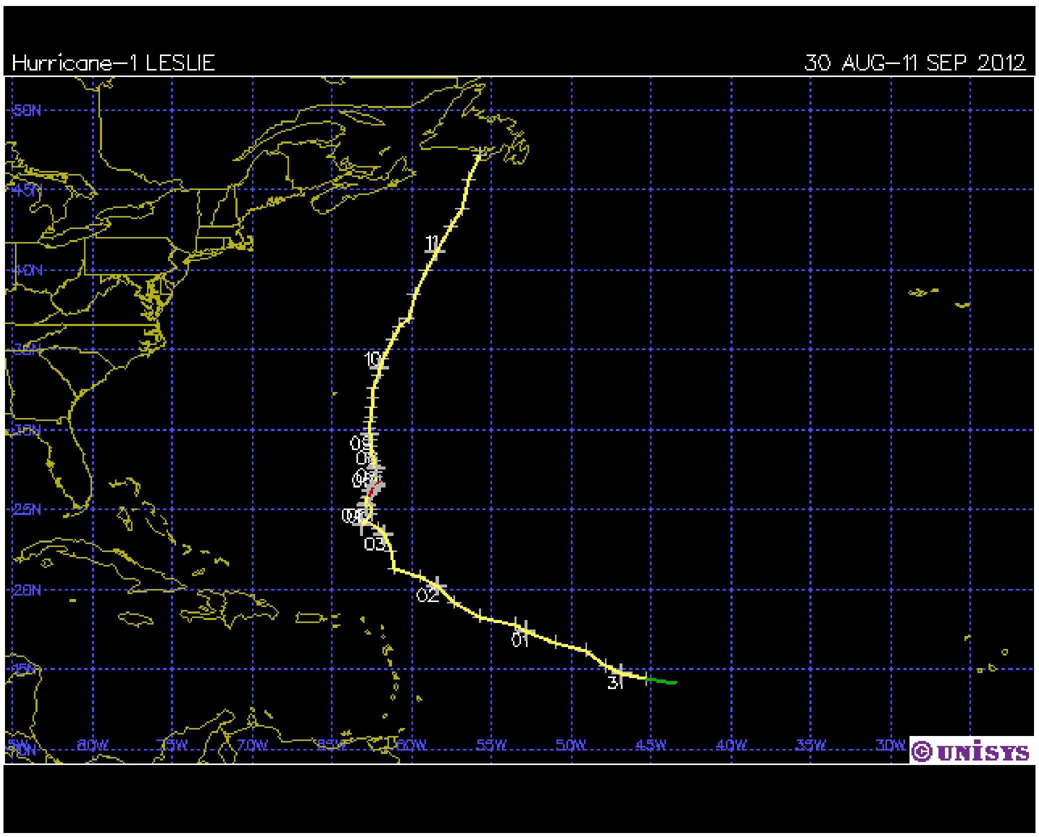

Figure 12: Track of Hurricane Leslie. Figure courtesy of Unisys Weather. The red line indicates a system at hurricane strength, the yellow line indicates a system at tropical storm strength, while the green line indicates a system at tropical depression strength.

Name	NSD	HD	MHD	ACE	NTC
Leslie	12.00	1.75	0.00	14.7	9.8

Hurricane Michael (#13): Michael formed from an upper-level low in the northeast tropical Atlantic on September 3 (Figure 13). Despite being in a somewhat marginal environment for intensification, it intensified into a hurricane on September 6 and a major hurricane later that day. It weakened somewhat over the next 24 hours, as it slowed down, due to being trapped between two upper-level lows. The tenacious system remained as a Category 2 hurricane for the next couple of days. By late on September 9, a weakening trend occurred, as stronger southwesterly shear began to impinge on the TC. Michael weakened to a tropical storm early on September 11 and was declared extra-tropical shortly thereafter, as strong northeasterly shear decimated the system.

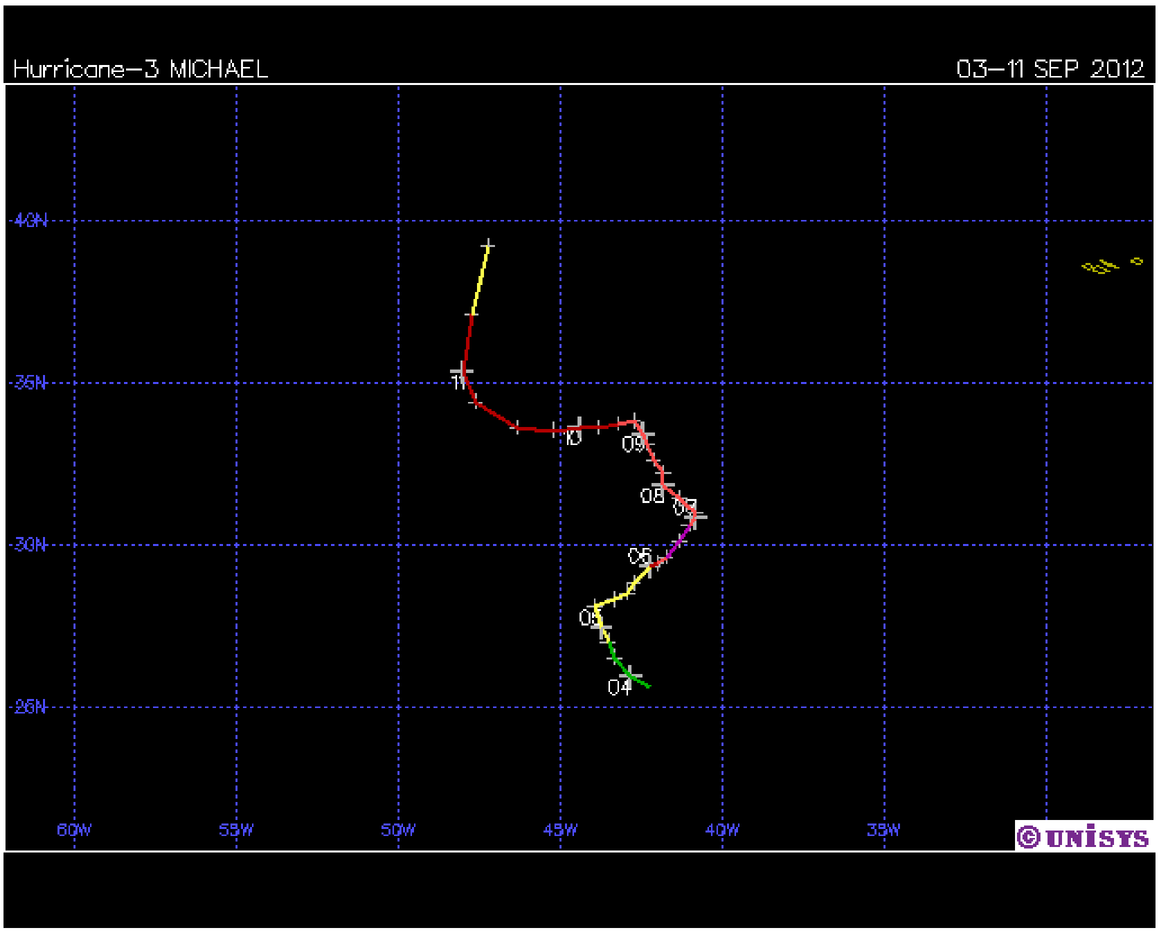

Figure 13: Track of Hurricane Michael. Figure courtesy of Unisys Weather. The purple line indicates a system at major hurricane strength, the red line indicates a system at hurricane strength, the yellow line indicates a system at tropical storm strength, while the green line indicates tropical depression strength.

Name	NSD	HD	MHD	ACE	NTC
Michael	7.50	5.25	0.25	17.0	18.8

Hurricane Nadine (#14): Nadine formed from a tropical wave over the central tropical Atlantic on September 11 (Figure 14). It intensified into a tropical storm the following day as it moved northwestward. It continued moving northwestward and intensified into a hurricane early on September 15. It began recurving towards the north and east over the next couple of days and weakened back to a tropical storm as it encountered stronger westerly shear. Over the next couple of days, Nadine continued to weaken and slow down, as it encountered an area of weaker steering flow. Nadine then restrengthened, with some help from baroclinic influences, as it continued to move slowly eastward near the Azores. It slowly transitioned into a sub-tropical cyclone on September 21 and was declared post-tropical early on September 22. Nadine continued to drift southwestward, and convection re-developed near its center, which caused the reinstatement of TC advisories on September 23. It continued its westward drift and then began to turn towards the northwest, as it neared the western periphery of a high pressure area. It began to intensify as it encountered somewhat warmer SSTS and weaker vertical wind shear. Nadine regained hurricane status on September 28. By September 30, Nadine again encountered stronger vertical shear which caused the TC to weaken as it made a clockwise loop. It was downgraded to a tropical storm on October 1. It began to encounter strong northwesterly vertical wind shear and accelerated towards the northeast as a strong upper-level trough approached the TC. It made a second pass through the Azores, before finally completing its second post-tropical transition on October 4. Nadine accrued the most named storm days for a single TC since Ginger in 1971.

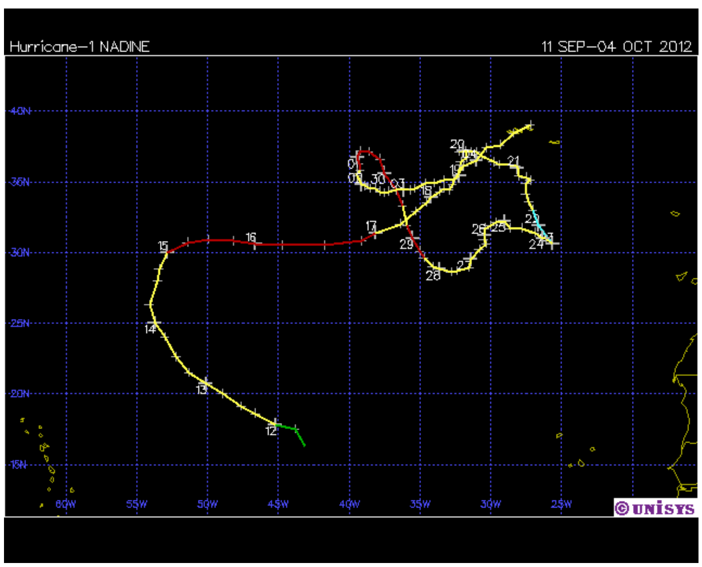

Figure 14: Track of Hurricane Nadine. Figure courtesy of Unisys Weather. The red line indicates a system at hurricane strength, the yellow line indicates a system at tropical storm strength, the green line indicates a system at tropical depression strength, while the cyan line indicates a system that is post-tropical.

Name	NSD	HD	MHD	ACE	NTC
Nadine	21.25	5.00	0.00	26.1	15.2

Tropical Storm Oscar (#15): Oscar formed from a tropical wave over the central Atlantic on October 3. It intensified into a tropical storm early the following day. Fairly strong southwesterly shear prevented significant intensification of Oscar. A large low pressure area over the North Atlantic moved southward, causing Oscar to accelerate northeastward. Oscar became embedded in the larger extra-tropical low and was absorbed by the larger system later on October 5.

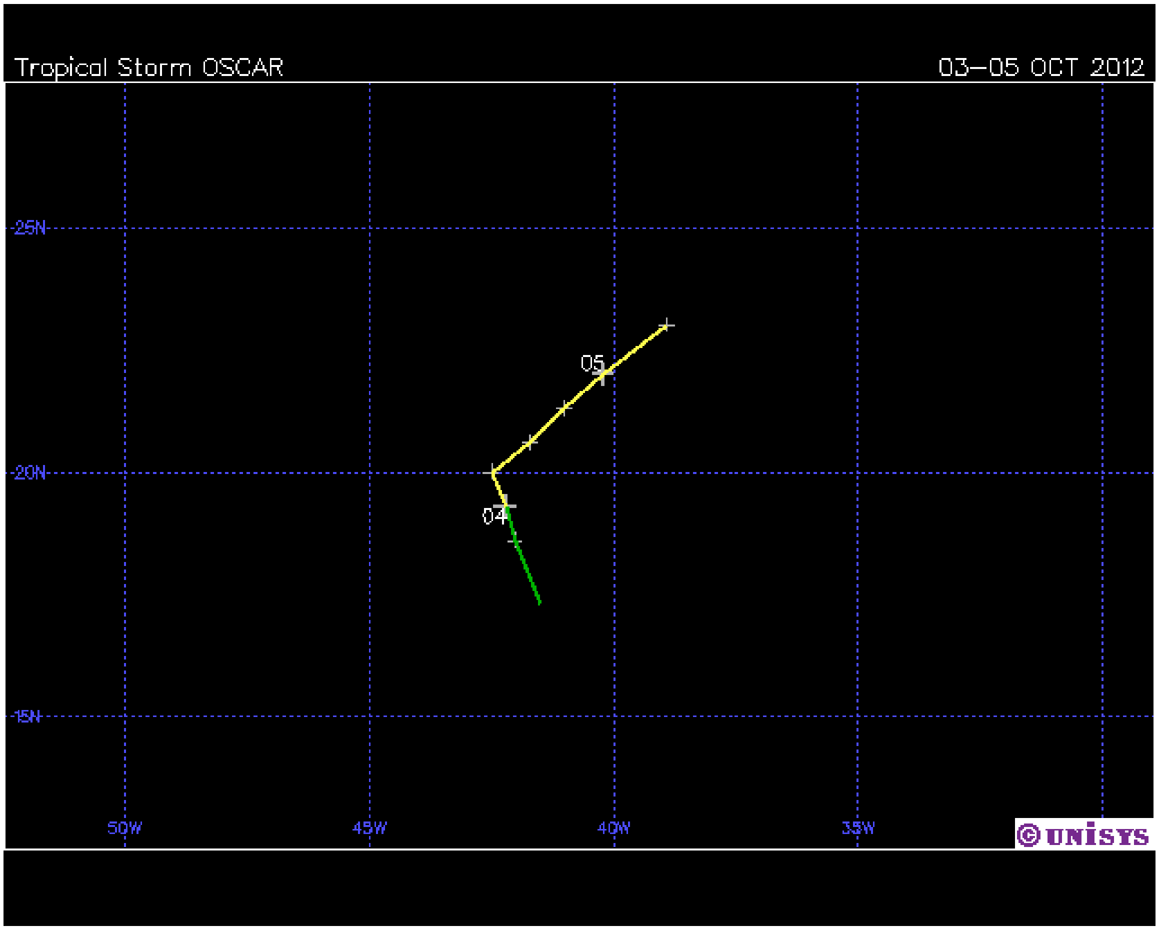

Figure 15: Track of Tropical Storm Oscar. Figure courtesy of Unisys Weather. The yellow line indicates a system at tropical storm strength, and the green line indicates a system at tropical depression strength.

Name	NSD	HD	MHD	ACE	NTC
Oscar	2.00	0.00	0.00	1.3	2.4

Tropical Storm Patty (#16): Patty formed from an area of low pressure east of the Bahamas on October 11 (Figure 16). It was upgraded to a tropical storm shortly thereafter. A strong upper-level ridge imparted southwesterly shear over Patty, and it weakened back to a tropical depression the following day while moving little. Continued strong shear elongated the TC even further, and it was downgraded to a remnant low on October 13.

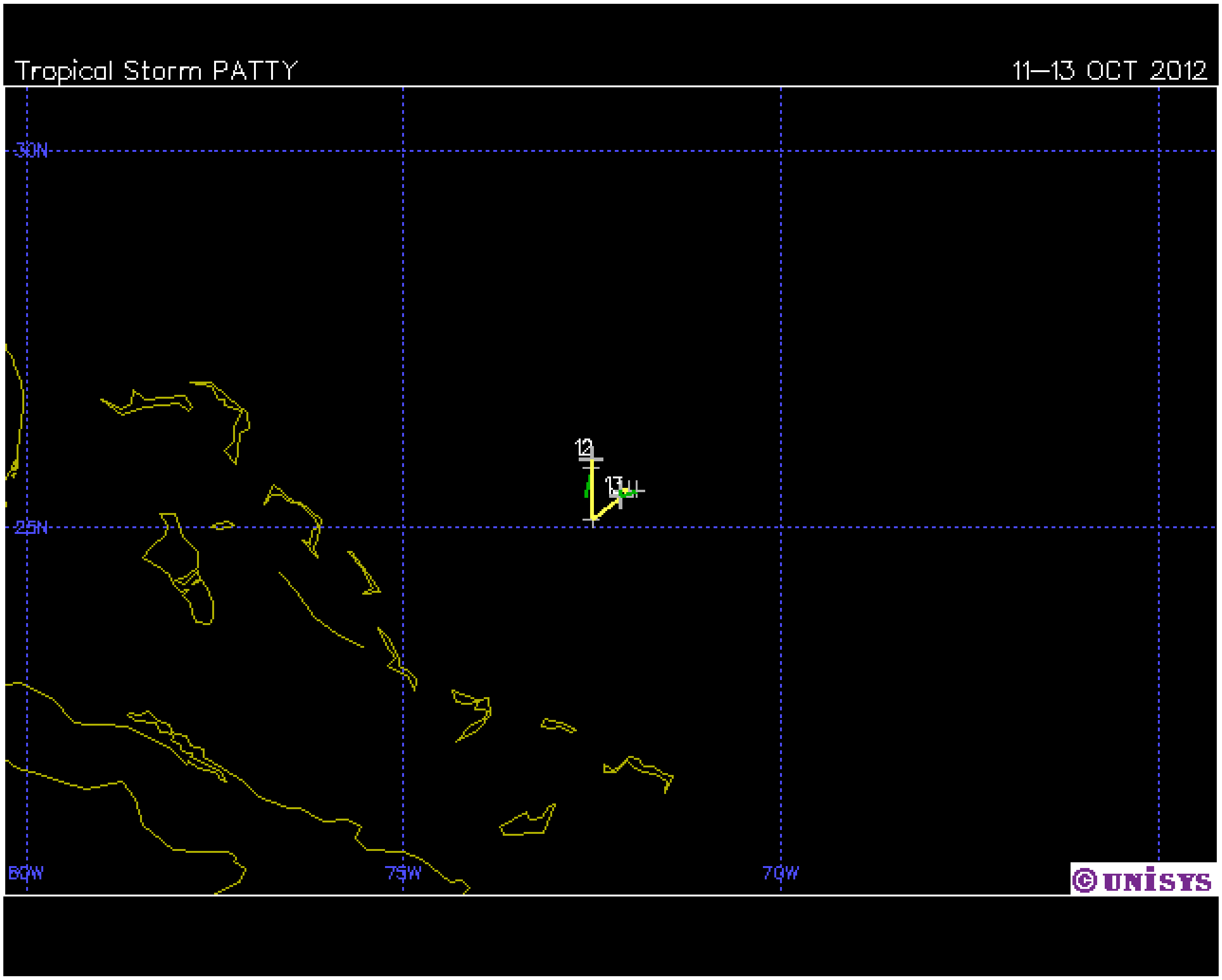

Figure 16: Track of Tropical Storm Patty. Figure courtesy of Unisys Weather. The yellow line indicates a system at tropical storm strength, while the green line indicates tropical depression strength.

Name	NSD	HD	MHD	ACE	NTC
Patty	1.25	0.00	0.00	0.7	2.2

Hurricane Rafael (#17): Rafael formed in the eastern Caribbean early on October 13 (Figure 17). It drifted northwestward with little change in strength during the early part of its lifetime due to fairly strong southwesterly shear. As the shear began to relax, Rafael began to strengthen, reaching hurricane strength on October 16. Rafael accelerated towards the north and then northeast, due to an approaching mid-latitude trough. By late on October 17, a strong front associated with the mid-latitude trough impinged upon the cyclone, turning Rafael from a hurricane into a strong extra-tropical cyclone.

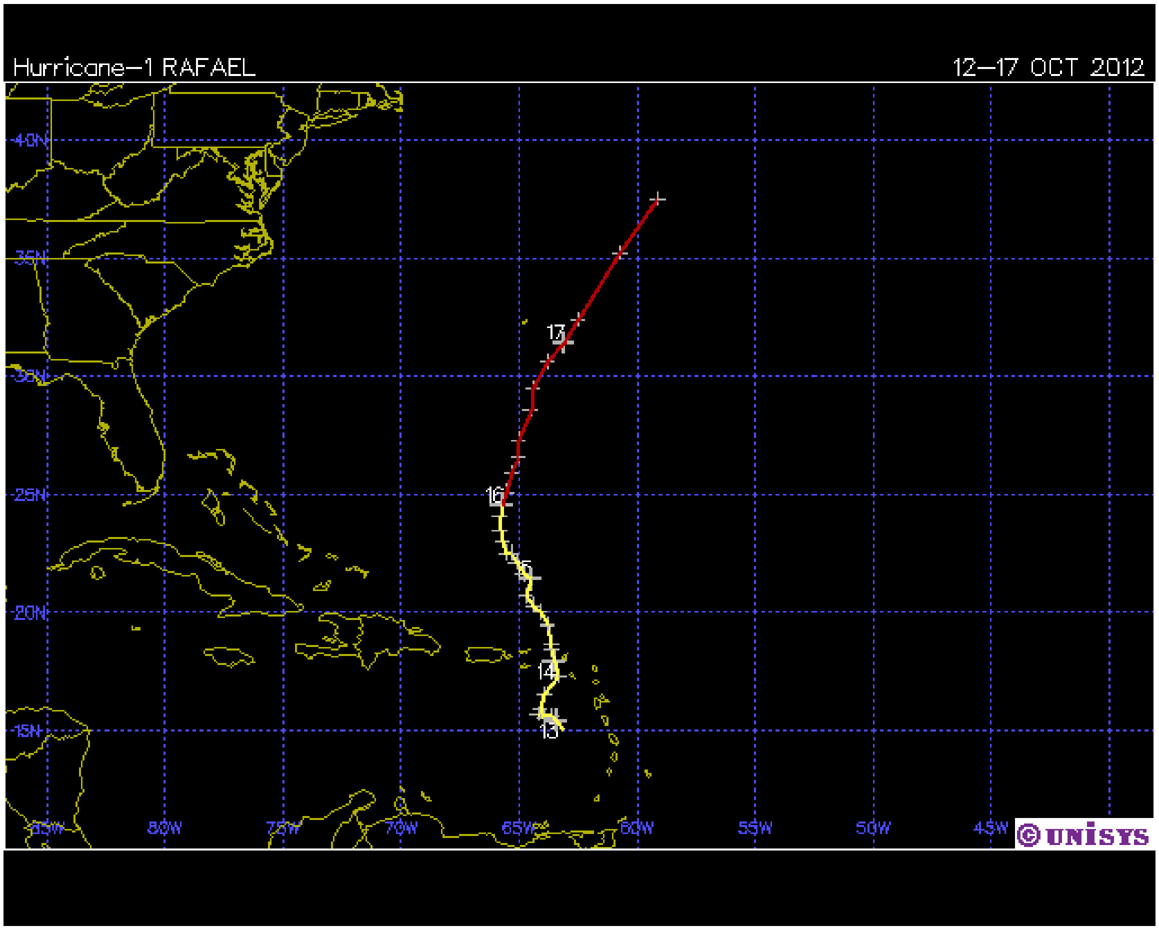

Figure 17: Track of Hurricane Rafael. Figure courtesy of Unisys Weather. The red line indicates a system at hurricane strength, the yellow line indicates a system at tropical storm strength, while the green line indicates tropical depression strength.

Name	NSD	HD	MHD	ACE	NTC
Rafael	5.25	2.25	0.00	7.4	7.9

Hurricane Sandy (#18): Sandy formed from an area of low pressure in the southwest Caribbean on October 22. It soon intensified into a tropical storm as it was located in an environment of high upper oceanic heat content and light to moderate vertical wind shear. By October 24, Sandy reached hurricane strength as it approached Jamaica. After making landfall in eastern Jamaica, Sandy continued to strengthen, reaching strong Category 2 status before making a second landfall in Cuba. Passage over the mountainous terrain of Cuba, along with strong southwesterly shear and dry air intrusion caused Sandy to weaken significantly. It buffeted the Bahamas as a Category 1 hurricane as it continued its slow march northward. A strongly negatively tilted trough steered Sandy northeastward, but then caused the system to move towards the northwest towards the US mainland. Strong baroclinic interaction with the trough caused Sandy to deepen as it approached the coastline. It was classified as post-tropical just before making landfall near Cape May, NJ. Sandy was a massive cyclone when it made landfall, with tropical storm-force winds extending nearly 500 miles from the center of the circulation. While damages from the TC are still being assessed, it is estimated to have caused over 40 billion dollars in insured damage. Sandy has been responsible for nearly 200 deaths in the Caribbean and the Northeast US.

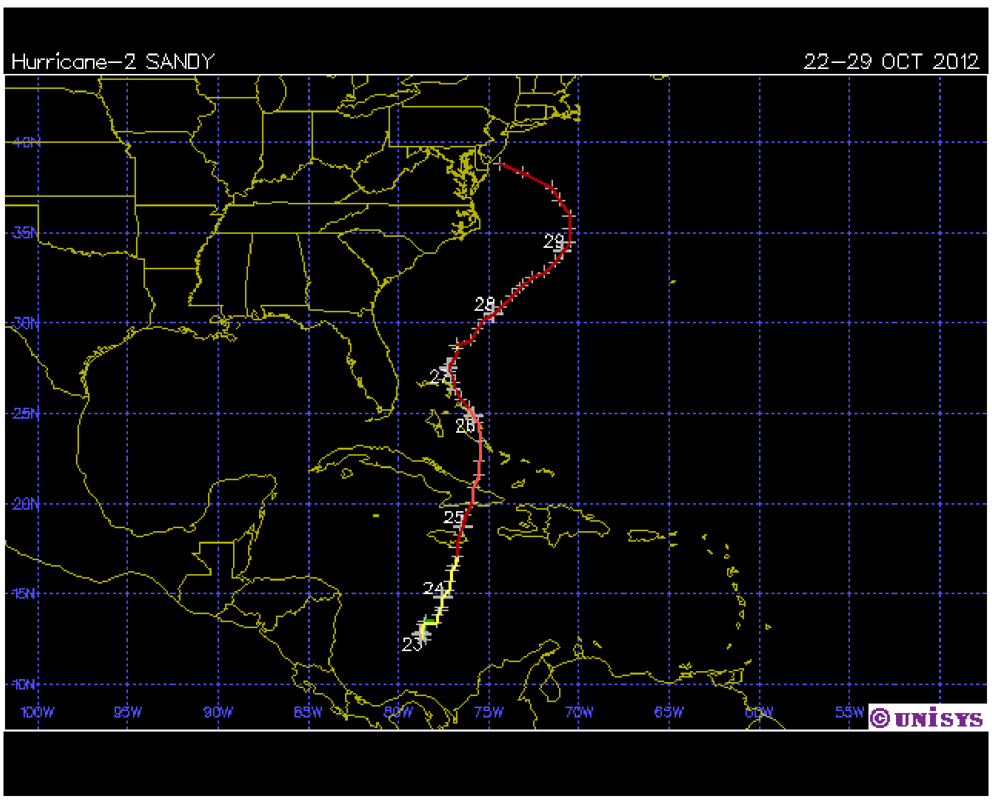

Figure 18: Track of Hurricane Sandy. Figure courtesy of Unisys Weather. The red line indicates when Sandy was a hurricane, the yellow line indicates when Sandy was a tropical storm, while the green line indicates the system was a tropical depression.

Name	NSD	HD	MHD	ACE	NTC
Sandy	7.25	5.50	0.00	13.6	10.8

Tropical Storm Tony (#19): Tony formed from an area of low pressure in the Central Atlantic on October 22. By early on October 24, Tony strengthened into a tropical storm while moving northeastward. Strong southwesterly vertical wind shear prevented significant intensification of the TC. It reached its maximum intensity of 45 knots later on October 24 before succumbing to the strong shear and weakening. Tony was classified as post-tropical the following day.

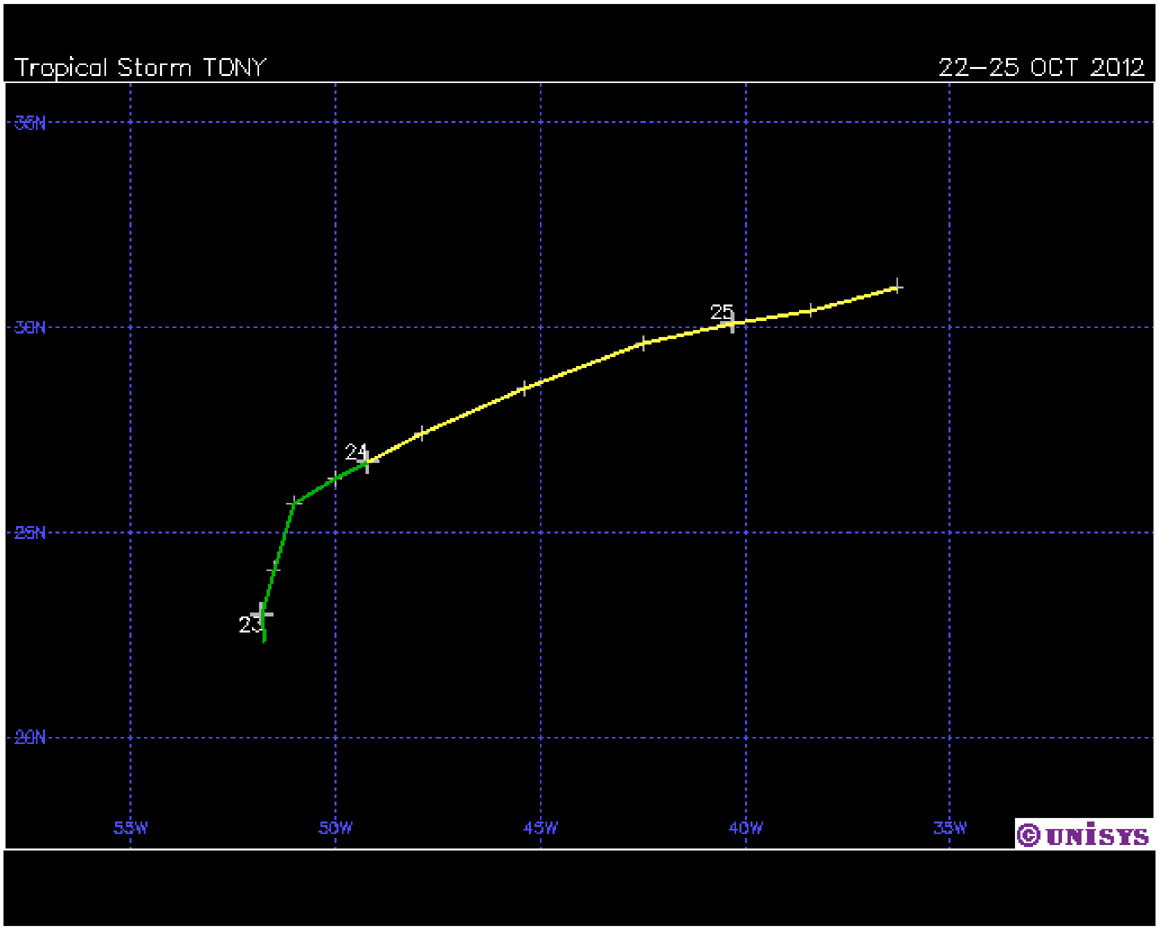

Figure 19: Track of Tropical Storm Tony. Figure courtesy of Unisys Weather. The yellow line indicates when Tony was a tropical storm, while the green line indicates that the system was a tropical depression.

Name	NSD	HD	MHD	ACE	NTC
Tony	1.75	0.00	0.00	1.2	2.3

U.S. Landfall. Figure 20 shows the tracks of Tropical Storm Beryl and Debby, along with Hurricane Isaac which made United States landfall this year. Table 3 summarizes the landfalling statistics for these systems. Damage and fatality estimates were obtained from Wikipedia. Note that Sandy was classified as post-tropical before landfall, and consequently, it does not count as a TC landfall.

Figure 20: Tracks of Tropical Storms Beryl and Debby, along with Hurricane Isaac. The red line indicates a TC at tropical storm strength, while the green line indicates a TC at hurricane strength.

Table 3: Summary US TC landfall statistics for 2012. Sandy is not listed, due to its re-classification as an extra-tropical cyclone before landfall.

	Landfall Date(s)	Location(s)	Insured Damage (Millions)	Fatalities
Tropical Storm Beryl	May 28	FL	Minimal	4
Tropical Storm Debby	June 26	FL	$300	7
Hurricane Isaac	August 28	LA	$2000	41

4 Special Characteristics of the 2012 Hurricane Season

The 2012 hurricane season had the following special characteristics:

- Nineteen named storms occurred during 2012. Only 2005 (28) and 1933 (21) have had more named storms than 2012. This is most unusual for a season which only accrued 0.25 major hurricane days and had only one hurricane (Sandy) with a central pressure below 964 mb.

- 99.50 named storm days (NSD) occurred in 2012. This is the 3rd most NSD to occur in a single season since 1944. Only 1995 (121.25 NSD) and 2005 (131.50 NSD) had more NSD than 2012.

- Ten hurricanes occurred in 2012. Only five other years have had more than ten hurricanes occur in a single season since 1944.

- One major hurricane formed in 2012. This is the fewest major hurricanes to occur in the Atlantic basin since 1997.

- 0.25 major hurricane days occurred in 2012. This is the fewest major hurricane days to occur in the Atlantic basin since 1994.

- No Category 5 hurricanes developed in 2012. This is the fifth consecutive year with no Category 5 hurricanes. The last time that five or more years occurred in a row with no Category 5 hurricanes was 1993-1997.

- No TCs reached Category 4 or 5 hurricane strength in 2012. The last time that this occurred was in 2006.

- No major hurricanes made US landfall in 2012. The last major hurricane to make US landfall was Wilma (2005), so the US has now gone seven years without a major hurricane landfall. Since 1878, the US has never had a seven-year period without a major hurricane landfall.

- The maximum intensity reached by any TC this year was 100 knots (Michael). This is the weakest maximum intensity achieved by the most intense TC of a season since 1994 (Florence - 95 knots).

- Beryl became the strongest off-season TC on record to make US landfall, when it made landfall on May 28th at 60 knots near Jacksonville, FL.

- Hurricane Nadine tied Hurricane Ginger (1971) for the most named storm days accrued (21.25) by a single storm since the dawn of aircraft reconnaissance in 1944.

- Post-tropical Cyclone Sandy (aka Superstorm Sandy) generated the lowest pressure ever recorded in the Northeast US at landfall (943 mb), breaking the record set by the Long Island Express (1938) (946 mb).

5. Superstorm Sandy's Special Characteristics

Superstorm Sandy's landfall of October 29-30 was an unusual (but not unprecedented) low probability weather event which resulted from the infrequent merging of a warm-core tropical cyclone and a strong mid-latitude cold-core cyclone. Such merging occurs every few years but seldom in such a highly populated and vulnerable location, the northeast US coastline.

Sandy's extra-large sized cyclonic vortex was the primary reason why the system was as destructive as it was. The large radius of outer winds drove a massive ocean surge and heavy rainfall over an unusually broad area of the northeast US coastline. Sandy had a high pressure ridge to its north side. This caused it to track towards the northwest and then west onto the southern New Jersey coastline. Sandy's track and strong outer winds produced an ocean surge which drove high ocean water toward the narrowing and land-funneling coastal sections of greater New York City (Figure 21). A high tide and full moon near the time of highest surge acted to further enhance the coastal flooding. A broad coastal area from southern New England to the Maryland coast was impacted by a large storm tide. Sandy's broad wind profile and slow motion before and after landfall acted to prolong the period of high water, wind, and rainfall.

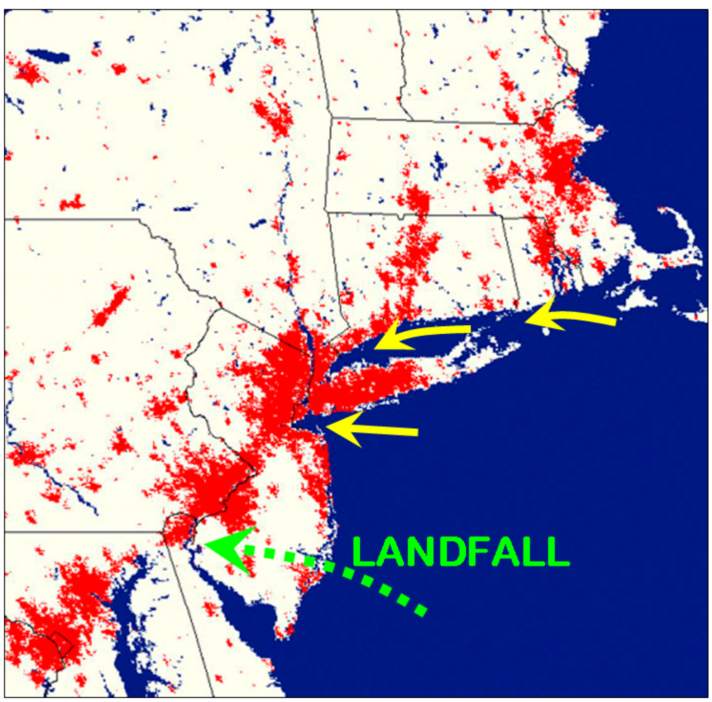

Figure 21: Illustration of the funneling of storm surge (yellow arrows) into the surrounding high population areas (in red) of New York City and Long Island by Sandy's easterly-driven winds to the north of its landfall (green arrow) in southern New Jersey (courtesy of NASA).

Sandy's simultaneous merging of two notable weather events (a tropical cyclone and a mid-latitude cyclone) with an atypical high latitude westerly track was extremely unusual but within nature's complex climate variability. Very similar high water driven by storm surge occurred in New York in 1821. There have also been several tropical cyclones that have barely missed New York City since written records began nearly 400 years ago. Similar tropical cyclone and mid-latitude cyclone merger events have occurred many times in the past, but very few have occurred at such a highly vulnerable location as the New York City metropolitan area.

Figures 22-25 show tracks of TCs in the past when:

1. Notable hurricanes and tropical cyclones passed over New York City (Figure 22),

2. Hurricanes impacted Long Island (Figure 23),

3. Hurricanes and strong tropical cyclones at higher latitudes (>35°N) had a westward track component (Figure 24).

4. Notable early American hurricanes impacted the northeast US coastline during the 17^{th} – 19^{th} centuries (Figure 25).

Figure 22: Notable cyclones with direct impacts on New York City.

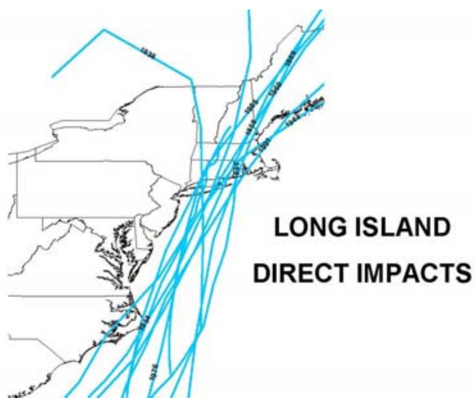

Figure 23: Destructive tropical cyclones directly impacting Long Island.

Figure 24: US landfalling tropical cyclones making western track turns about 35°N.

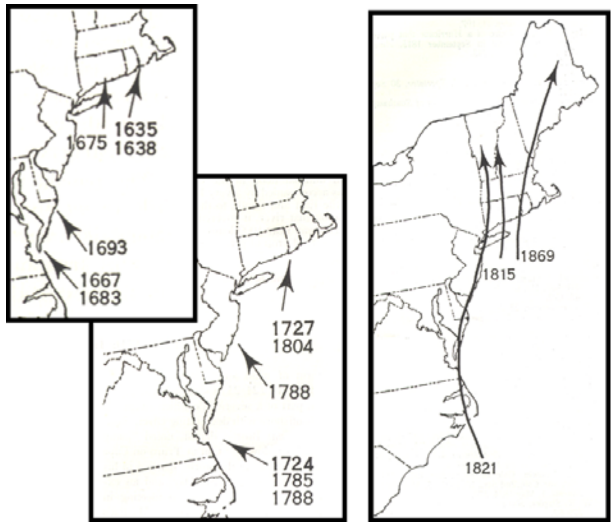

Figure 25: Notable early American hurricanes that influenced the northeast US coastline as reported by D.M. Ludlum (1963).

<u>Characteristics of Superstorm Sandy's Lifespan</u>. Sandy's unprecedented destruction resulted from a merging of a northward-moving Category 1 hurricane off the US East Coast and an easterly moving strong cold front approaching from the Midwest. As the cold front and associated trough moved further eastward, its southern portion split off to form a large upper-level cold-core cyclone. This cut off trough then moved around Sandy's southern fringe and acted to greatly enhance Sandy's outer-core southern circulation. While this was happening, a high pressure area to the north of Sandy was building. This acted to greatly broaden and increase Sandy's easterly winds on its poleward side. Figures 26-28 give an idealized three-stage portrayal of the progression of the merging of these two separate cyclones which led to the unusually damaging event that emerged along the NJ and NY shorelines.

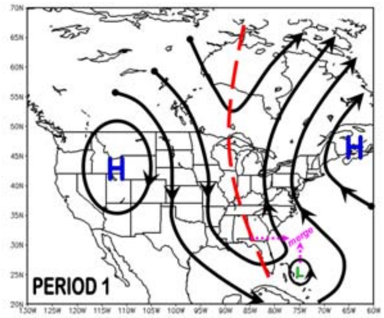

Figure 26: Idealized mid-tropospheric (500 mb – 5 km ht.) flow patterns showing the beginning of the merging of the long north-south trough (in red) with the poleward moving Category 1 Hurricane Sandy. The trough then splits, with its northern branch moving northeastward, while the southern part of the trough is advected around Sandy's southern flank. This acts to greatly enhance Sandy's upper-level wind strength.

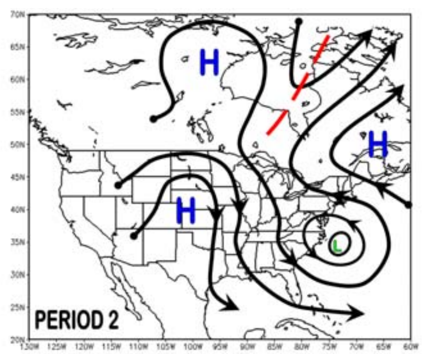

Figure 27: Continued progression of the merger of Sandy with the upper-level trough. The southern part of the trough has been advected around Sandy which enhanced the broad outer-core circulation of the developing superstorm.

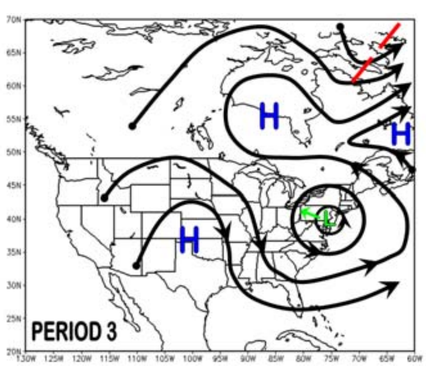

Figure 28: Flow pattern near the period of Sandy's landfall in southern New Jersey. At this point, Sandy was generating its maximum storm surge around New York City.

The maximum sustained winds of Sandy at landfall were only about 60 mph with gusts 10-20 mph higher. These winds were substantially lower than would normally be expected with a central pressure as low as 943 mb. Despite its low central pressure near landfall, Sandy was not judged to have sustained winds of hurricane strength. It was also reclassified as an extra-tropical cyclone before landfall. What caused Sandy to be so destructive was:

1. An extraordinary large outer-wind structure such that a landfall in southern NJ would cause catastrophic flooding in and around New York City.

2. Its landfall near a vulnerable location where storm surge could be maximized in and around New York City. The special funneling of surge-driven water into New York Harbor just to the north of Sandy Hook is very rare. Such narrowing inlets like New York Harbor and Long Island Sound cause an oceanic funneling and a mechanically forced higher rise in ocean level (Figure 21).

3. The westerly motion of Sandy at landfall in southern NJ brought in the storm surge around New York from an easterly direction. This meant that the height of the storm surge could be enhanced by the cyclone's winds in combination with the cyclone's motion. This also allowed the time period of highest wind and surge-induced water level to last longer than it would have if Sandy had come, like most other tropical cyclones affecting New York City, from the south.

4. Ocean surge was also maximized by occurring near high tide and at a full moon.

We do not believe that Hurricane Sandy, or other destructive tropical cyclones of the past ten years (e.g., Ivan, Katrina, Rita, Wilma, Ike, etc.) are a direct consequence of human-induced global warming. Any impacts of climate change on hurricanes are believed to be quite small and within the noise level. A more complete discussion of Hurricane Sandy and climate change, along with a more in-depth discussion of trends in Atlantic basin TC activity will be given in a follow-on manuscript.

6 Verification of Individual 2012 Lead Time Forecasts

Table 4 is a comparison of our forecasts for 2012 for three different lead times along with this year’s observations. The 2012 Atlantic hurricane season was quite unusual, with near record-high numbers of named storms and named storm days observed. Conversely, the season was associated with a negligible amount (one six-hour period) of major hurricane activity.

Table 4: Verification of our 2012 seasonal hurricane predictions.

Forecast Parameter and 1981-2010 Median (in parentheses)	4 April 2012	Update 1 June 2012	Update 3 Aug 2012	Observed 2012 Total	% of 1981-2010 Median
Named Storms (NS) (12.0)	10	13	14	19	158%
Named Storm Days (NSD) (60.1)	40	50	52	99.50	166%
Hurricanes (H) (6.5)	4	5	6	10	154%
Hurricane Days (HD) (21.3)	16	18	20	26.00	122%
Major Hurricanes (MH) (2.0)	2	2	2	1	50%
Major Hurricane Days (MHD) (3.9)	3	4	5	0.25	6%
Accumulated Cyclone Energy (ACE) (92)	70	80	99	129	140%
Net Tropical Cyclone Activity (NTC) (103%)	75	90	105	121	117%

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. Nine of 24 (38%) predictions for the 2012 hurricane season were within one standard deviation of observed values, while 17 of 24 (71%) predictions were within two standard deviations. This year's seasonal forecasts were somewhat of an under-prediction. The distribution of this year's TCs was highly unusual and presented a significant challenge for any model to forecast correctly. We consider our aggregate forecasts for ACE, and especially for NTC, to have been reasonably successful this year. The late-season breakdown of a developing El Niño event posed a significant forecast problem for us.

Table 5: Verification of our 2012 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. Error bars for storms are rounded to the nearest storm. For example, the hurricane prediction in early April would be 1.8-6.2, which with rounding would be 2-6.

Forecast Parameter and 1981-2010 Median (in parentheses)	Update 4 April 2012	Update 1 June 2012	Update 3 Aug 2012	Observed 2012 Total
Named Storms (NS) (12.0)	**10** (±4.0)	**13** (±3.8)	**14** (±2.3)	19
Named Storm Days (NSD) (60.1)	**40** ±(19.4)	**50** (±18.3)	**52** (±17.4)	99.50
Hurricanes (H) (6.5)	**4** (±2.2)	**5** (±2.1)	**6** (±1.6)	10
Hurricane Days (HD) (21.3)	**16** (±9.5)	**18** (±9.0)	**20** (±8.6)	26.00
Major Hurricanes (MH) (2.0)	**2** (±1.4)	**2** (±1.2)	**2** (±0.9)	1
Major Hurricane Days (MHD) (3.9)	**3** (±4.4)	**4** (±4.5)	**5** (±3.5)	0.25
Accumulated Cyclone Energy (ACE) (92)	**70** (±39)	**80** (±39)	**99** (±36)	129
Net Tropical Cyclone Activity (NTC) (103%)	**75** (±41)	**90** (±37)	**105** (±34)	121

6.1 Preface: Aggregate Verification of our Last Thirteen 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 thirteen 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 thirteen years (1999-2012).

Tropical Cyclone Parameter	Early April	Early June	Early August
NS	11/14	12/14	11/14
NSD	11/14	11/14	11/14
H	11/14	11/14	11/14
HD	9/14	10/14	11/14
MH	10/14	11/14	12/14
MHD	10/14	11/14	11/14
NTC	9/14	10/14	12/14
Total	**71/98 (72%)**	**76/98 (78%)**	**79/98 (81%)**

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. 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 1984-2011.

6.2 Verification of Two-Week Forecasts

This is the fourth 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 2012 hurricane season and shows their verification. All forecasts verified in the correct category except for the forecast from August 31 - September 13, which missed by two ACE units.

Table 8: Two-week forecast verification for 2012. Forecasts that verified in the correct category are highlighted in blue and forecasts that missed by one category are highlighted in green.

Forecast Period	Predicted ACE	Observed ACE
8/3 – 8/16	**Above-Average (9 or More)**	**10**
8/17 – 8/30	**Above-Average (19 or More)**	**20**
8/31 – 9/13	**Average (20-37)**	**39**
9/14 – 9/27	**Below-Average (14 or Less)**	**14**
9/28 – 10/11	**Average (8 - 15)**	**11**
10/12 – 10/25	**Above-Average (9 or More)**	**15**

The MJO tended to propagate in a rather coherent manner from August-October, except for a period where the MJO tended to stall in the middle of September. Figure 29 displays the propagation of the MJO based on the Wheeler-Hendon classification scheme from early August through late October.

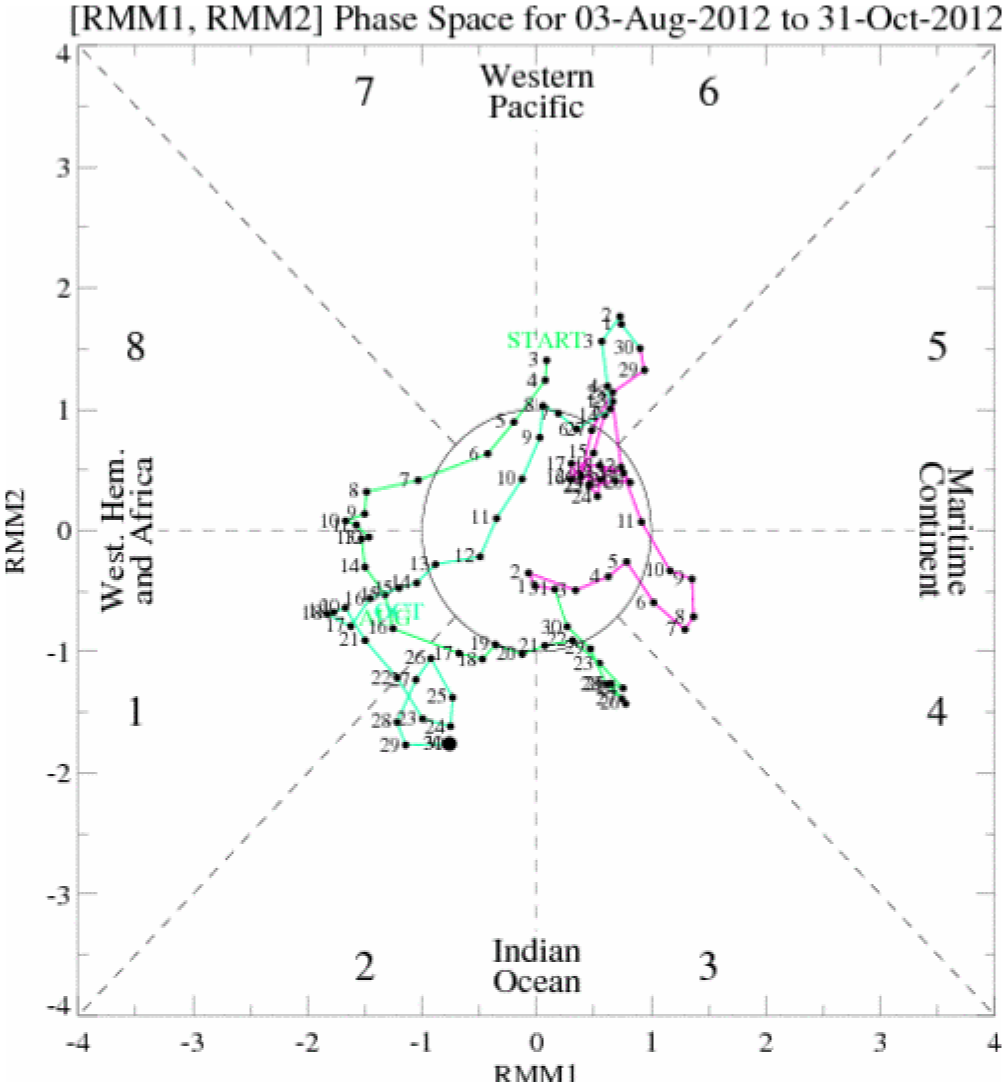

Figure 29: Propagation of the Madden-Julian Oscillation (MJO) based on the Wheeler-Hendon classification scheme over the period from August 3 to October 31. The MJO tended to propagate in a relatively consistent manner for most of the three-month period, with some stalling during mid- to late September. The Maritime Continent refers to Indonesia and the surrounding islands. RMM stands for Real-Time Multivariate MJO.

6.3 Verification of Caribbean Basin Forecasts

Our October-November Caribbean basin forecast for hurricane days and ACE in the Caribbean verified reasonably 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 approximately average activity in the Caribbean, and this forecast verified quite well. 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)	1.25	0.75
Accumulated Cyclone Energy Index (6.3)	6	5

7 Landfall Probabilities

7.1 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 2012.

Landfall probabilities for the 2012 hurricane season were estimated to be slightly below their long-period averages for the early April and early June predictions due to the forecasts of a slightly below-normal hurricane season. These probabilities were close to normal with the August seasonal forecast, when we raised our forecast somewhat. The 2012 hurricane season was relatively quiet from a U.S. landfall perspective, with only one Category 1 hurricane (Isaac) and two tropical storms (Beryl and Debby) making U.S. landfall this year. Please note that while Sandy caused major devastation along the Eastern Seaboard, it was classified as post-tropical before landfall, and consequently does not count as a landfalling tropical cyclone or hurricane. 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. This year's landfall numbers were 3 named storms, 1 hurricane and 0 major hurricanes.

Four tropical cyclones passed through the Caribbean (10-20°N, 60-88°W) during 2012. Isaac and Rafael were at tropical-storm strength, Ernesto reached Category 1 hurricane strength, and Sandy reached Category 2 hurricane strength.

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 30). These 11 units are further subdivided into 205 coastal and near-coastal counties. The climatological and current-year probabilities are available online via the Landfalling Hurricane Probability Webpage at http://www.e-transit.org/hurricane.

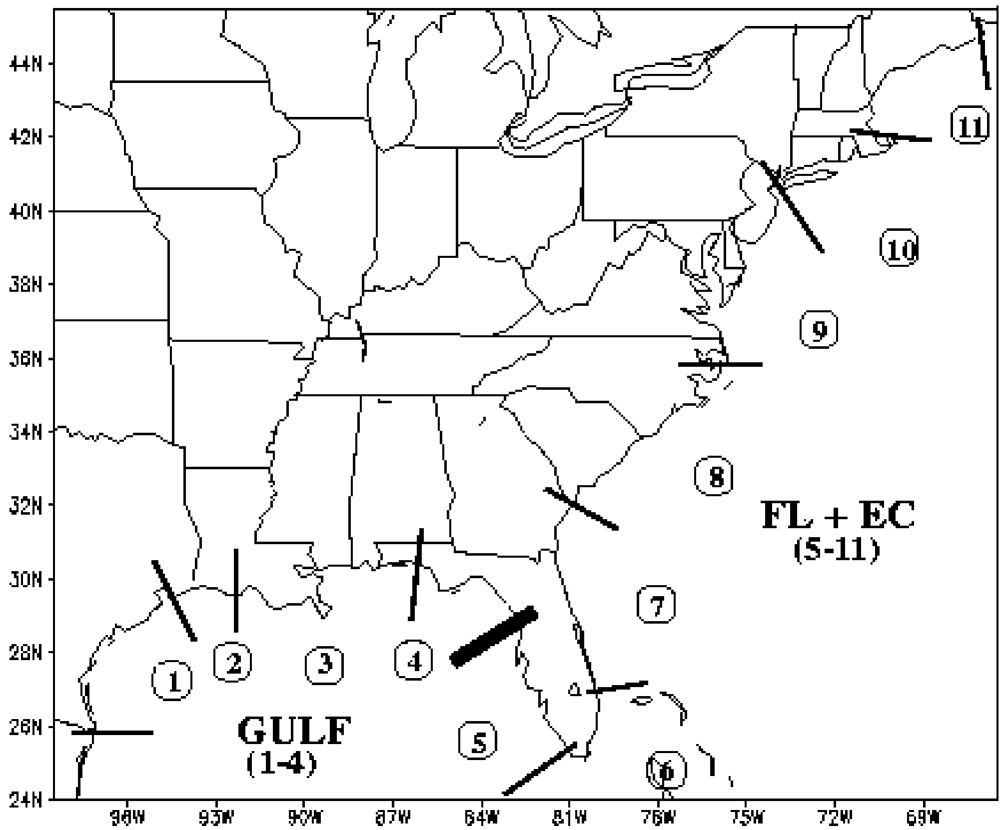

Figure 30: Location of the 11 coastal regions for which separate hurricane landfall probability estimates are made. These subdivisions were determined by the historical frequency of landfalling major hurricanes.

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 2012 at various lead times. The mean annual percentage of one or more landfalling systems during the 20th century is given in parentheses in the 3 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

	4 Apr.	1 June	3 August	Observed Number
TS	69%	76%	76% (80%)	2
HUR (Cat 1-2)	57%	64%	64% (68%)	1
HUR (Cat 3-4-5)	42%	48%	48% (52%)	0
All HUR	75%	81%	81% (84%)	1
Named Storms	92%	95%	95% (97%)	3

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

	4 Apr.	1 June	3 August	Observed Number
TS	48%	55%	55% (59%)	1
HUR (Cat 1-2)	34%	39%	39% (42%)	1
HUR (Cat 3-4-5)	24%	28%	28% (30%)	0
All HUR	54%	56%	56% (61%)	1
Named Storms	74%	80%	80% (83%)	2

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

	4 Apr.	1 June	3 August	Observed Number
TS	41%	47%	47% (51%)	1
HUR (Cat 1-2)	35%	41%	41% (45%)	0
HUR (Cat 3-4-5)	24%	28%	28% (31%)	0
All HUR	51%	56%	57% (62%)	0
Named Storms	71%	77%	77% (81%)	1

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

	4 Apr.	1 June	3 August	Observed Number
TS	73%	79%	79% (82%)	2
HUR (Cat 1-2)	47%	53%	53% (57%)	2
HUR (Cat 3-4-5)	34%	39%	39% (42%)	0
All HUR	65%	71%	71% (75%)	2
Named Storms	90%	94%	94% (96%)	4

7.2 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.

<u>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.</u>

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 63 (1950-2012) 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 63-year period from 1950-2012.

	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 < 53	10	4	1	12	5	1	22	9	2	12	2	1
Top 20 Observed NTC years > 129	39	19	10	41	23	8	80	42	18	93	57	30
Bot 20 Observed NTC years ≤ 83	23	9	4	17	8	3	40	17	7	29	9	4
Top 32 Observed NTC years ≥ 100	56	30	12	66	36	14	122	66	26	133	74	38
Bot 31 Observed NTC years < 100	49	20	8	38	18	7	87	38	15	51	19	9

Table 12 shows the number of landfalling tropical cyclones which occurred in our 12 most active forecasts when our real time projects' 1 June prediction of the number of hurricanes was 8 or more versus those 12 years when our 1 June prediction of the seasonal number of hurricanes was 6 or less and 1993 and 1997 (when 7 hurricanes but only 25 hurricane days were predicted). Notice the greater than 2 to 1 difference in landfall of major hurricanes and the nearly 2 to 1 difference in landfalling hurricanes for the entire United States. The ratios for the Caribbean are similar, with a nearly 4 to 1 ratio for Caribbean major hurricanes.

Table 12: Number of U.S. and Caribbean landfalling tropical cyclones in the 12 years when our 1 June forecast was for 8 or more hurricanes versus those 12 years when our 1 June prediction was for 6 or fewer hurricanes and 1993 and 1997 (when 7 hurricanes but only 25 hurricane days were predicted).

Forecast H	US NS	US H	US MH	Carib NS	Carib H	Carib MH
≥ 8 (12 years)	59	30	12	53	28	15
≤ 6 & 1993 (12 years)	39	17	5	30	15	4

Our individual season forecasts of the last 28 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.

8 Summary of 2012 Atmospheric/Oceanic Conditions

In this section, we go into detail discussing large-scale conditions that were present in the atmosphere and in the ocean during the 2012 Atlantic basin hurricane season.

8.1 ENSO

As is usually the case, El Niño-Southern Oscillation (ENSO) represented a major late spring/early summer challenge for our 2012 seasonal hurricane forecasts. In our early April 2012 forecast for 2012, we believed that the probability of development of El Niño was relatively high. We became somewhat less certain about El Niño's development in early June. We still anticipated a weak El Niño to develop with our early August seasonal forecast. There may have been a brief transition to El Niño conditions in the tropical Pacific during the middle part of the summer (dependent on which ENSO metric is examined). Since that time, the apparent onsetting of El Niño has reverted back to neutral conditions. The following are several quotes from our 2012 forecasts regarding ENSO this year:

(4 April 2012) –

"Based on the above information, our best estimate is that we will likely transition to neutral conditions in the next few weeks with a possible transition to El Niño conditions during the early part of the hurricane season."

(1 June 2012) –

“It appears to us that another westerly wind burst is going to be required to move from neutral to El Niño conditions. These westerly wind bursts are often triggered by Madden-Julian Oscillation (MJO) events or other equatorial wave activity. Over the past several weeks, the MJO has been relatively weak. Current model projections indicate continued weak MJO conditions for the next couple of weeks, which adds much uncertainty as to the fate of ENSO for the peak of this year's hurricane season."

(3 August 2012) –

"Based on this information, our best estimate is that we will likely experience weak El Niño conditions during the 2012 hurricane season. A slightly stronger ENSO event could potentially significantly dampen the Atlantic basin hurricane season, while neutral ENSO conditions could potentially allow for much more TC activity than is being forecast here."

Our definition of weak, moderate and strong El Niño events for the August-October period has historically been based on the August-October-averaged Nino 3.4 index. When this index is between 0.5-1.0°C, we define it as a weak El Niño event, when the index is between 1.0-1.5°C, we define it as a moderate El Niño event, and when the index is greater than 1.5°C, we define it as a strong El Niño event. The August-October-averaged Nino 3.4 index in 2012 was approximately 0.5°C, or a borderline weak El Niño event.

A weak-to-moderate La Niña occurred during the winter of 2011/2012, with a rapid transition to neutral conditions during the spring months. This warming began to wane in the tropical eastern and central Pacific during the middle part of the summer, with a reversion back to neutral ENSO conditions by October. 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 2012 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 2012 are in parentheses.

Region	January 2012 Anomaly (ºC)	April 2012 Anomaly (ºC)	July 2012 Anomaly (ºC)	October 2012 Anomaly (ºC)
Nino 1+2	-0.6	1.3 (+1.9)	1.0 (+1.6)	-0.2 (+0.4)
Nino 3	-0.7	0.1 (+0.8)	0.9 (+1.6)	0.0 (+0.7)
Nino 3.4	-1.1	-0.4 (+0.7)	0.5 (+1.6)	0.3 (+1.4)
Nino 4	-1.2	-0.3 (+0.9)	0.1 (+1.3)	0.5 (+1.7)

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 2011/2012 through September-October 2012 are listed in Table 14. Note the rapid increase in the MEI from December-January through June-July, and the considerable decline in the index in recent months.

Table 14: Bi-monthly values of the MEI from December-January 2011/2012 through September-October 2012. The change from December-January 2011/2012 is also provided.

MEI Months	MEI Value	Change from Dec-Jan 2011/2012
Dec-Jan	-1.0	
Jan-Feb	-0.7	+0.3
Feb-Mar	-0.4	+0.6
Mar-Apr	0.1	+1.1
Apr-May	0.7	+1.7
May-Jun	0.9	+1.9
Jun-Jul	1.1	+2.1
Jul-Aug	0.6	+1.6
Aug-Sep	0.3	+1.3
Sep-Oct	0.1	+1.1

One of the reasons why we believe that ENSO conditions did not develop this year was due to the persistence of anomalously strong trade winds near the International Date Line. These stronger-than-normal trades helped to promote mixing and upwelling and prevented the development of eastward propagating Kelvin waves that tend to warm the eastern and central Pacific. Figure 31 displays the low-level wind anomalies across the tropical Pacific from mid April to mid October. Other than one strong westerly wind burst in the middle of June and some weak westerlies in early October, trade winds remained near- or stronger-than-normal for most of the past few months.

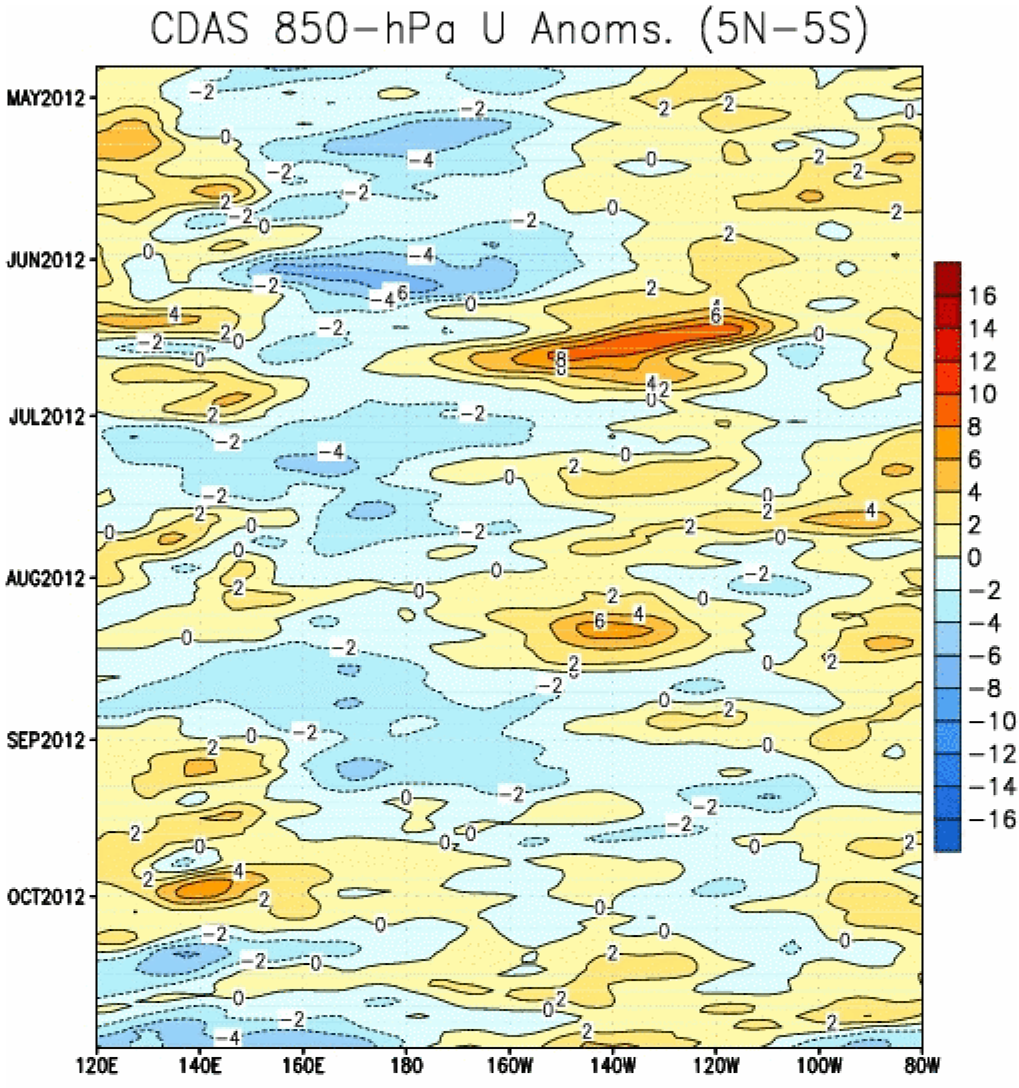

Figure 31: Equatorial wind anomalies in the Indo/Pacific sector. Note the persistence of anomalous easterlies (e.g., stronger trades) near the International Date Line. Figure courtesy of the Climate Prediction Center.

8.2 Intra-Seasonal Variability

Unlike the past two years, intra-seasonal (MJO) variability was relatively active during the peak months of this year's Atlantic hurricane season. Figure 32 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-September. There was some significant clustering of Atlantic TCs throughout the course of the season, which generally coincided with enhanced convection over the Western Hemisphere and Indian Ocean (Phases 1-3). These phases tend to be associated with reduced vertical shear and enhanced vertical motion over the Atlantic Main Development Region. For example, six TCs formed during August 16-30, during which time, the MJO was in Phases 1-3. Four TCs also formed from October 12-25, during which the MJO was in Phase 1-2.

Conversely, no new TCs formed in the Atlantic from September 13 - October 3, during which the convectively-enhanced phase of the MJO was predominately located over the Pacific Ocean. These phases are typically associated with subsidence and increased vertical shear over the tropical Atlantic. Table 15 displays the number of TC formations by MJO phase during the 2012 Atlantic hurricane season. The results from the 2012 Atlantic hurricane season are in line with the findings of Klotzbach (2010, 2012).

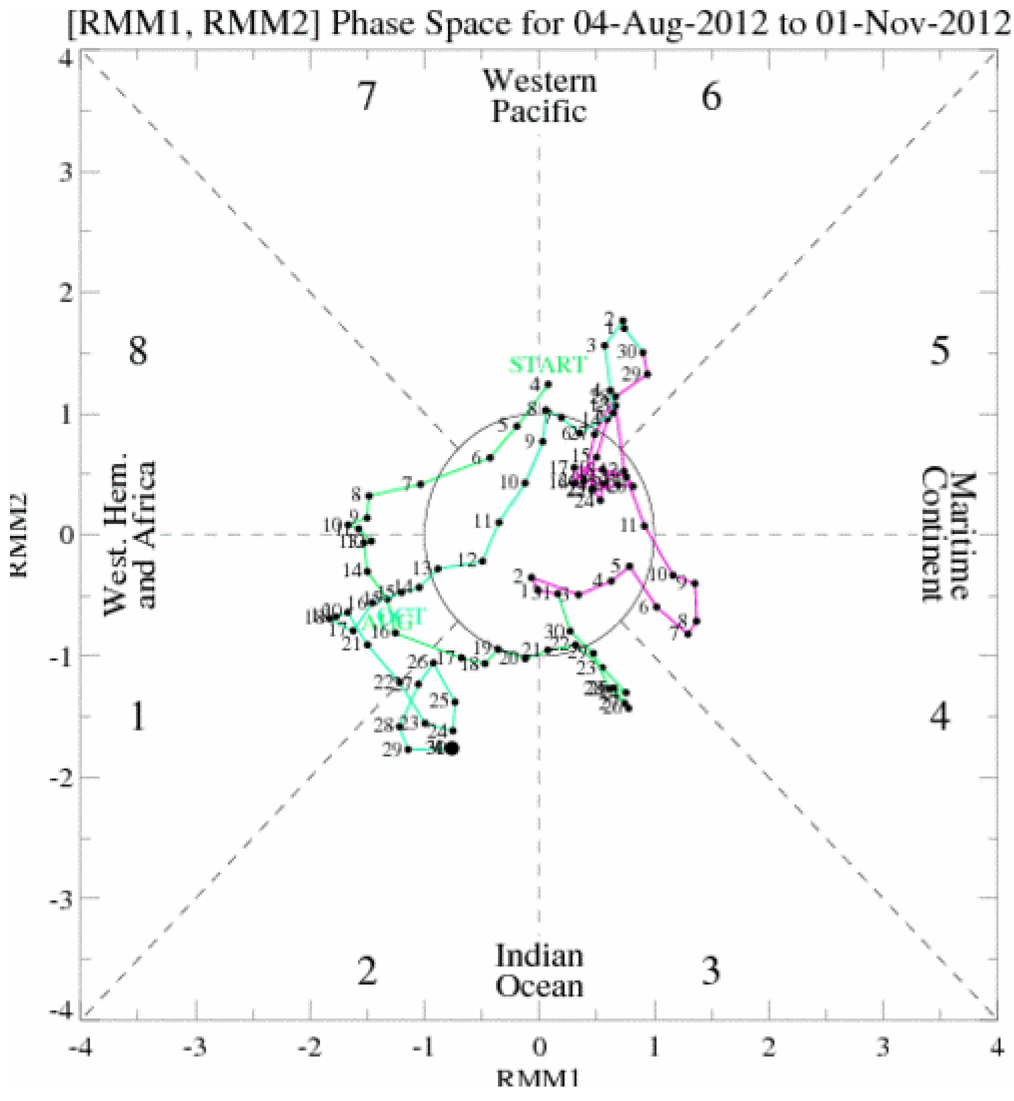

Figure 32: Progression of the MJO, as calculated by the WH index, over the period from August 4 - November 1, 2012. Active periods during the 2012 Atlantic hurricane season were typically associated with enhanced convection over Africa and the Indian Ocean, while inactive periods were associated with enhanced convection over the tropical Pacific.

Table 15: TC formations by MJO phase during the 2012 Atlantic hurricane season.

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

8.3 Atlantic SST

The tropical Atlantic was characterized by dramatic SST anomaly changes over the course of 2012. Positive SST anomalies rapidly disappeared during the winter months, likely associated with a very strongly positive North Atlantic Oscillation (NAO) (Figure 33) that cooled the Main Development Region (MDR) considerably during January – March. This cooling was followed up a rapid warmup in the MDR, associated with a strongly negative NAO (Figure 34). A positive NAO is associated with stronger-than-normal trade winds across the tropical Atlantic (Figure 35). Strong trades drive enhanced mixing and upwelling and consequently force anomalous cooling (Figure 36). Figure 37 shows the SST anomaly difference between late May and late January. Note the strong cooling that took place in the eastern part of the tropical and subtropical Atlantic.

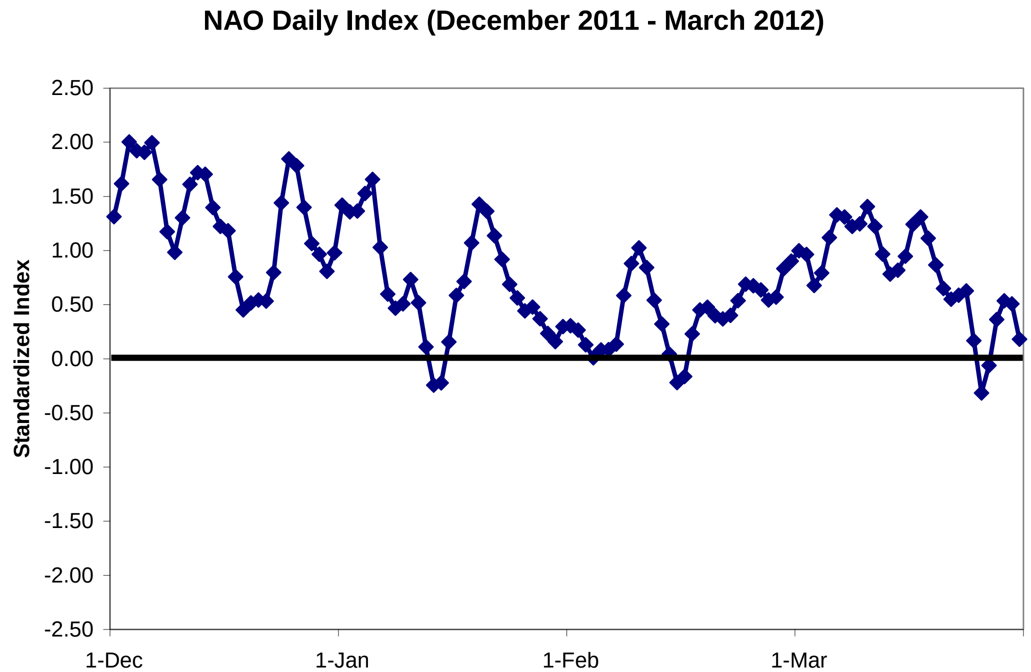

Figure 33: 1 December 2011 – 31 March 2012 daily NAO anomaly. Note that anomalously positive NAO conditions occurred throughout the four-month period.

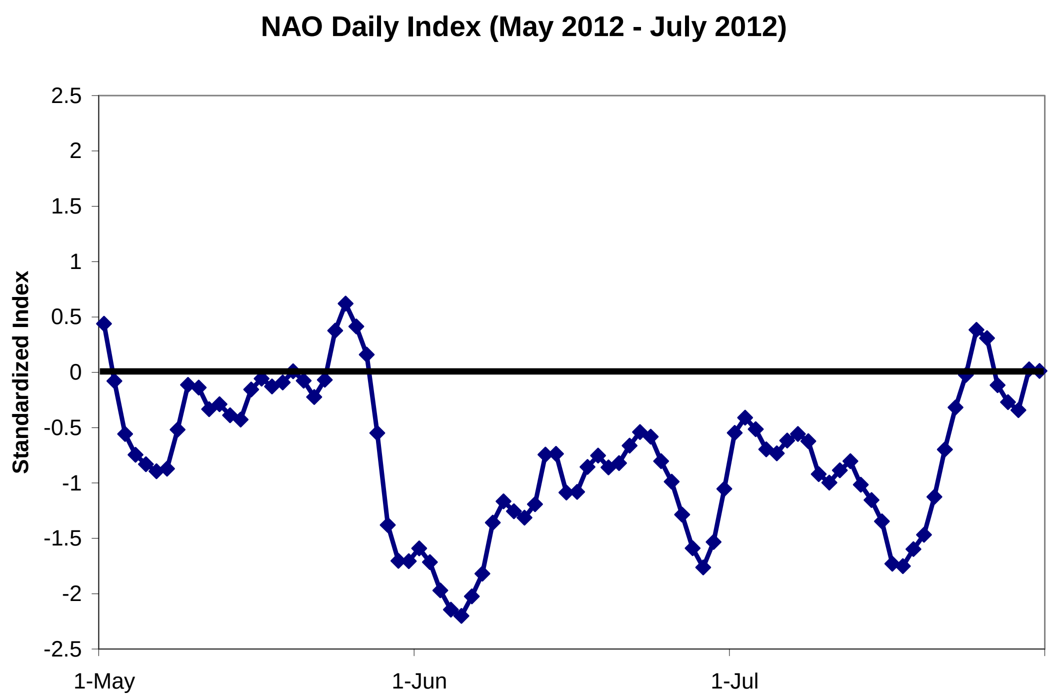

Figure 34: 1 May 2012 – 31 July 2012 daily NAO anomaly. Note that anomalously negative NAO conditions occurred throughout the three-month period.

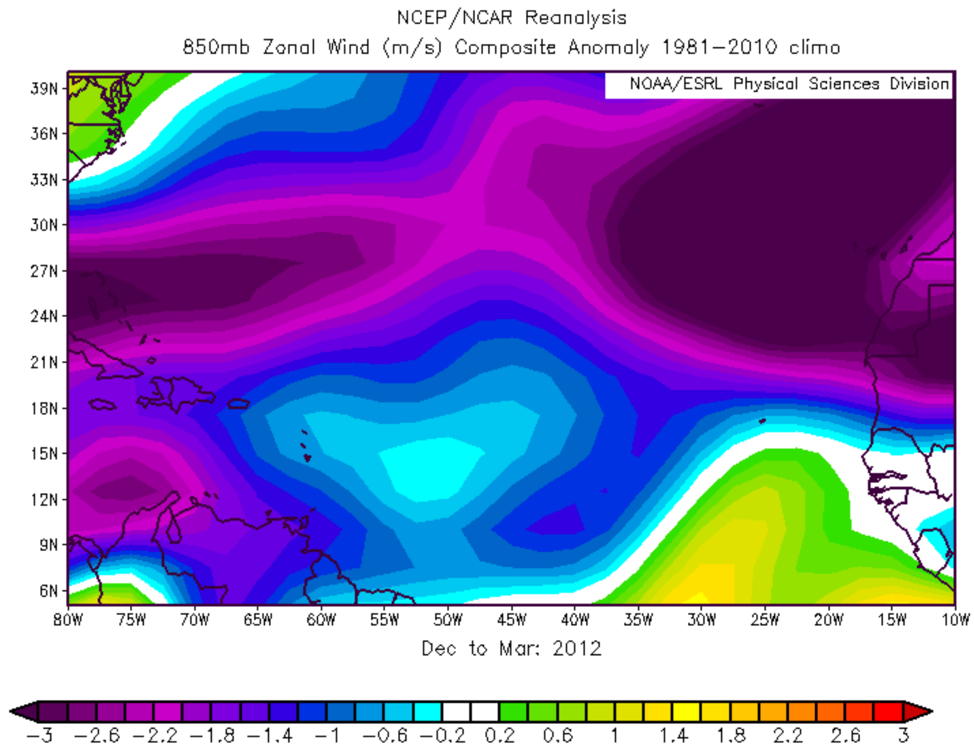

Figure 35: December 2011 to March 2012 mean 850-mb zonal wind anomalies across the tropical and subtropical Atlantic. Note the significant easterly anomalies (e.g., stronger trades) throughout most of the sub-tropical and tropical Atlantic. These conditions are typically associated with a weak thermohaline circulation, cooling SSTs, and higher sea level pressure anomalies in the tropical Atlantic.

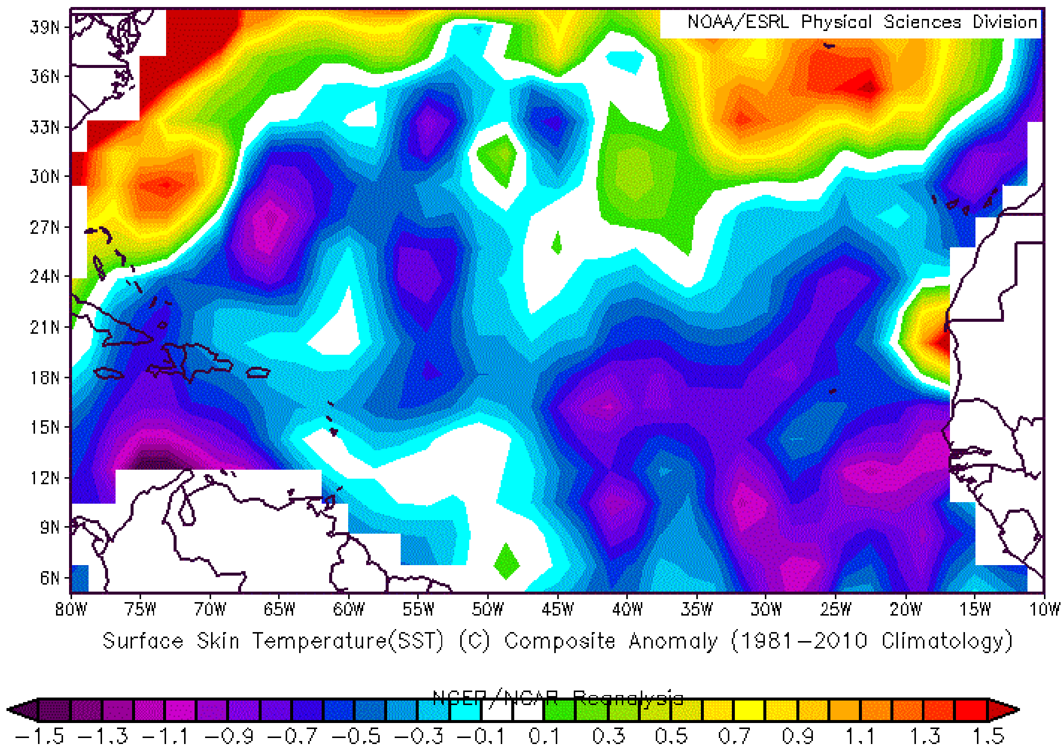

Figure 36: Late March 2012 minus late November 2011 mean SST anomaly change.

Weak trade winds (Figure 37) and anomalous warming of the tropical Atlantic (Figure 38) occurred with the negative phase of the NAO. By the peak of the Atlantic hurricane season, SSTs in the tropical Atlantic had rebounded to above-normal levels (Figure 39), where they have remained for the rest of this year's hurricane season. Figure 40 displays the NAO from 1 December 2011 through 1 August 2012, which demonstrates the dramatic shift in the polarity of the NAO from positive to negative around 1 May.

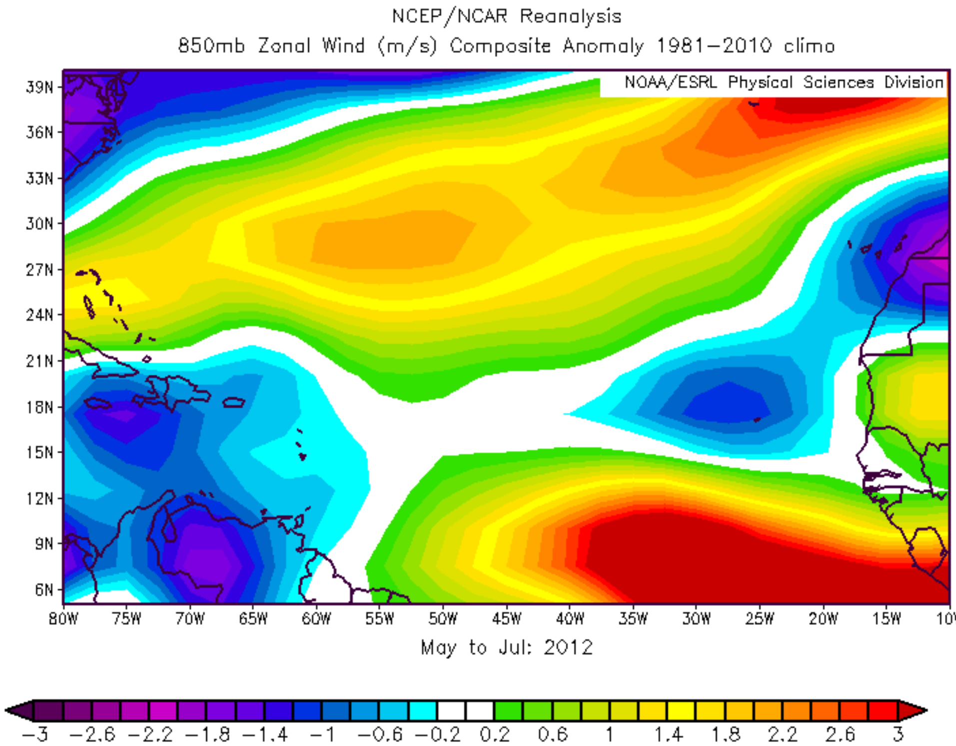

Figure 37: May through July 2012 average 850-mb zonal wind anomalies across the tropical and subtropical Atlantic. Note the significant westerly anomalies (e.g., weaker trades) throughout most of the sub-tropical and tropical Atlantic.

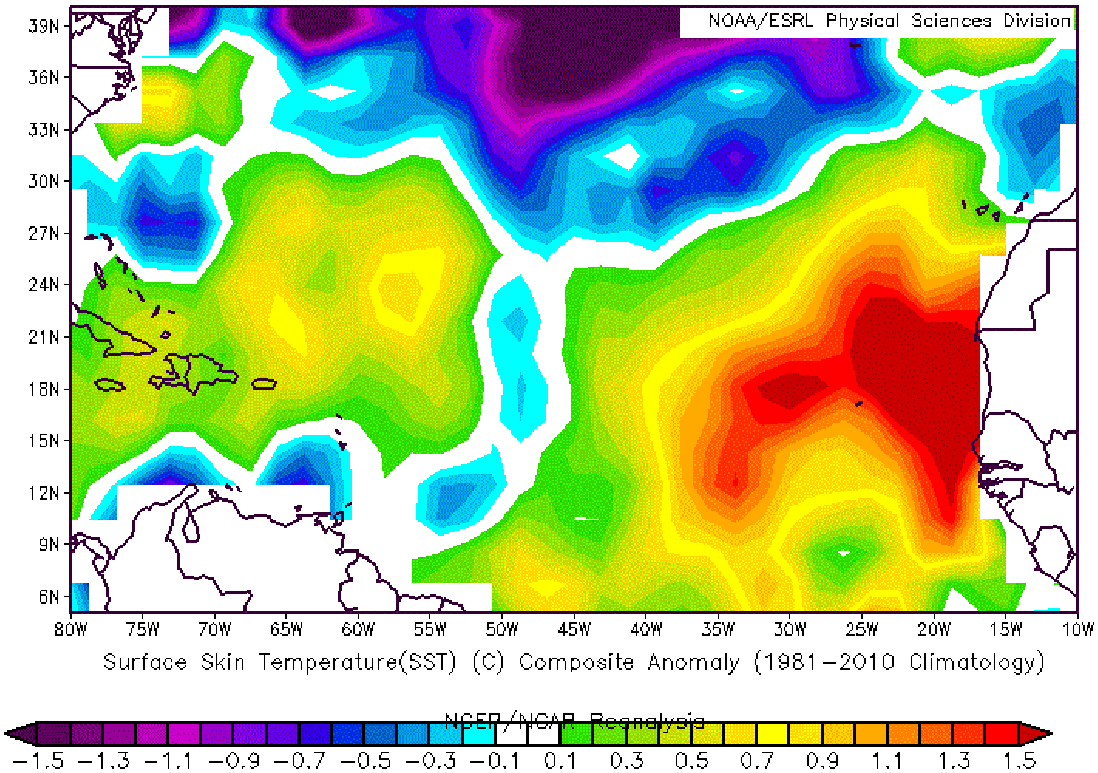

Figure 38: Late July 2012 minus late April 2012 SST changes.

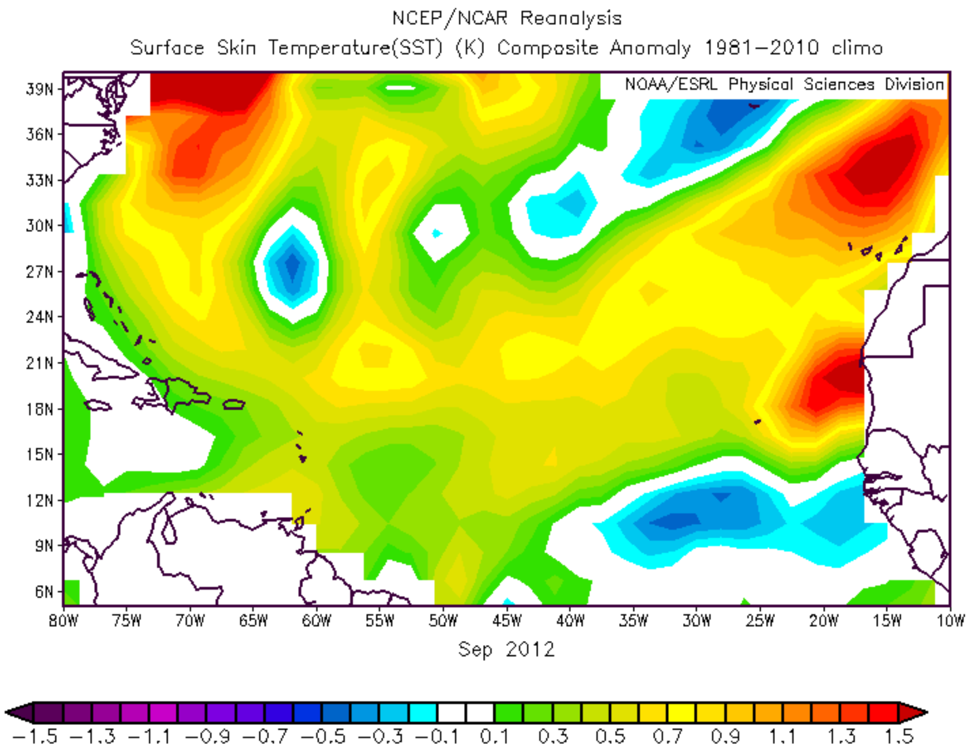

Figure 39: SST anomaly pattern observed across the tropical and subtropical Atlantic in September 2012. The significantly warmer-than-normal SST anomalies in the subtropical northeast Atlantic may be partially responsible for the anomalous development and intensification of TCs in this region.

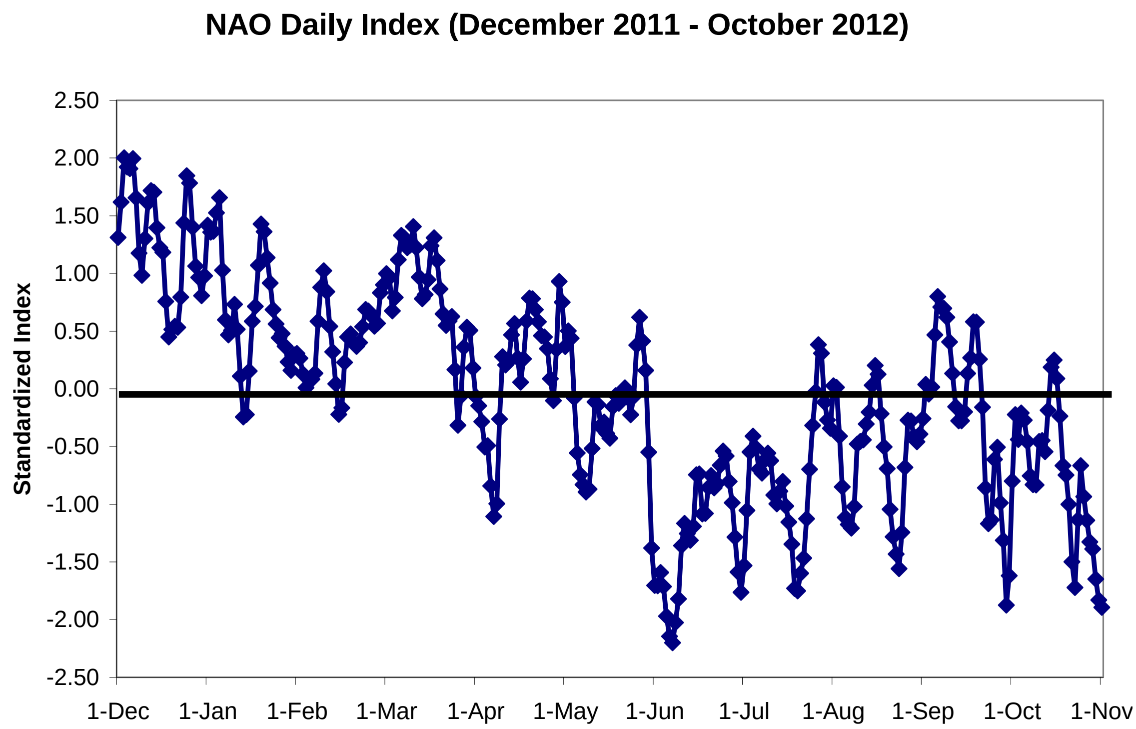

Figure 40: 1 December 2012 – 1 Nov 2012 daily NAO anomaly. Note the shift from positive NAO anomalies during the winter and early spring to negative anomalies from around 1 June through the remainder of the year.

8.4 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 2012 Atlantic hurricane season was characterized by below-normal sea level pressures throughout the Atlantic basin, with well below-normal sea level pressure anomalies observed across the subtropical Atlantic. Some of the anomalously low sea level pressure anomalies in the sub-tropics may be due to the copious amount of TC activity that occurred there this year. Figure 41 displays August-October 2012 tropical and sub-tropical sea level pressure anomalies in the North Atlantic.

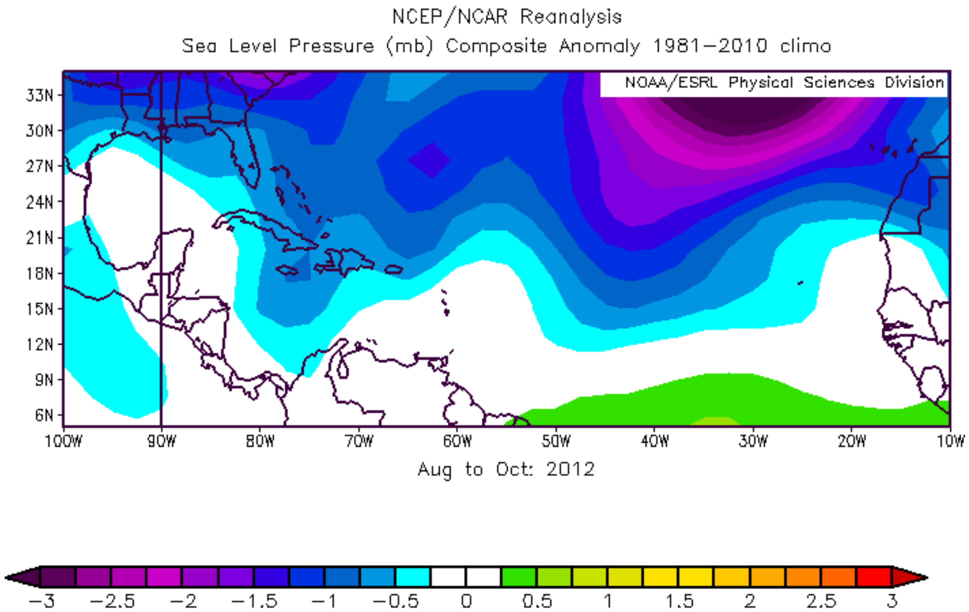

Figure 41: August-October 2012 tropical and sub-tropical North Atlantic sea level pressure anomalies. Sea level pressure anomalies were slightly below average across the tropical Atlantic and well below average across the sub-tropical Atlantic.

8.5 Tropical Atlantic Vertical Wind Shear

Tropical Atlantic vertical wind shear was lower in 2012 than it was in 2011 (Figure 42). Vertical shear anomalies were below-average across the Main Development Region (MDR) (highlighted in the blue box). Typically, reduced vertical wind shear is associated with more TC formation and a greater likelihood for intensification. Despite these relatively favorable vertical wind shear conditions in the MDR, little hurricane activity was observed in the eastern portion of the MDR this year. Instead, TC activity was concentrated in the subtropics. One of the critical reasons for this was likely a drier-than-average mid-level atmosphere, which is discussed in the following section.

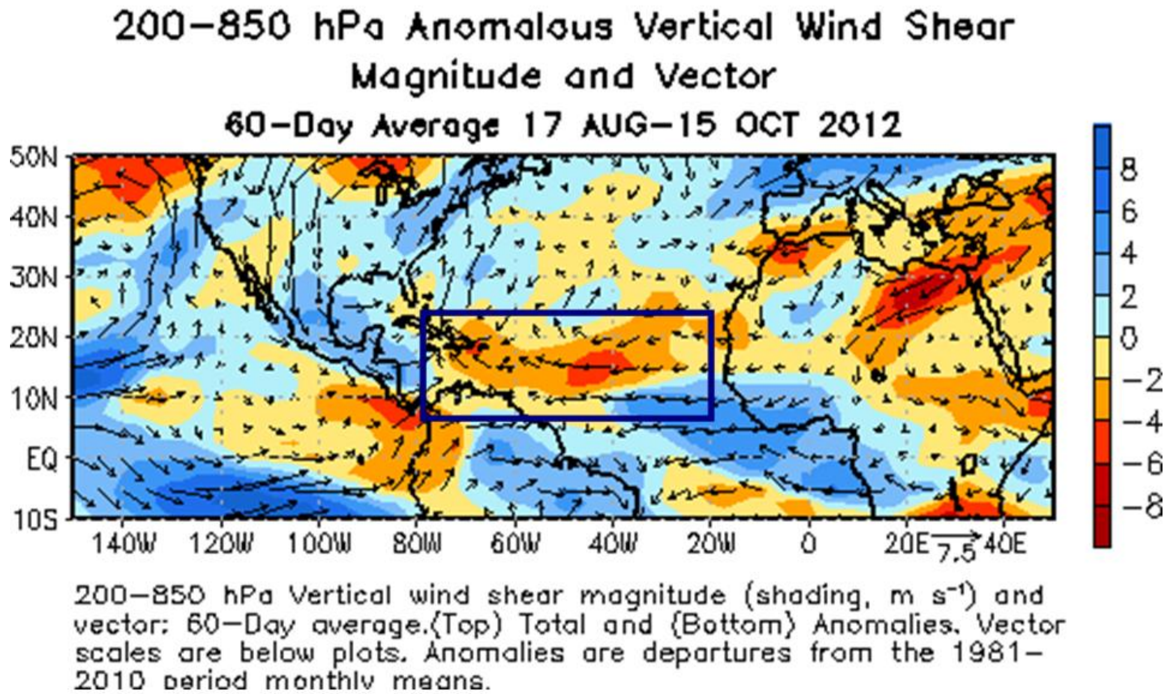

Figure 42: Anomalous vertical wind shear as observed across the Atlantic from August 17 – October 15, 2012. Vertical wind shear was anomalously weak across most of the MDR during the peak 60 days of the 2012 Atlantic hurricane season.

8.6 Tropical Atlantic Moisture

One of the primary reasons why TC activity was not as active in the MDR as would be expected given the favorable vertical shear and SST conditions was the anomalous dryness that persisted across the tropical Atlantic, especially in July and 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 16 displays relative humidity, specific humidity and omega rankings for July-September 2012 at 300-mb, 500-mb and 700-mb, compared with the 1979-2012 average. A ranking of one indicates the driest (and most downward vertical motion) during the time period. Note the anomalous dryness and subsidence that occurred during July and September, which is likely why TCs failed to form or intensify in the MDR during these two months.

Table 16: Specific humidity, relative humidity and omega rankings for July 2012, August 2012 and September 2012 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 34 would imply the wettest (or most enhanced vertical motion) month of the last 34 years across the MDR. According to the reanalysis, 2012 had the lowest moisture and most subsidence at 500-mb of any of the past 34 years in both July and September.

Specific Humidity			
	300-mb	500-mb	700-mb
July 2012	2	1	17
August 2012	10	11	28
September 2012	3	1	5
Relative Humidity			
	300-mb	500-mb	700-mb
July 2012	2	1	7
August 2012	7	11	28
September 2012	4	1	1
Omega			
	300-mb	500-mb	700-mb
July 2012	1	1	3
August 2012	16	16	16
September 2012	2	1	1

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. Figures 43 and 44 display upper-level velocity potential anomalies in July and September 2012. Note the strongly positive anomalies that persisted across the Atlantic in both months.

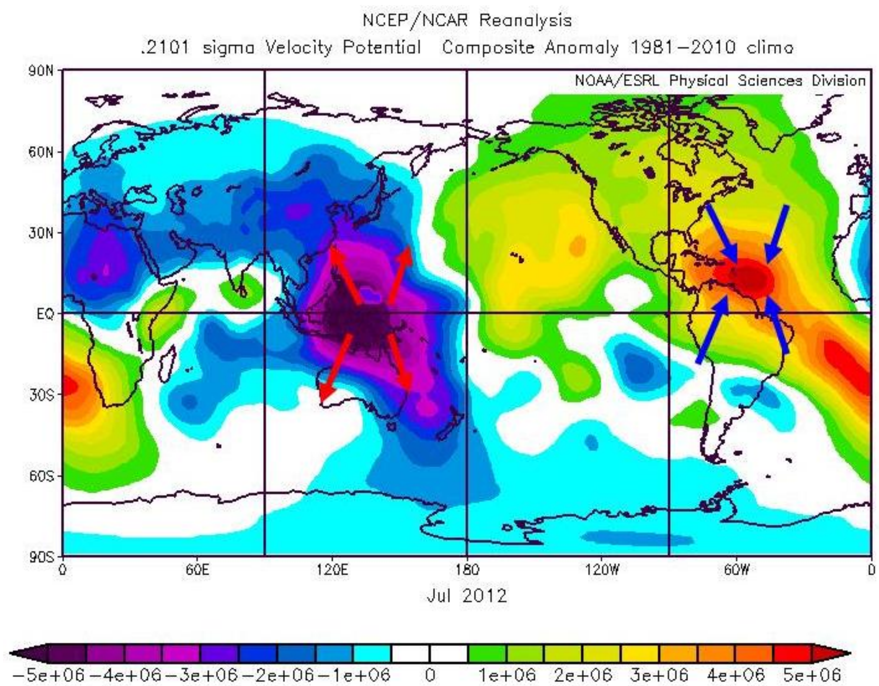

Figure 43: Upper-level velocity potential anomalies in July 2012. Note the positive velocity potential anomalies that occurred during the month. The red arrows indicate upper-level divergence, while the blue arrows indicate upper-level convergence.

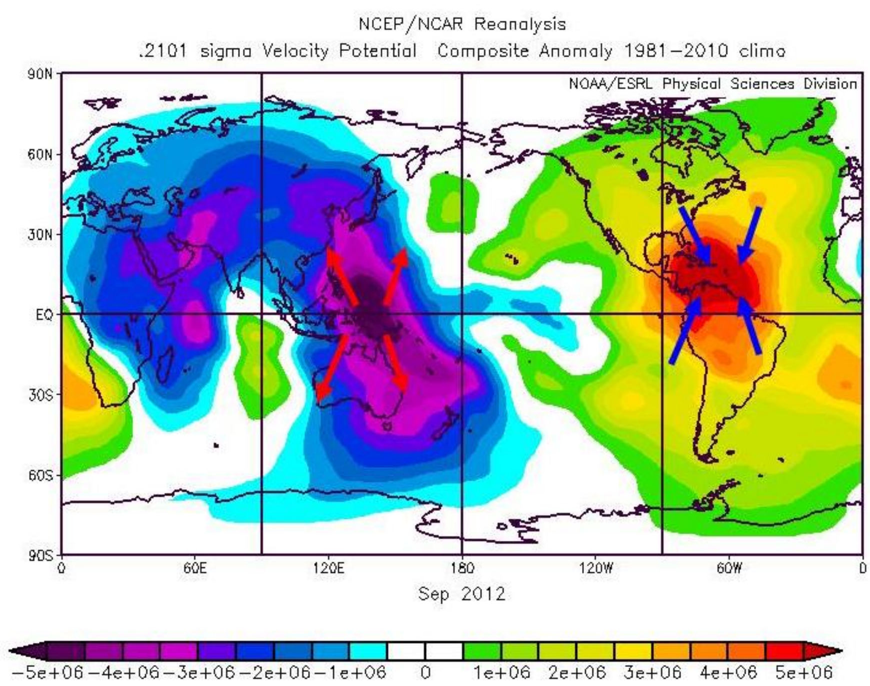

Figure 44: Upper-level velocity potential anomalies in September 2012. Note the positive velocity potential anomalies that occurred during the month across the tropical Atlantic. The red arrows indicate upper-level divergence, while the blue arrows indicate upper-level convergence.

8.7 Steering Currents

As was the case in both 2010 and 2011, most tropical cyclones that formed in the MDR this year recurved before impacting the United States coastline (with the exception of Hurricane Isaac). The United States has now gone seven years without a landfalling major hurricane. A trough of low pressure centered over the Ohio Valley and extending into the western Atlantic generated southerly winds which helped steer systems tracking toward the United States mainland out to sea (Figure 45).

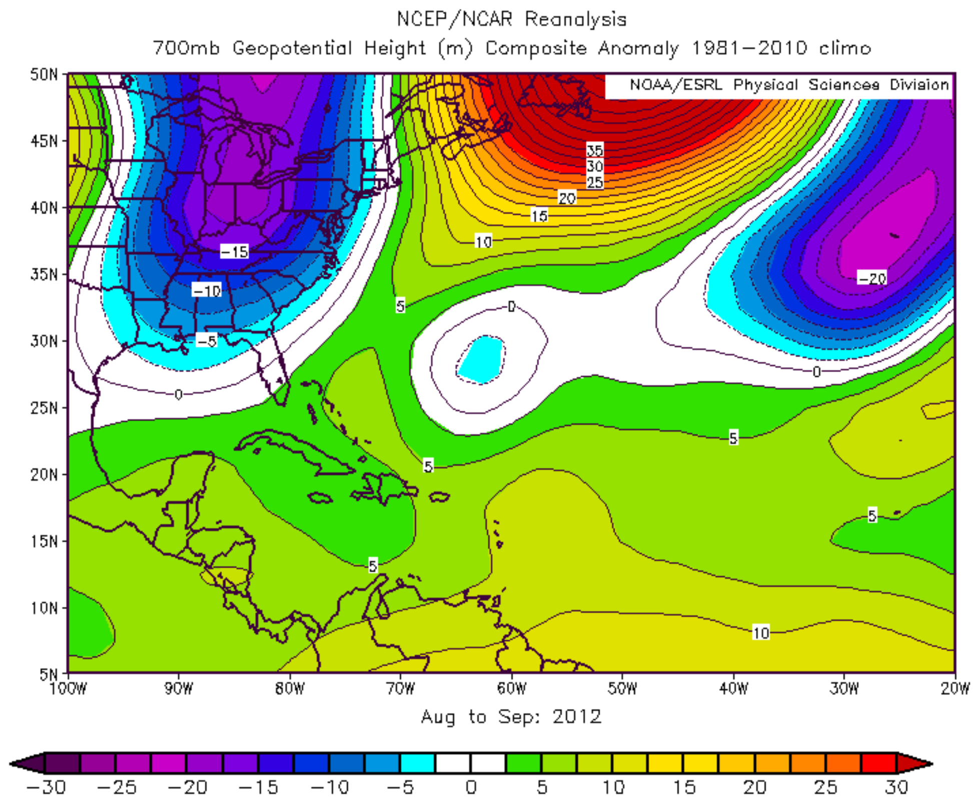

Figure 45: 700-mb height anomalies in the central and western part of the Atlantic in August-September 2012. Anomalous troughing dominated along the East Coast of the United States, thereby imparting steering currents that helped cause most TCs to recurve before making US landfall.

8.8 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 46). 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 46). 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 47 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.

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).

We believe that the positive AMO (and strong THC) that has typically been present since 1995 experienced a brief significant weakening during the second half of the winter of 2011, but then restrengthened in the late spring and early summer of 2012. We infer these changes from the dramatic fluctuations in the strength of the NAO that were observed during the winter of 2011/2012 and spring/summer of 2012 and strongly influenced 2012 hurricane activity.

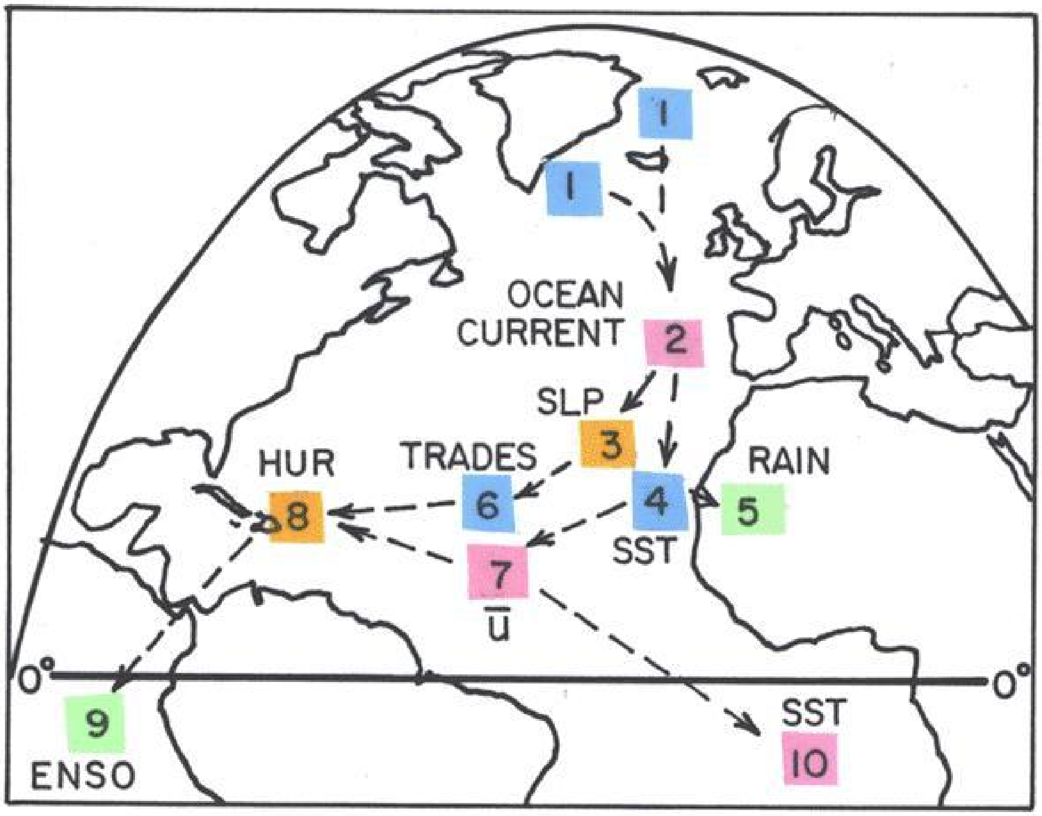

Figure 46: Schematic showing the large number of parameters that are closely related to the AMO or THC.

8.9 Summary

The 2012 Atlantic basin hurricane season had above-average tropical cyclone activity, more than what was predicted in our seasonal forecasts. The likely reason for this was due to the warmer tropical Atlantic and lack of development of El Niño. Despite these TC-enhancing conditions in the tropical Atlantic, the MDR was relatively quiet, likely due to the strong dry anomalies and subsidence that were present over the MDR during the months of July and September. A weakness in the subtropical ridge located near the East Coast helped induce the recurvature of several systems that might otherwise have threatened the U.S. coastline. We have now gone seven years since the last major hurricane made U.S. landfall (Wilma – October 2005).

9 Forecasts of 2012 Hurricane Activity

We will be issuing our first outlook for the 2013 hurricane season on Friday, 7 December 2012. This forecast will provide a qualitative outlook for factors likely to impact the 2013 hurricane season. This December forecast will include the dates of all of our updated 2012 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 17: Verification of the authors' early August forecasts of Atlantic named storms and hurricanes between 1984-2012. 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 28 years for named storms and 22 of 28 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	14	5	9
Average	**11.0**	**10.9**	**6.3**	**6.2**
1984-2012 Correlation		**0.62**		**0.59**

Table 18: Summary verification of the authors' four previous years of seasonal forecasts for Atlantic TC activity between 2008-2011. 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	26.00
Named Storm Days	85	80	80	80	89.75
Major Hurricanes	5	5	5	5	4
Major Hurricane Days	10	10	10	10	4.50
Net Tropical Cyclone Activity	180	175	175	175	145