SUMMARY OF 2011 ATLANTIC TROPICAL CYCLONE ACTIVITY AND VERIFICATION OF AUTHOR'S SEASONAL AND TWO-WEEK FORECASTS

The 2011 hurricane season had above-average tropical cyclone activity but not to the levels that we predicted. It was notable for having many weak tropical cyclones but only slightly above-average intense tropical cyclone activity.

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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 2011

Forecast Parameter and 1950-2000 Climatology (in parentheses)	8 Dec 2010	Update 6 April 2011	Update 1 June 2011	Update 3 Aug 2011	Observed 2011 Total
Named Storms (NS) (9.6)	17	16	16	16	19*
Named Storm Days (NSD) (49.1)	85	80	80	80	90.50
Hurricanes (H) (5.9)	9	9	9	9	7*
Hurricane Days (HD) (24.5)	40	35	35	35	25
Major Hurricanes (MH) (2.3)	5	5	5	5	3
Major Hurricane Days (MHD) (5.0)	10	10	10	10	4.50
Accumulated Cyclone Energy (ACE) (96.2)	165	160	160	160	125
Net Tropical Cyclone Activity (NTC) (100%)	180	175	175	175	137

*Nate was upgraded to a hurricane in the National Hurricane Center's post-season analysis. An unnamed tropical storm has been identified by the National Hurricane Center in post-season analysis as well.

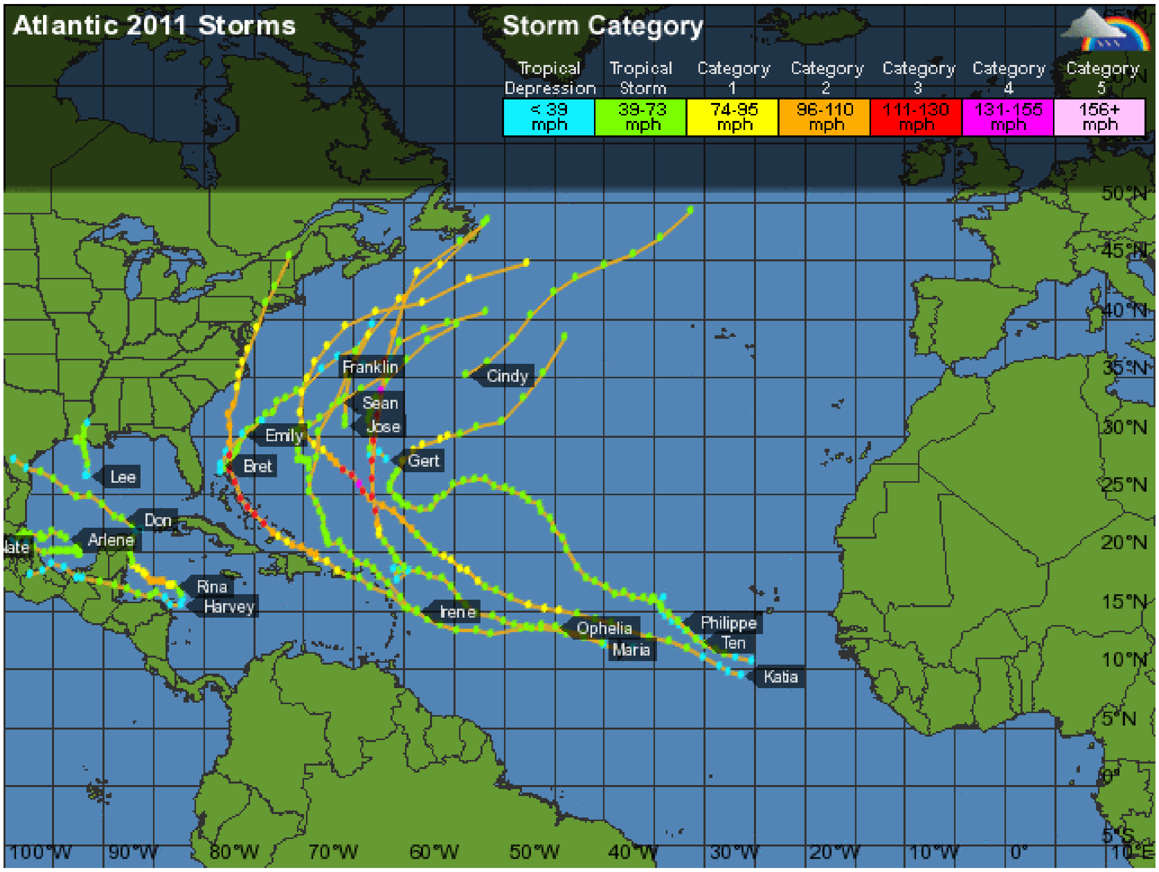

Figure courtesy of Weather Underground (http://www.wunderground.com)

ABSTRACT

This report summarizes tropical cyclone (TC) activity which occurred in the Atlantic basin during 2011 and verifies the authors' seasonal Atlantic and Caribbean basin forecasts. Also verified are an October-November-only Caribbean forecast and two-week Atlantic basin forecasts during the peak months of the hurricane season. A forecast was initially issued for the 2011 season on 6 December 2010 with updates on 6 April, 1 June, and 3 August of this year. These seasonal forecasts also contained estimates of the probability of U.S. and Caribbean hurricane landfall during 2011. Our Atlantic basin seasonal hurricane forecasts predicted a very active hurricane season. We slightly under-predicted named storms and named storm days while we over-predicted more intense hurricane activity for the entire Atlantic basin and particularly for the Caribbean.

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 reasonably accurate this year. Our first October-November Caribbean basin-only forecast successfully predicted an active end of the season in the Caribbean.

Atlantic basin hurricane activity in 2011 was well above-average for the number of weak TCs, while more intense TC activity was at slightly above- average levels. Integrated measures such as Net Tropical Cyclone (NTC) activity and Accumulated Cyclone Energy (ACE) were at somewhat above-average levels. This was likely due to a combination of anomalously warm tropical Atlantic sea surface temperatures (SSTs) and a La Niña event. Anomalously cool sub-tropical Atlantic SSTs and a positive Indian Ocean Dipole (IOD) event were likely responsible for the stronger vertical shear and drier mid-levels that were experienced this year compared with 2010. This stronger-than-normal vertical shear and drier-than-normal middle levels in the atmosphere were responsible for the unexpectedly low levels of more intense TC activity.

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 10-20°N, 20-70°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

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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.

Tropical Meteorology Project Changes for 2012

There will be a couple of changes to our forecasts for the 2012 Atlantic basin hurricane season. Our December forecast will contain only a qualitative discussion of physical features (such as ENSO and the AMO) that are likely to be responsible for dictating how much tropical cyclone activity will occur. We will not be releasing a quantitative forecast with our December outlook for 2012. We will release our December forecast on December 7, 2011. Our first quantitative forecast for the 2012 Atlantic hurricane season will be given in early April.

We are changing our climatology from the 1950-2000 mean to the 1981-2010 median. The primary reason we are doing this is to take into account the increased number of weaker named storms during the latter part of the 20th century and early part of the 21st century. This is due to the fact that with vastly improved observational capabilities, more weak tropical cyclones are being identified.

While a sixty-year climatology is needed to take into account the full observed Atlantic multi-decadal variability associated with the Atlantic Multi-decadal Oscillation (AMO) or thermohaline circulation (THC), we are using a shorter, thirty-year climatology. We feel this is justified because about half of the years from 1981-2010 were part of an active phase of the AMO (1995-2010) while the other half were part of an inactive phase of the AMO (1981-1994). We are also changing to use the median as opposed to the mean, as the median is more robust to large outlier seasons (such as 2004 and 2005). Table A compares the 1950-2000 mean climatology versus our new 1981-2010 median climatology.

Table A: The 1950-2000 climatological mean (our old climatology baseline) and the 1981-2010 climatological median (our new climatology baseline).

Forecast Parameter	1950-2000 Mean	1981-2010 Median
Named Storms (NS)	9.6	12.0
Named Storm Days (NSD)	49.1	60.1
Hurricanes (H)	5.9	6.5
Hurricane Days (HD)	24.5	21.3
Major Hurricanes (MH)	2.3	2.0
Major Hurricane Days (MHD)	5.0	3.9
Accumulated Cyclone Energy (ACE)	96	92
Net Tropical Cyclone Activity (NTC)	100	103

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 initial early December forecast scheme (started in 1991 for the 1992 hurricane season) 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 2011

Figure A and Table 2 summarize Atlantic basin TC activity which occurred in 2011. An above-average season was experienced for most TC parameters.

3 Individual 2011 Tropical Cyclone Characteristics

The following is a brief summary of each of the named tropical cyclones in the Atlantic basin for the 2011 season. Figure A shows the tracks of all of this season's tropical cyclones (except the newly classified unnamed tropical cyclone – for which no track or storm description were currently available), 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, except for Cindy, Don, Franklin, Gert, and Nate, where data from the final best track was available. Online entries from Wikipedia (http://www.wikipedia.org) were very helpful in putting together these tropical cyclone summaries.

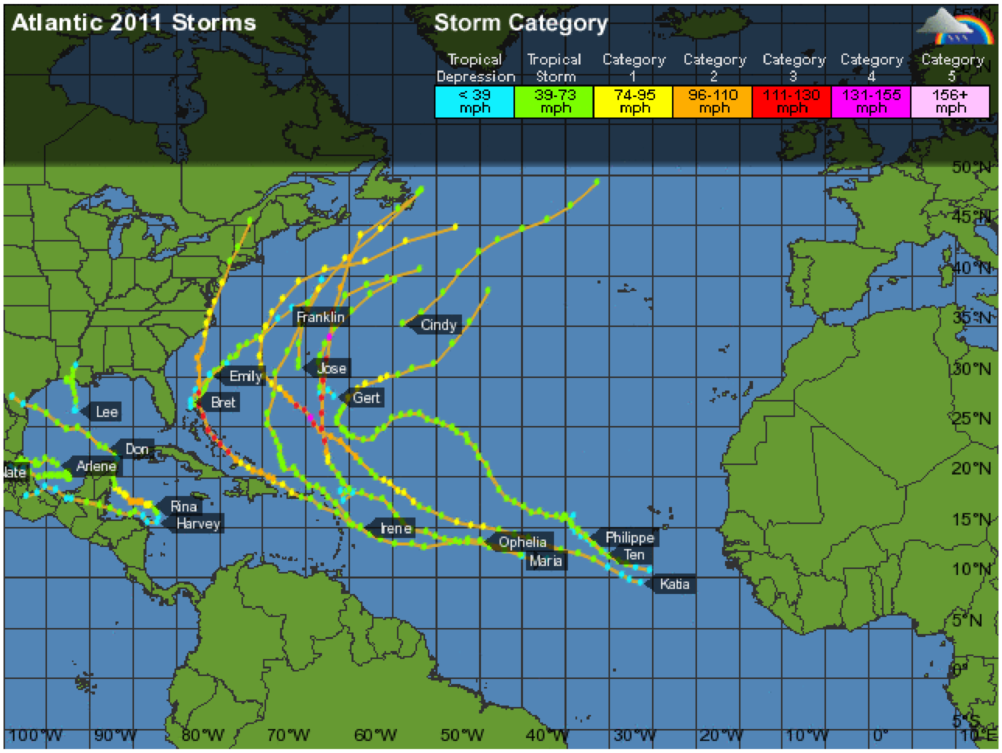

Figure A: Tracks of 2011 Atlantic Basin tropical cyclones. Figure courtesy of Weather Underground (http://www.wunderground.com).

Table 2: Observed 2011 Atlantic basin tropical cyclone activity.

Highest Category	Name	Dates	Peak Sustained Winds (kts)/lowest SLP (mb)	NSD	HD	MHD	ACE	NTC
TS	Arlene (1)	June 29 – 30	55 kt/993 mb	2.00			1.7	2.4
TS	Bret (2)	July 18 – 21	55 kt/998 mb	4.00			3.0	3.1
TS	Cindy (3)	July 20 – 22	60 kt/994 mb	2.50			2.3	2.6
TS	Don (4)	July 27 – 30	45 kt/997 mb	2.50			1.6	2.6
TS	Emily (5)	August 1 – 4	45 kt/1004 mb	3.00			2.1	2.8
TS	Franklin (6)	August 13	40 kt/1004 mb	0.50			0.3	1.9
TS	Gert (7)	August 14 – 16	55 kt/1000 mb	2.25			1.9	2.5
TS	Harvey (8)	August 19 – 21	50 kt/994 mb	1.75			1.4	2.3
MH-3	Irene (9)	August 20 - 28	105 kt/942 mb	8.25	6.25	1.50	20.3	23.9
TS	Jose (10)	August 28 – 29	40 kt/1007 mb	1.25			0.7	2.2
MH-4	Katia (11)	August 30 – September 10	115 kt/946 mb	11.25	9.00	1.00	25.7	25.1
TS	Unnamed (12)	September 1 – 2	40 kt/1002 mb	1.50			0.8	2.2
TS	Lee (13)	September 2 – 5	50 kt/986 mb	3.00			2.0	2.8
H-1	Maria (14)	September 7 – 16	70 kt/979 mb	9.50	1.25		9.1	8.6
H-1	Nate (15)	September 7 – 11	65 kt/994 mb	4.50	0.50		4.5	6.4
MH-4	Ophelia (16)	September 21 – 25, September 28 - October 3	120 kt/940 mb	10.25	3.75	2.00	19.4	24.5
H-1	Philippe (17)	September 24 – October 8	80 kt/976 mb	14.25	1.25		15.0	10.2
H-2	Rina (18)	October 24 – 28	95 kt/966 mb	4.75	3.00		9.2	8.2
TS	Sean (19)	November 8 - 11	55 kt/983 mb	3.50			3.5	2.9
Totals	19			90.50	25.00	4.50	124.5	137.2

*An unnamed tropical storm was identified north of Bermuda on September 1-2. The intensity estimate for this system is preliminary.

Tropical Storm Arlene (#1): Arlene formed late on June 28 in the southwestern Gulf of Mexico (Figure 1). The system became better organized the following day, although westerly wind shear prevented Arlene from strengthening significantly. It reached its maximum intensity of 55 knots early on June 30 while making landfall near Cabo Rojo, Mexico. Following landfall, Arlene weakened rapidly over the mountainous terrain of central Mexico and was downgraded to a remnant low early on July 1. Flooding rains from Arlene were responsible for 25 deaths in Mexico.

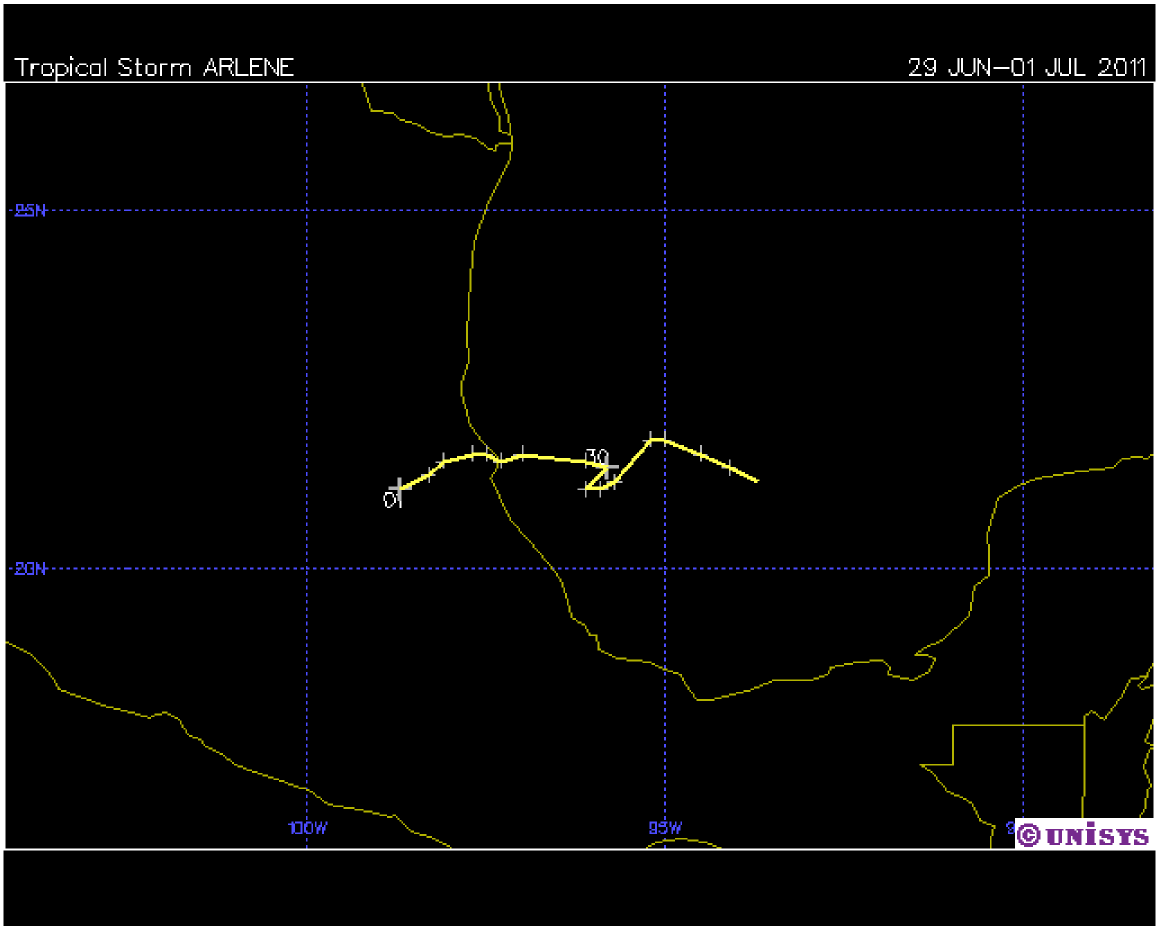

Figure 1: Track of Tropical Storm Arlene. Figure courtesy of Unisys Weather. The yellow line indicates a system at tropical storm strength.

Tropical Storm Bret (#2): Bret formed form an area of low pressure on July 17 while located just to the north of the northwestern Bahamas (Figure 2). It was upgraded to a tropical storm shortly thereafter. It drifted eastward and strengthened slowly over the next 24 hours, reaching a maximum intensity of 55 knots, before strong northeasterly shear and dry air began to take its toll on the system. Bret moved northeastward on the northern side of a subtropical ridge and encountered increasing shear as it tracked north of Bermuda. It was downgraded to a tropical depression early on July 22 and was classified as post-tropical later that day.

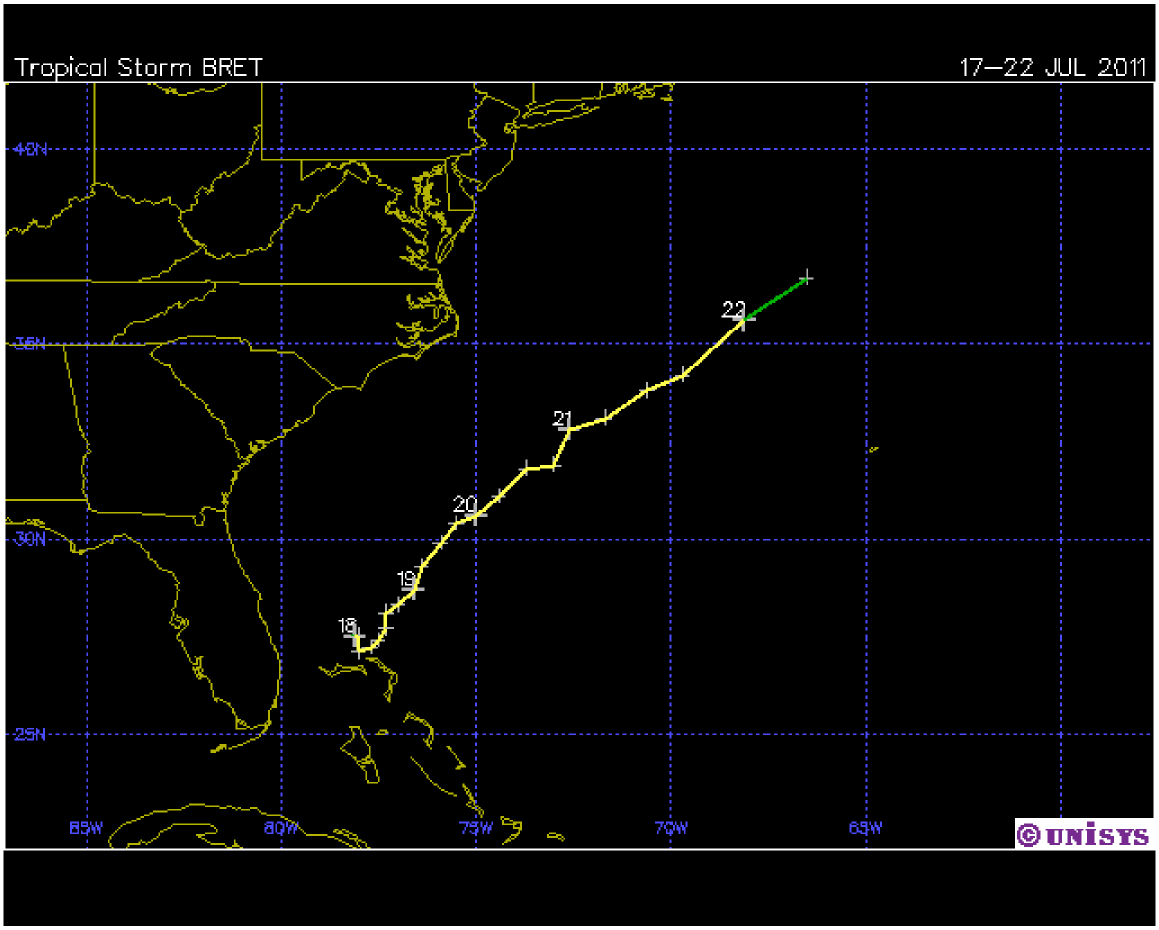

Figure 2: Track of Tropical Storm Bret. Figure courtesy of Unisys Weather. The yellow line indicates a system at tropical storm strength, while the green line indicates tropical depression strength.

Tropical Storm Cindy (#3): Cindy formed from an area of low pressure north of Bermuda on July 20 (Figure 3). The system reached its maximum intensity of 60 knots the following day while accelerating northeastward, being steered by a trough to its northwest. Cindy's convection began to wane early on July 22 as it encountered cooler sea surface temperatures, and it was declared post-tropical later that day.

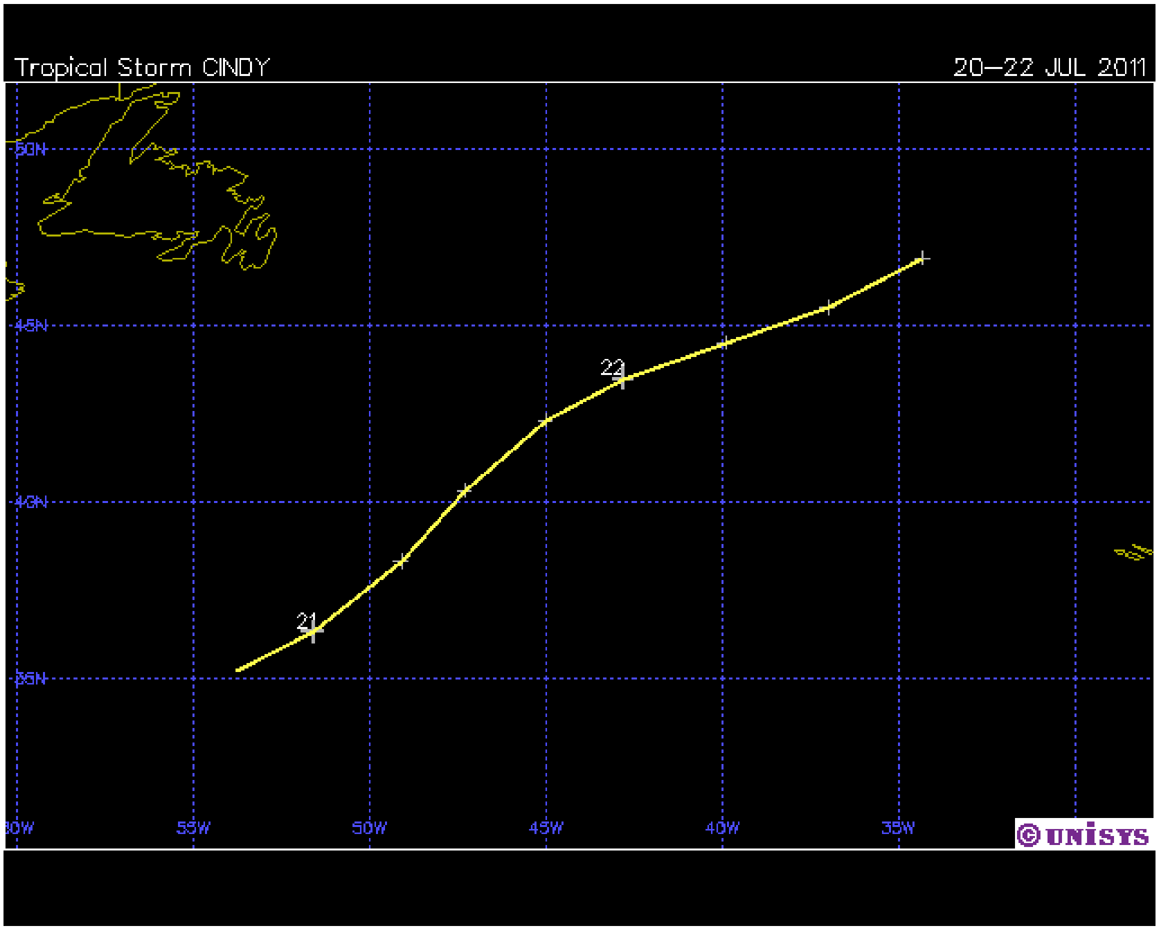

Figure 3: Track of Tropical Storm Cindy. Figure courtesy of Unisys Weather. The yellow line indicates a system at tropical storm strength.

Tropical Storm Don (#4): Don formed in the southern Gulf of Mexico from a tropical wave on July 27 (Figure 4). Northerly vertical shear prevented much strengthening as Don moved northwestward underneath a ridge. It reached its maximum intensity of 45 knots as it approached the Gulf Coast. Increasing northerly shear rapidly decimated the cyclone as it approached the Texas coast. Don was downgraded to a tropical depression before it made landfall near Baffin Bay on July 30. It was classified as post-tropical shortly thereafter.

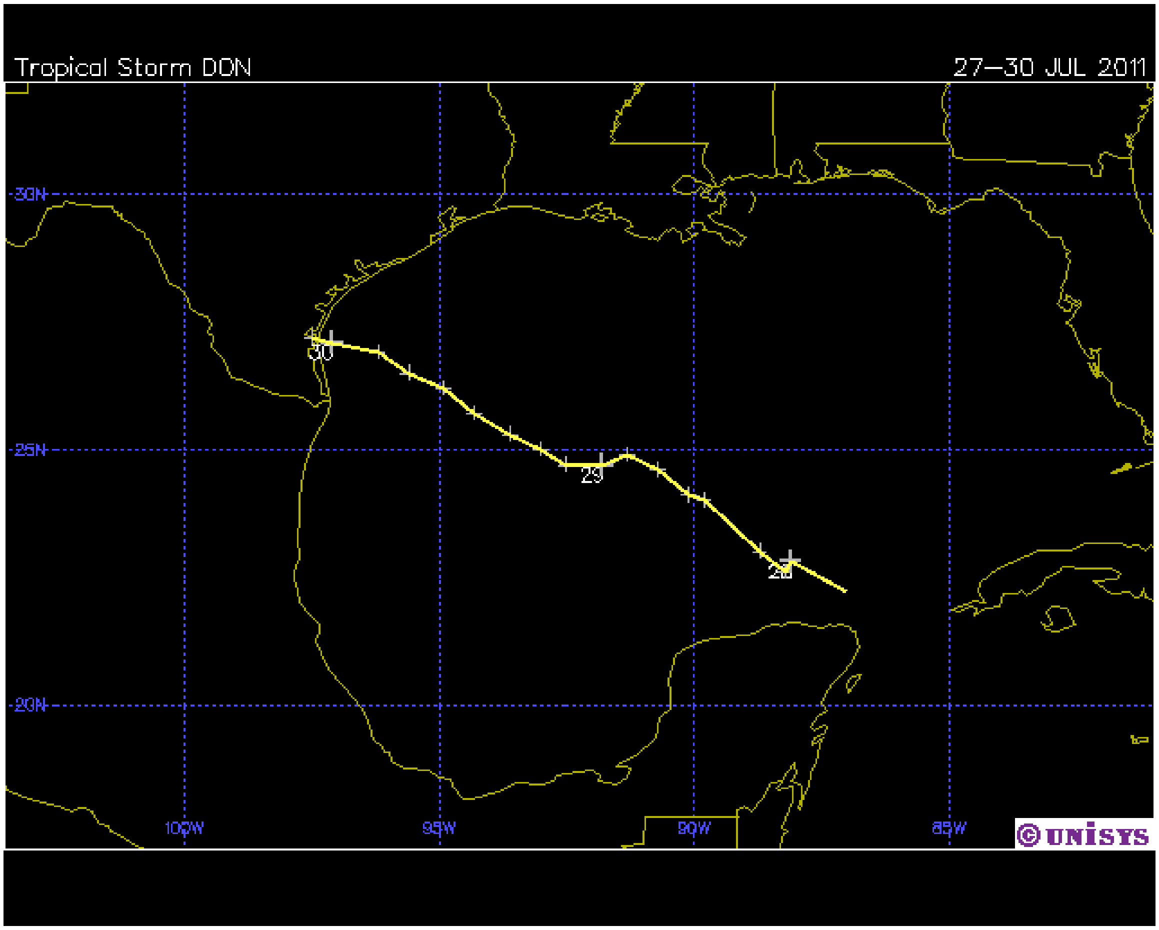

Figure 4: Track of Tropical Storm Don. The yellow line indicates a system at tropical storm strength.

<u>Tropical Storm Emily (#5)</u>: Emily formed near Dominica on August 1 from a tropical wave. Significant dry air to the system's northwest prevented much intensification during the early part of Emily's lifespan. By late on August 2, Emily intensified to its maximum intensity of 45 knots; however westerly shear prevented additional intensification. Emily's relatively weak circulation was decimated by the high terrain of Hispaniola, and it was downgraded to a trough of low pressure on August 4. The system became re-classified as a tropical depression on August 6, but continued dry air and northeasterly shear prevented much intensification, and Emily eventually dissipated north of the Bahamas on August 7.

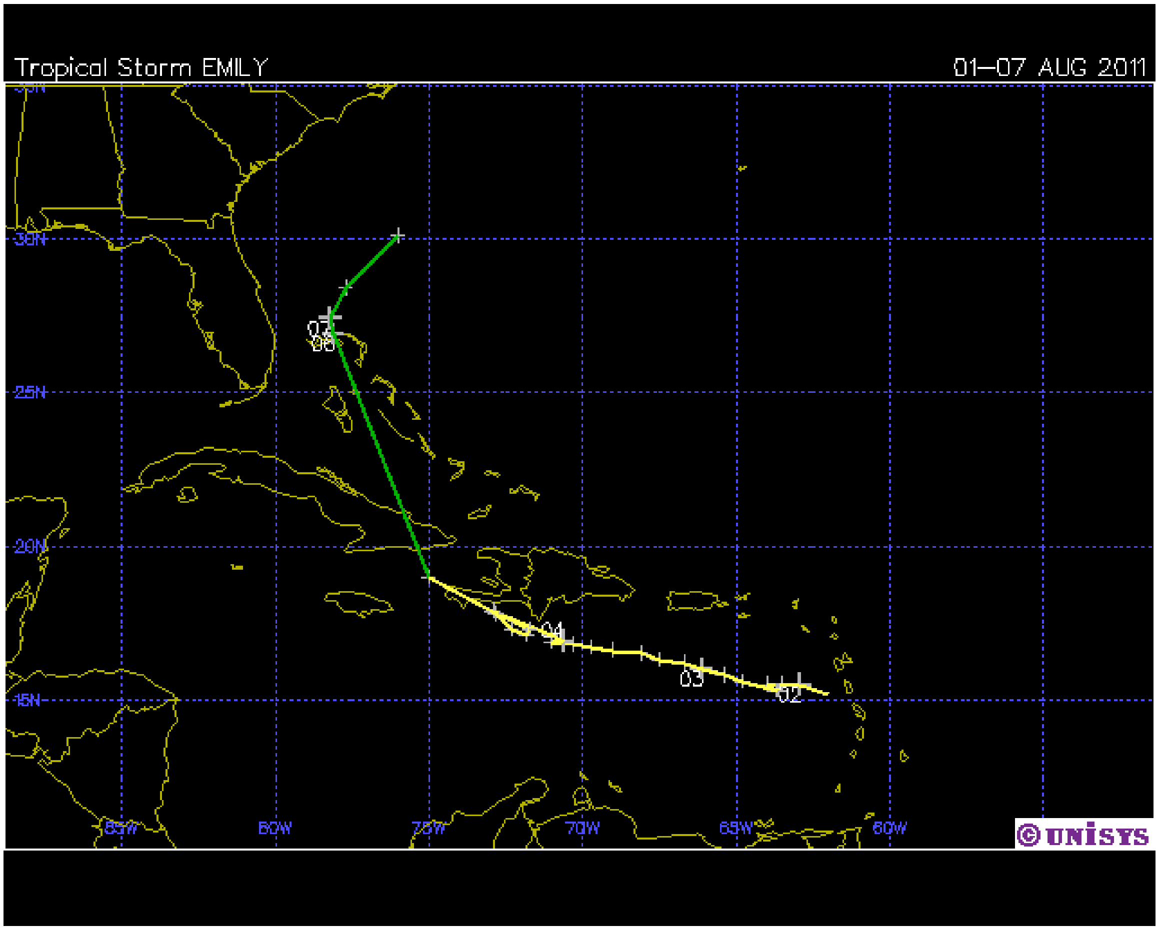

Figure 5: Track of Tropical Storm Emily. Figure courtesy of Unisys Weather. The yellow line indicates a system at tropical storm strength, while the green line indicates tropical depression strength.

Tropical Storm Franklin (#6): Franklin formed form an area of low pressure north of Bermuda on August 12. It intensified to a tropical storm the following day while tracking northeastward along the northern periphery of the subtropical ridge. Increasing levels of vertical shear and cooler water rapidly weakened the cyclone, and it was classified as post-tropical late on August 13.

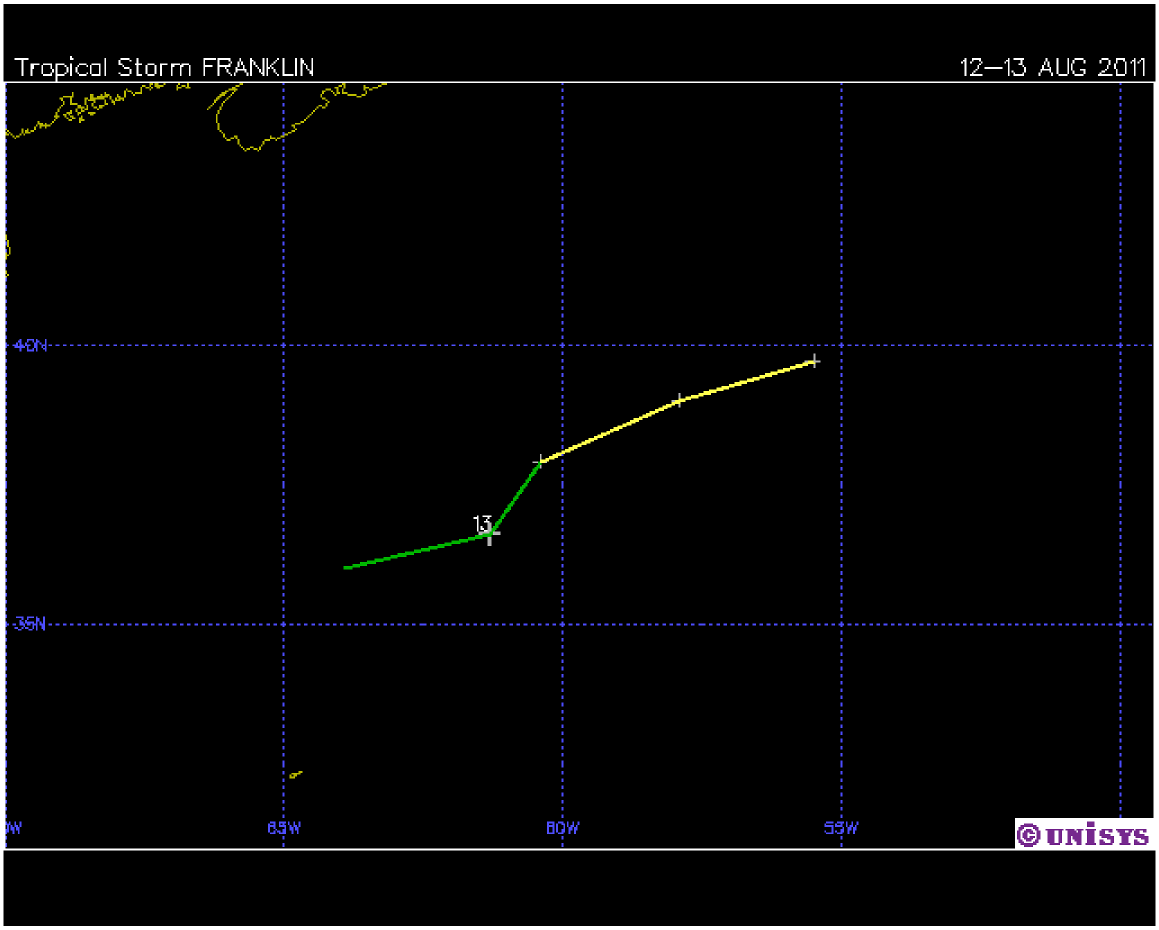

Figure 6: Track of Tropical Storm Franklin. Figure courtesy of Unisys Weather. The yellow line indicates a system at tropical storm strength, while the green line indicates tropical depression strength.

Tropical Storm Gert (#7): Gert formed from an area of low pressure while located southeast of Bermuda on August 14 (Figure 7). It intensified to a tropical storm later that day while moving northward. A small upper-level low to the south of Gert helped to improve the outflow from the system, and it intensified to a 55-knot tropical cyclone while tracking just southeast of Bermuda. As the system moved toward cooler water, it began to weaken. The combination of cooler water and increasing southwesterly shear caused Gert to transition to a post-tropical cyclone as it moved northeastward into the North Atlantic on August 16.

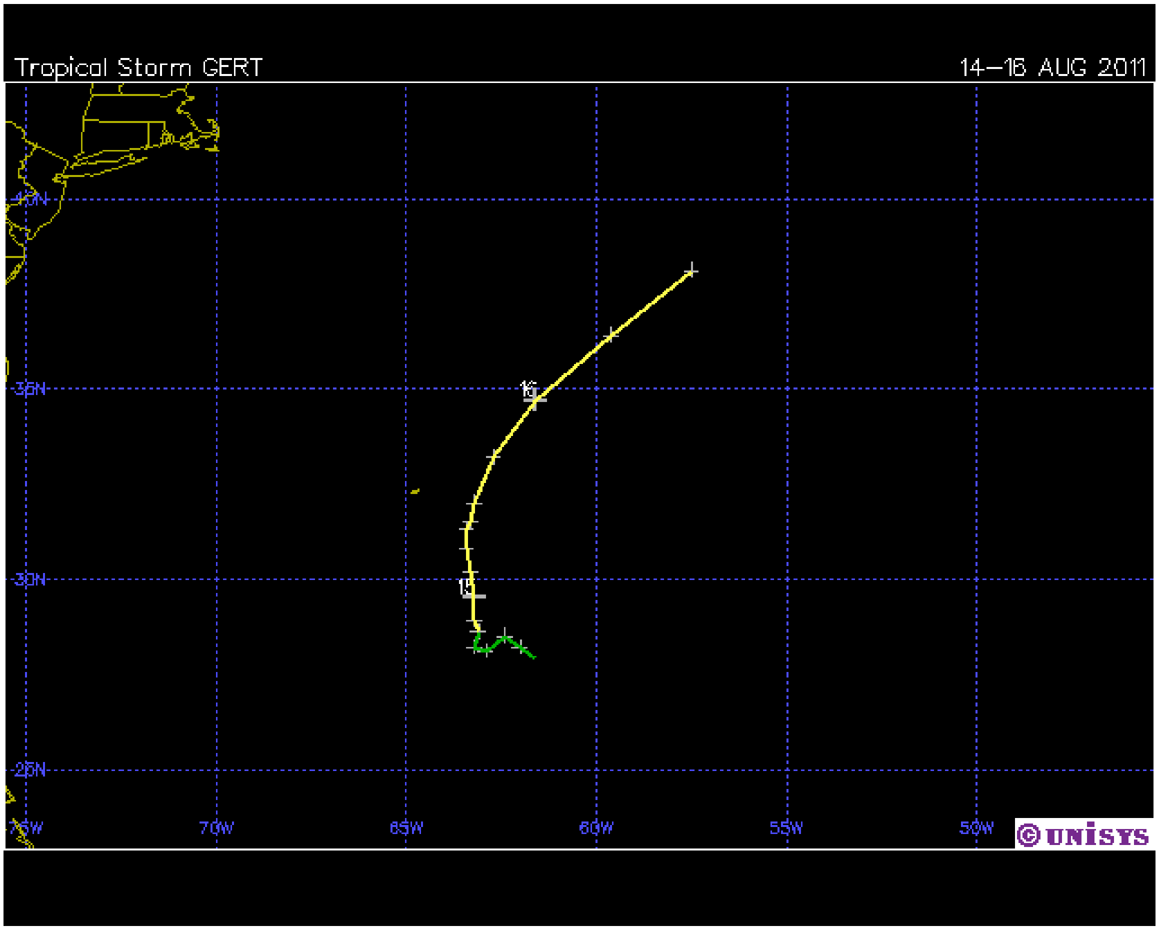

Figure 7: Track of Tropical Storm Gert. Figure courtesy of Unisys Weather. The yellow line indicates a system at tropical storm strength, while the green line indicates tropical depression strength.

<u>Tropical Storm Harvey (#8):</u> Harvey developed from a tropical wave in the western Caribbean on August 18. A mid-level ridge steered Harvey westward just off the coast of northern Honduras. It intensified to a tropical storm the following day as it approached the coast of Belize. Harvey reached its maximum intensity of 50 knots before making landfall in Belize on August 20. It weakened to a tropical depression the following day, briefly re-emerging over the southern Bay of Campeche before dissipating over Mexico on August 22. Heavy rainfall from Harvey was responsible for three deaths in Mexico, while minimal damage was attributed to the system.

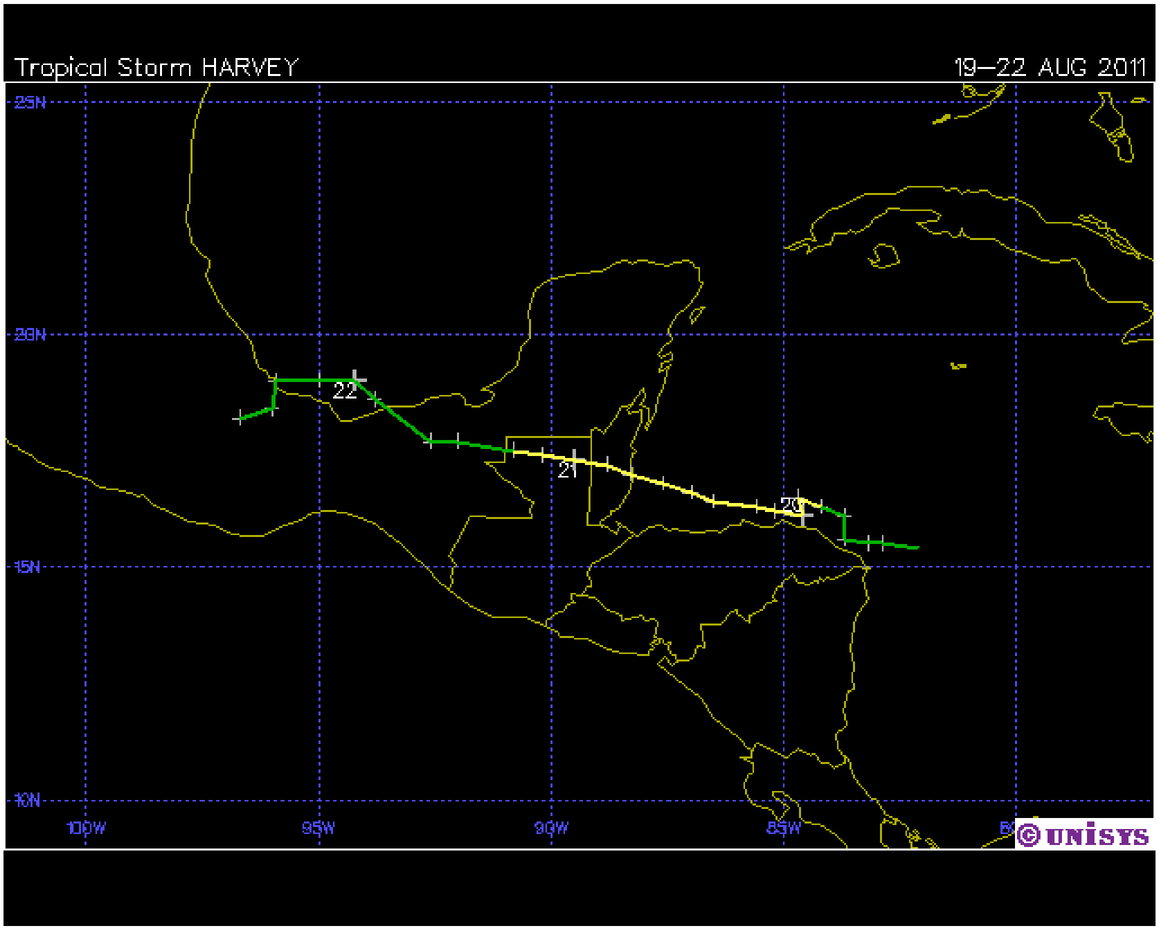

Figure 8: Track of Tropical Storm Harvey. Figure courtesy of Unisys Weather. The yellow line indicates a system at tropical storm strength, while the green line indicates tropical depression strength.

<u>Major Hurricane Irene (#9)</u>: Irene formed just east of the Lesser Antilles late on August 20 and was classified as a tropical storm at its first advisory. It brought heavy rains to the Lesser Antilles as well as Puerto Rico as it passed through the island chain. A subtropical ridge steered Irene towards the northwest during the earlier part of its lifetime. By August 22, Irene was upgraded to the first hurricane of the 2011 season. It brushed by the northern part of Hispaniola as it continued to trek northwestward. Irene moved over very warm waters near 30°C as it approached the Bahamas, and consequently, it continued to intensify into a major hurricane on August 24. Irene battered most of the islands of the Bahamas with very strong winds and heavy rain as it began to recurve towards the north, due to a break in the subtropical ridge. Irene slowly weakened as it encountered some southwesterly shear along with slightly cooler SSTs. During its lifetime, Irene expanded in size and was a very large TC by the time that it made landfall in North Carolina as a weakening Category 1 hurricane on August 27. It then rapidly accelerated northward, making a second landfall in New Jersey before undergoing extra-tropical transition over northern New England. Irene was responsible for considerable wind and flooding damage throughout the Lesser Antilles, Puerto Rico, the Bahamas and the US East Coast. Up to three billion dollars in damage is estimated to have occurred in the Caribbean and the Bahamas, while estimates range as high as $10-$15 billion dollars in damage for the United States. Vermont, upstate New York and New Jersey were especially devastated by Irene's flooding.

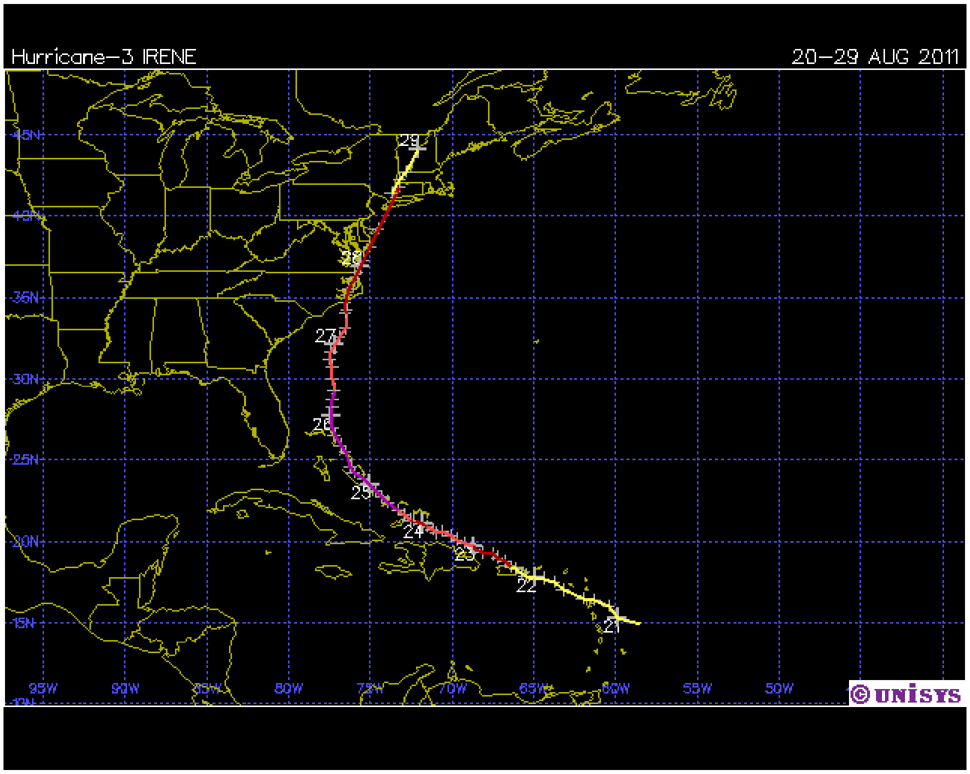

Figure 9: Track of Major Hurricane Irene. Figure courtesy of Unisys Weather. The purple line indicates a system at major hurricane strength, the red line indicates a system at hurricane strength, and the yellow line indicates a system at tropical storm strength.

Tropical Storm Jose (#10): Tropical Storm Jose formed while located southwest of Bermuda on August 28. It briefly intensified to an estimated maximum intensity of 40 knots, before strong easterly shear decimated the tropical cyclone. It merged with a frontal boundary on August 29. Jose did bring some tropical-storm force wind gusts to Bermuda, but no significant damage was reported.

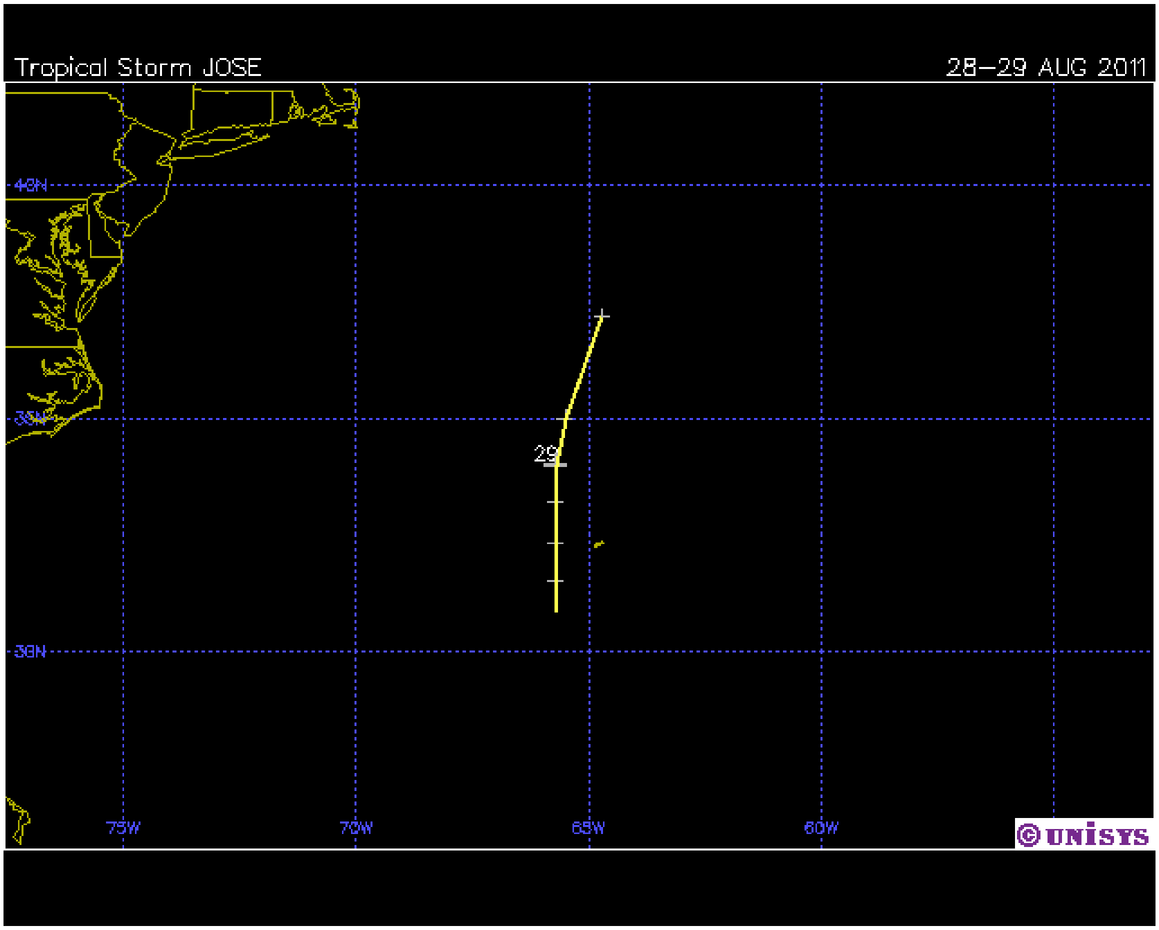

Figure 10: Track of Tropical Storm Jose. Figure courtesy of Unisys Weather. The yellow line indicates a system at tropical storm strength.

<u>Major Hurricane Katia (#11):</u> Katia was initially identified as a tropical depression on August 29 while located in the far eastern Atlantic (Figure 11). It intensified into a tropical storm the following day while tracking west-northwestward. By early on September 1, Katia was upgraded to the 2nd hurricane of the 2011 season. An upper-level low near Katia began to impart moderate southwesterly shear over Katia later that day, and it weakened back to a tropical storm. It reintensified to a hurricane the following day, but continued southwesterly shear caused Katia to weaken back to a tropical storm on September 4. Katia then began to track more northwestward and intensified as it moved away from the influence of the upper-level low. By the following day, Katia reached major hurricane strength as it tracked northwestward around the western periphery of the subtropical ridge, eventually reaching Category 4 status early on September 6. It began to weaken the following day as it went through an eyewall replacement cycle. By late on September 8, Katia began to turn northeastward ahead of a trough of low pressure off the East Coast of the United States. By September 10, Katia became a very strong post-tropical cyclone. Katia was responsible for two deaths due to rip currents and high seas in the United States, and its post-tropical remnants brought strong winds and heavy rain to England and Ireland.

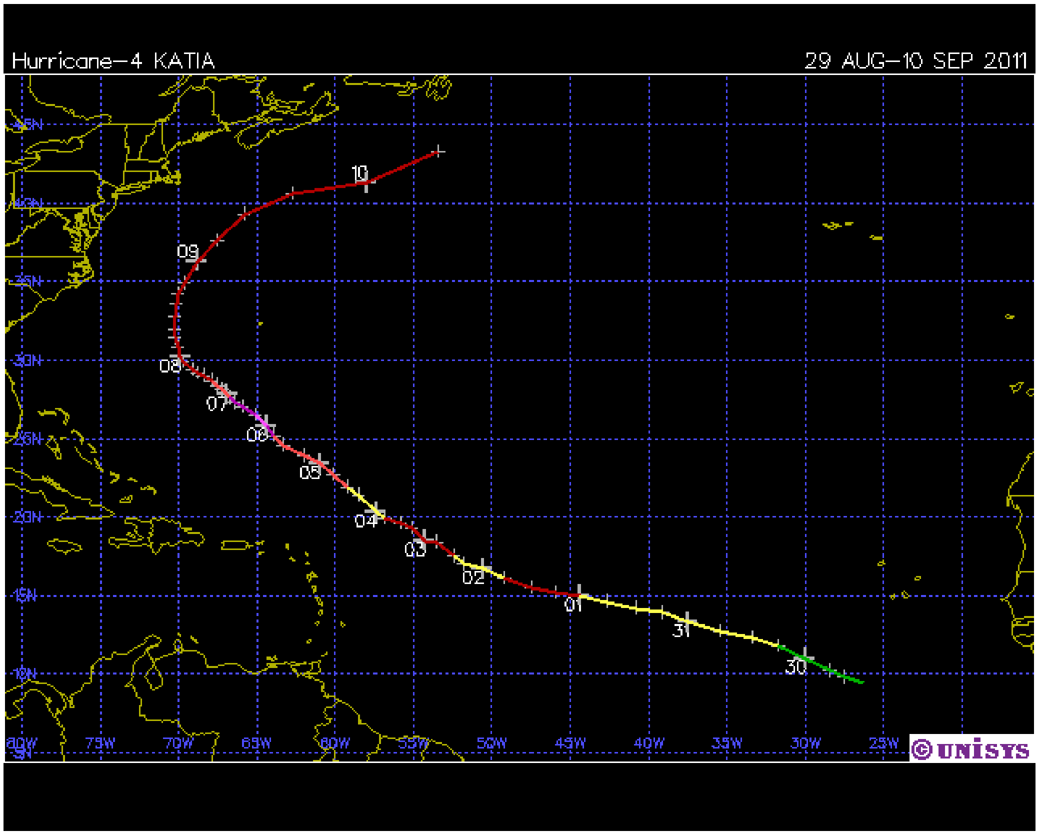

Figure 11: Track of Major Hurricane Katia. Figure courtesy of Unisys Weather. The purple line indicates a system at major hurricane strength, the red line indicates a system at hurricane strength, the yellow line indicates a system at tropical storm strength, while the green line indicates tropical depression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

Tropical Storm Lee (#12): Lee developed from a broad area of low pressure in the central Gulf of Mexico late on September 1 (Figure 12). The system slowly became better organized and intensified into a tropical storm the following day. A blocking pattern prevented much movement of Lee during most of its lifetime, and it slowly drifted north towards the central Louisiana coast. A small upper-level low to Lee's northwest imparted significant shear over the system and prevented rapid development. Despite these somewhat adverse conditions, Lee managed to strengthen into a 50-knot tropical storm before making landfall near Intracoastal City, Louisiana as a weakening tropical storm. By early on September 5, Lee was downgraded to a post-tropical cyclone. Lee was responsible for heavy amounts of rainfall from the Gulf Coast extending up the Eastern Seaboard. While helping to ameliorate drought conditions in Louisiana, Lee's rainfall compounded earlier flooding issues generated by Irene in both New York and Pennsylvania. A total of 21 fatalities have been blamed on Lee and its remnants, and damage from Lee is estimated at greater than 250 million dollars.

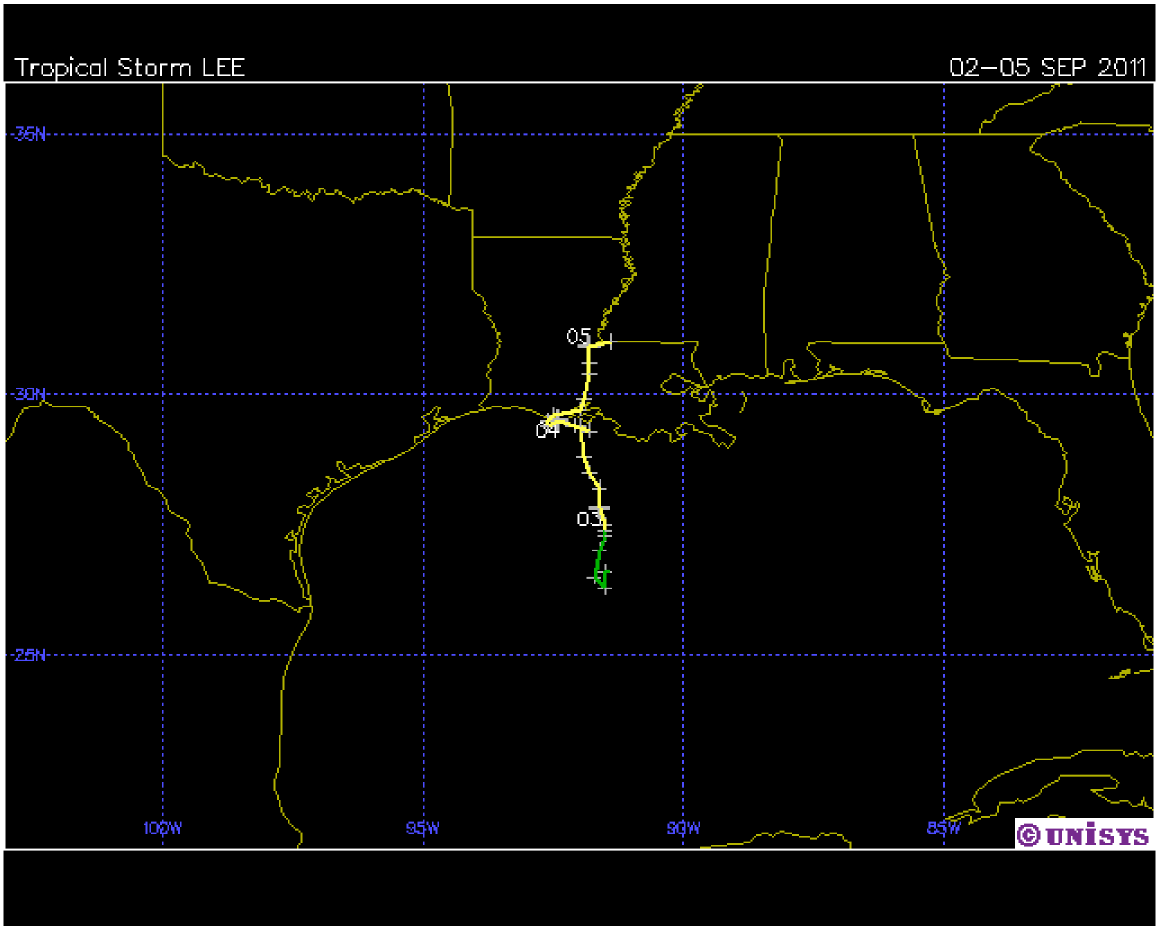

Figure 12: Track of Tropical Storm Lee. Figure courtesy of Unisys Weather. The yellow line indicates a system at tropical storm strength, while the green line indicates a system at tropical depression strength.

Hurricane Maria (#13): Maria developed in the eastern tropical Atlantic from a tropical wave (Figure 13). It intensified into a tropical storm as it moved rapidly westward on September 7. An upper-level low to Maria's northwest inhibited intensification throughout most of its lifetime, and Maria weakened to a marginal tropical storm on September 8. It continued to battle strong southwesterly shear as it approached the northern Leeward Islands. An upper-level trough moving off of the US East Coast began to recurve Maria towards the north and northeast. After battling strong southwesterly shear for several days, Maria encountered a more favorable environment as it passed west of Bermuda. It intensified into a hurricane, reaching a maximum intensity of 70 knots as it accelerated northeastward. Maria made landfall near Cape Pine, Newfoundland and underwent extra-tropical transition shortly thereafter. No fatalities or significant damage were reported in Newfoundland from Maria.

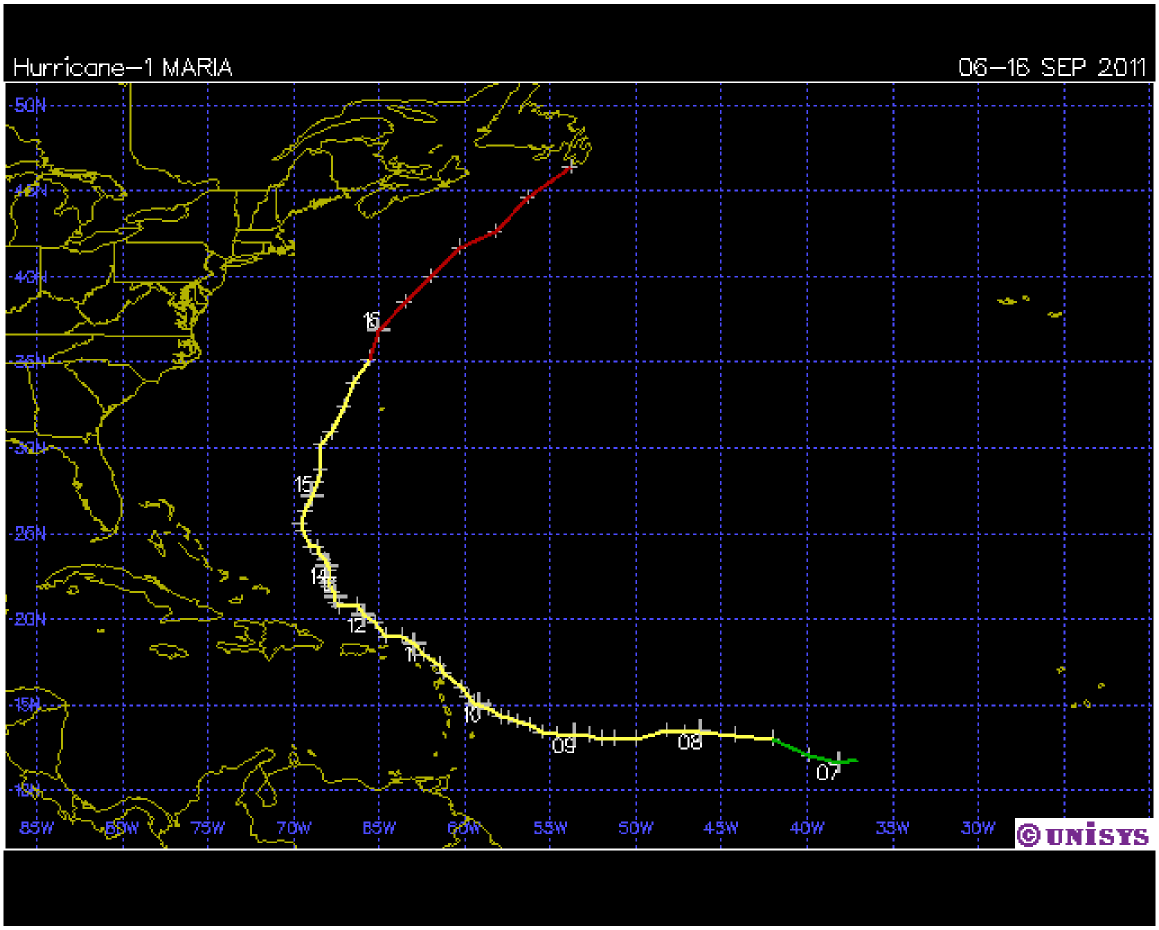

Figure 13: Track of Hurricane Maria. Figure courtesy of Unisys Weather. The red line indicates a system at hurricane strength, the yellow line indicates a system at tropical storm strength, while the green line indicates tropical depression strength.

<u>Hurricane Nate (#14):</u> Nate formed from a small area of low pressure in the southern Bay of Campeche on September 7. It was in an area of very little steering flow and drifted very slowly north-northwestward over the next couple of days. It reached its maximum intensity of 65 knots (upgraded from 60 knots in post-season analysis) the following day while it continued to move very slowly. Dry air in the western Gulf inhibited additional strengthening, and Nate weakened slowly as it approached the eastern coast of Mexico. Another potential weakening factor was that Nate upwelled significant amounts of cold water which it then slowly moved over as it drifted during the first few days of its lifetime. It made landfall near Barra de Nautla, Mexico as a 40-knot tropical storm and became post-tropical soon thereafter as it encountered the high terrain of the Sierra Madre. Five fatalities were attributed to Nate, while no significant damage was reported.

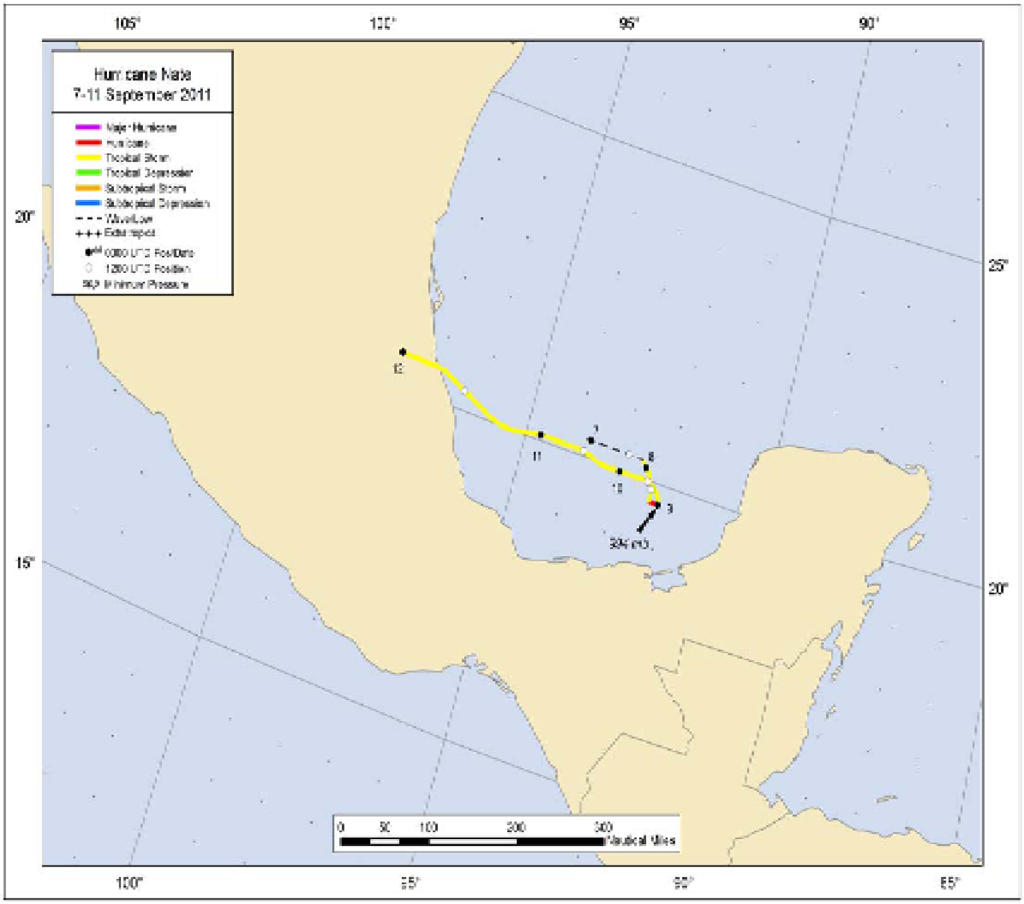

Figure 14: Track of Hurricane Nate. Figure courtesy of the National Hurricane Center. The yellow line indicates a system at tropical storm strength, and the red line indicates a system at hurricane strength. The dotted line indicates when Nate was a wave.

<u>Major Hurricane Ophelia (#15):</u> Ophelia formed from a tropical wave in the eastern Atlantic on September 21 (Figure 15). Ophelia slowly strengthened as it moved northwestward, although strong southwesterly shear from an upper-level low to the system's northwest prevented much strengthening. By September 24, the system began to succumb to the strong shear, and it degenerated into a tropical wave by late on September 25. On September 27, the shear abated somewhat, and Ophelia was re-classified as a tropical depression. The environment around Ophelia continued to improve, and the system strengthened into a tropical storm on September 28 and a hurricane on September 29. By the following day, Ophelia rapidly intensified into a major hurricane while tracking northward over the central Atlantic. It reached Category 4 status on October 1 as it tracked east of Bermuda. Stronger shear and cooler SSTs eventually weakened Ophelia to a tropical storm on October 2, and the system lost its tropical characteristics as it passed over Newfoundland the following day. Ophelia was responsible for minor flooding in the Lesser Antilles and brought tropical storm-force winds to Newfoundland. No fatalities were attributed to the system, and damage from Ophelia was minor.

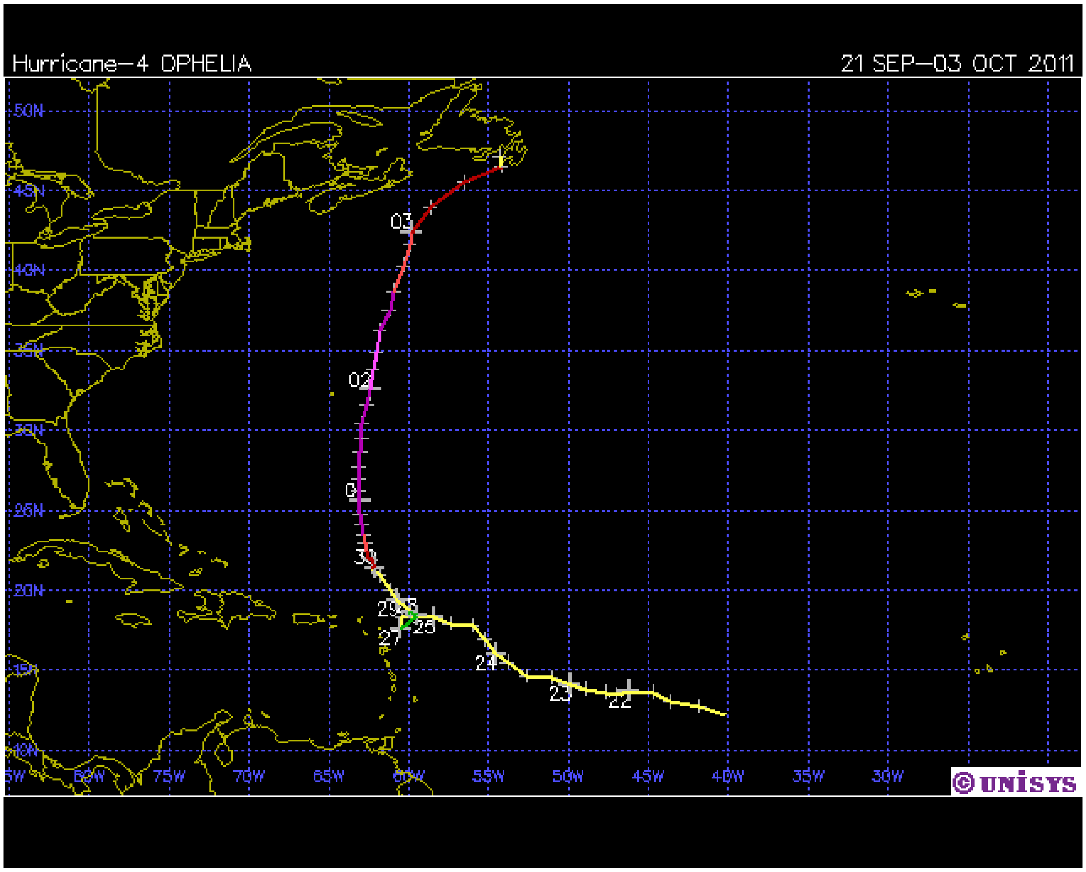

Figure 15: Track of Major Hurricane Ophelia. Figure courtesy of Unisys Weather. The purple line indicates a system at major hurricane strength, the red line indicates a system at hurricane strength, the yellow line indicates a system at tropical storm strength, while the green line indicates tropical depression strength.

Hurricane Philippe (#16): Philippe developed in the far eastern Atlantic on September 24. It was upgraded to a tropical storm later that day. It slowly tracked northwestward under the subtropical ridge for the next couple of days while intensifying slightly. A strong upper-level trough to the west of Philippe imparted strong southwesterly shear over the system, and it weakened to a 35-knot tropical storm on September 27. Over the next several days, Philippe slowly strengthened, despite strong southwesterly shear, only to suddenly weaken again on October 2. By the following day, the shear began to abate somewhat, and Philippe intensified again. As it reached the central Atlantic, Philippe began to recurve towards the north and then northeast as a strong trough weakened the western periphery of the subtropical ridge. It intensified into a hurricane on October 6, reaching a maximum intensity of 80 knots before weakening as it moved over cooler waters and encountered stronger shear. It merged with a frontal boundary on October 8 and was declared post-tropical at that time.

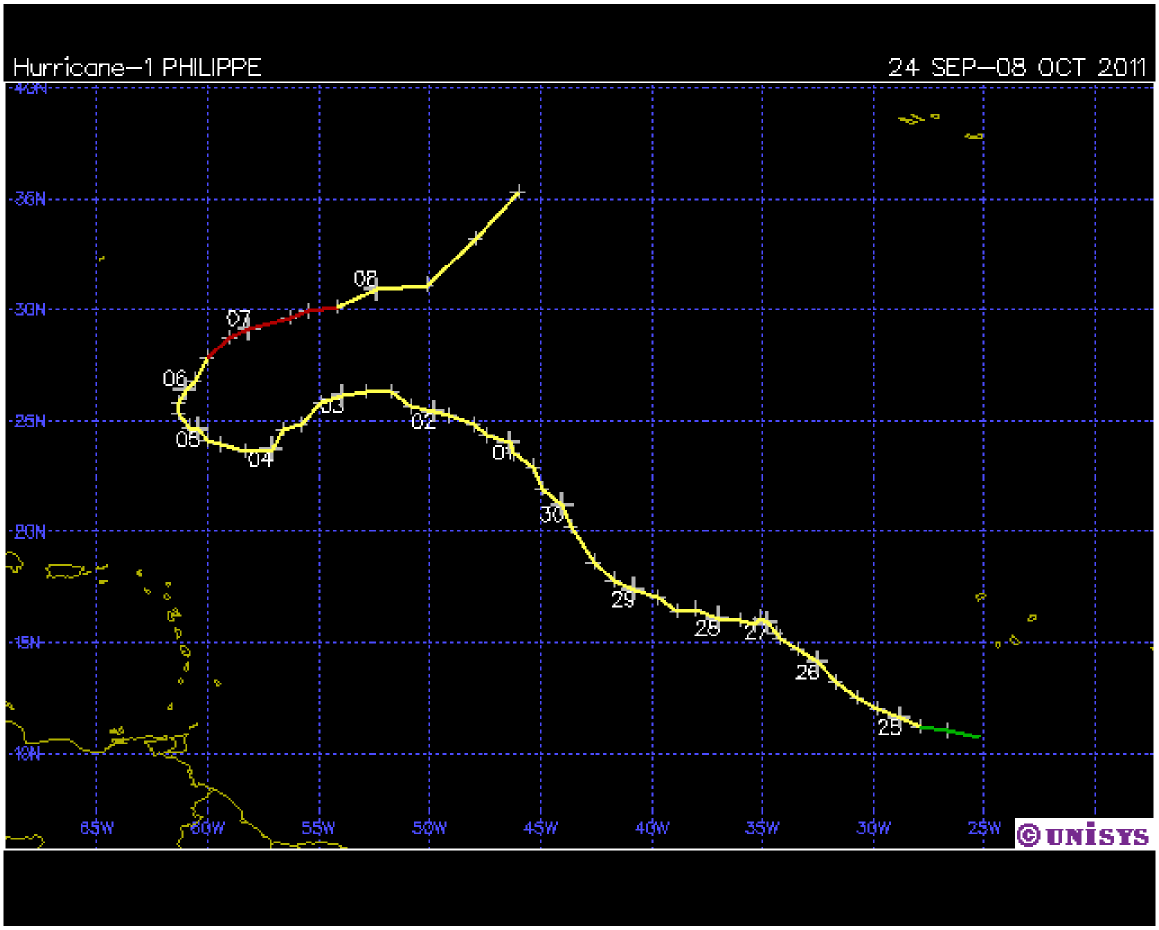

Figure 16: Track of Hurricane Philippe. Figure courtesy of Unisys Weather. The red line indicates a system at hurricane strength, the yellow line indicates a system at tropical storm strength, while the green line indicates tropical depression strength.

Hurricane Rina (#17): Rina formed in the northwest Caribbean on October 23 (Figure 17). It intensified into a tropical storm early on October 24 as it tracked slowly northwestward. It soon moved into an area of very high oceanic heat content where it rapidly intensified into a hurricane. It reached its maximum intensity of 95 knots on October 26 before encountering much stronger vertical shear and rapidly weakening to a 75-knot hurricane. The system stabilized as a Category 1 hurricane briefly before being downgraded to a tropical storm on October 27. It made landfall near Cozumel as a 50-knot tropical storm later that day. Continued strong vertical shear, dry air entrainment and interaction with the Yucatan Peninsula weakened the system further, and it was downgraded to a remnant low on October 28. No fatalities were attributed to Rina.

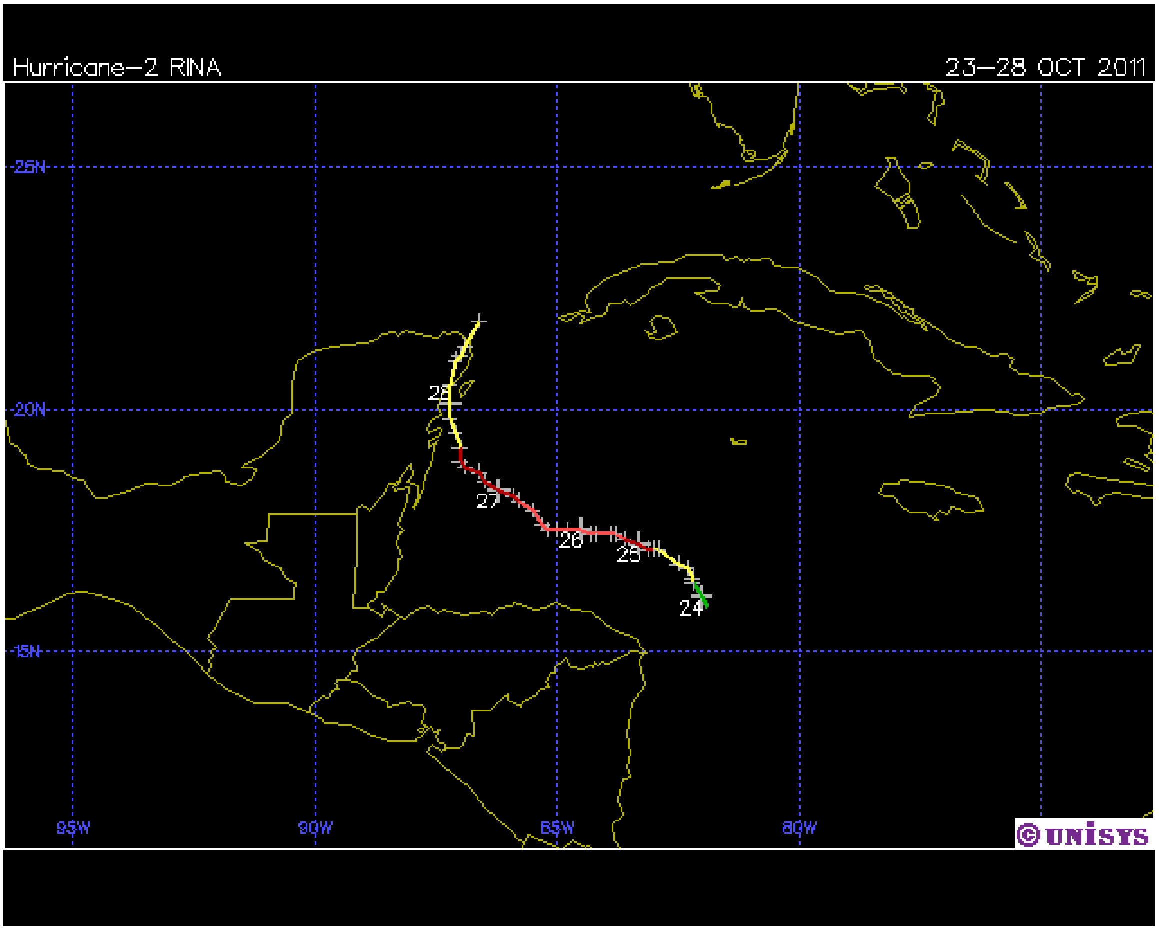

Figure 17: Track of Hurricane Rina. Figure courtesy of Unisys Weather. The red line indicates a system at hurricane strength, the yellow line indicates a system at tropical storm strength, while the green line indicates tropical depression strength.

<u>Tropical Storm Sean (#18):</u> Sean developed from a non-tropical low pressure area between the Bahamas and Bermuda on November 8. It was initially classified as sub-tropical, but as more convection developed near the center of the circulation, it was re-classified as a tropical storm. The system slowly moved northward and intensified, reaching a maximum intensity of 55 knots the following day. An approaching mid-latitude trough caused Sean to curve towards the northeast as it brushed past Bermuda. Cooler waters and increased shear caused Sean to weaken, and it soon merged with a cold front, being declared extra-tropical at that time.

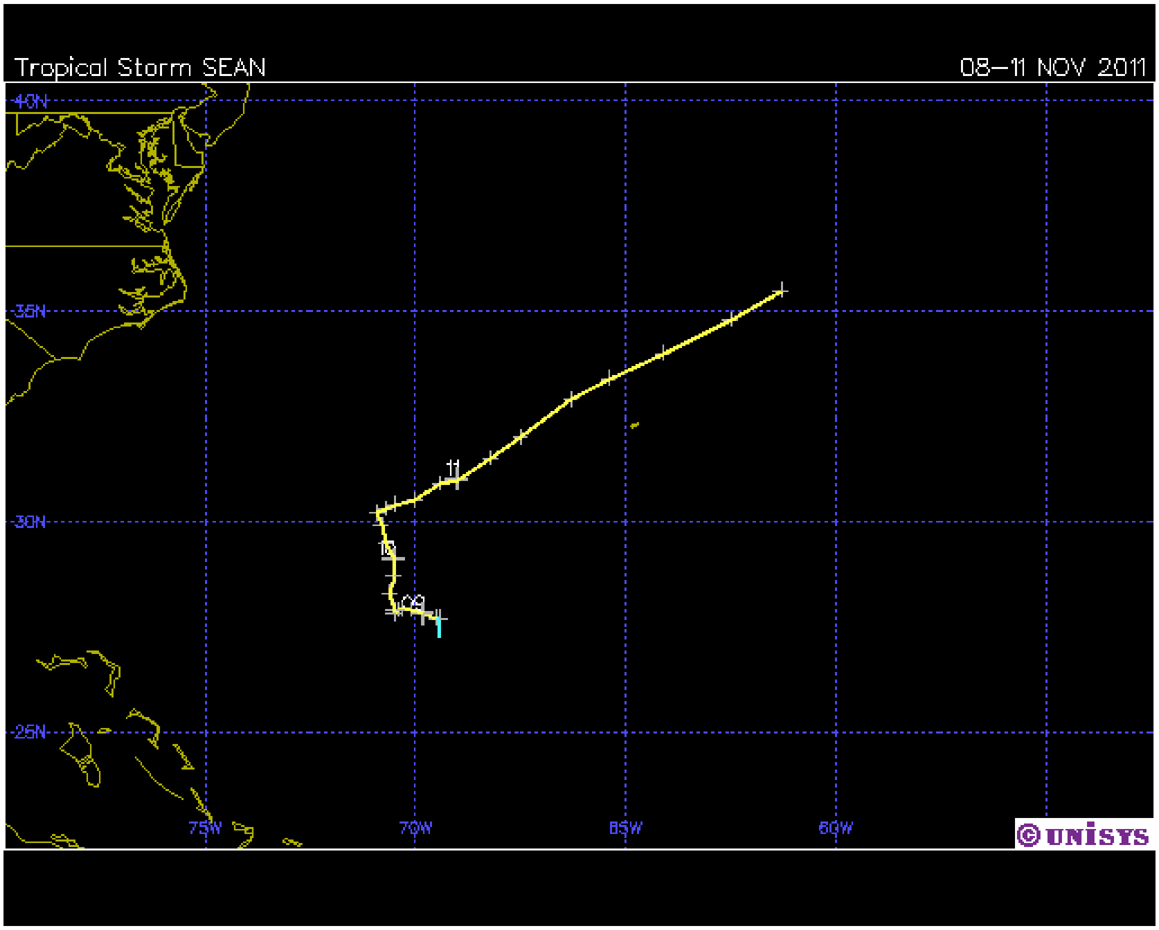

Figure 18: Track of Tropical Storm Sean. Figure courtesy of Unisys Weather. The yellow line indicates when Sean was a tropical storm, while the aqua line indicates the period where Sean was a sub-tropical storm.

U.S. Landfall. Figure 19 shows the tracks of Hurricane Irene and Tropical Storm Lee, which both made United States landfall this year. Table 3 summarizes the landfalling statistics for both of these systems. Damage and fatality estimates were obtained from Wikipedia.

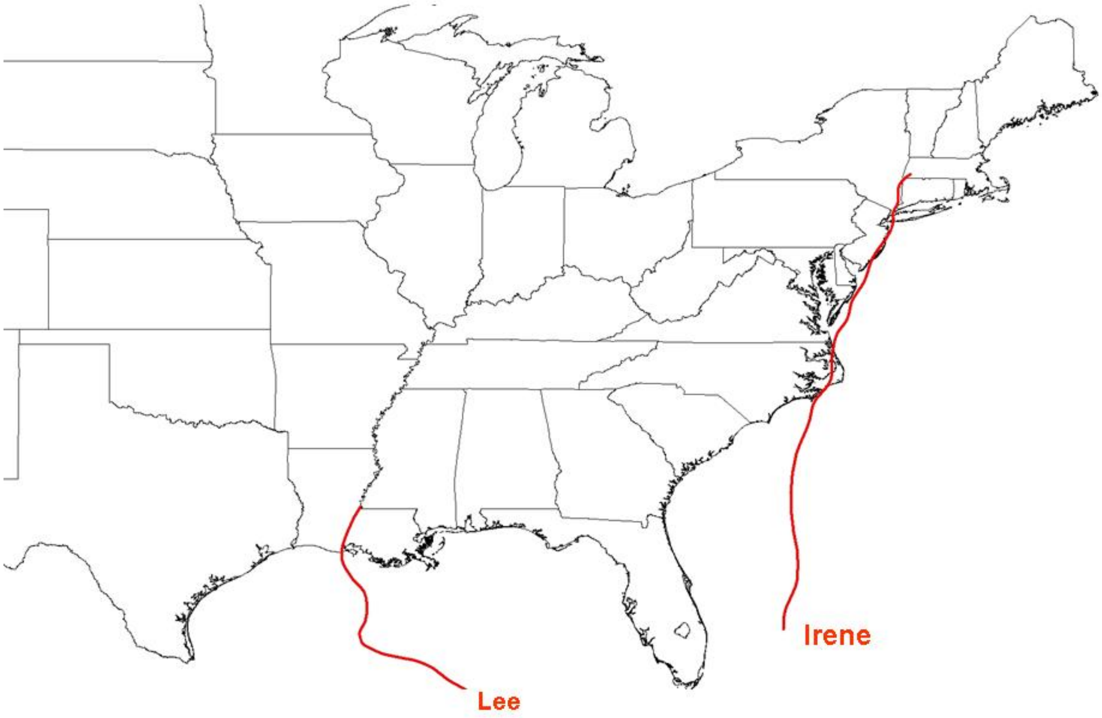

Figure 19: Tracks of Hurricane Irene and Tropical Storm Lee, both of which made landfall in the United States this year.

Table 3: Summary US landfall statistics for 2011.

	Landfall Date(s)	Location(s)	Insured Damage (Millions)	Fatalities
Hurricane Irene	August 27, 28	NC, NJ	\$3000-\$6000	45
Tropical Storm Lee	September 4	LA	>\$250	21

4 Special Characteristics of the 2011 Hurricane Season

The 2011 hurricane season had the following special characteristics:

- Nineteen named storms occurred during 2011. Only 2005 (28) and 1933 (21) have had more named storms than 2011.

- 90.5 named storm days occurred in 2011. This is the 6th most named storm days to occur in a single season since 1944.

- No Category 5 hurricanes developed in 2011. This is the fourth consecutive year with no Category 5 hurricanes. The last time that four or more years occurred in a row with no Category 5 hurricanes was 1999-2002.

- No major hurricanes made US landfall in 2011. The last major hurricane to make US landfall was Wilma (2005), so the US has now gone six years without a major hurricane landfall. Since 1878, the US has never had a six-year period without a major hurricane landfall.

- No named storms formed between September 24 – October 24. The last time that no named storms formed between these dates was 2002, when the last storm of the season (Lili) formed on September 21.

- Irene became the first hurricane of the season, following eight tropical storms. This is the longest string of tropical storms to start a season without a hurricane on record, breaking the old record of six in 2002.

- Hurricane Irene became the first hurricane to make US landfall since Hurricane Ike (2008).

- Hurricane Irene was the first system to make landfall at hurricane strength in New Jersey since 1903.

- Hurricane Philippe took the longest time of any system in recorded history (since 1851) to reach hurricane strength. Philippe was a named storm for 11.75 days before reaching hurricane strength for the first time.

5 Dearth of U.S. Major Hurricane Landfall Since 1995 (Except for 2004 and 2005)

The United States has been very fortunate during the recent 17-year active period (1995-2011) with regards to major hurricane landfalls. Approximately 80-85 percent of tropical cyclone-related damage is due to major hurricanes, when damage is normalized by population, inflation and wealth per capita (Pielke and Landsea 1998, Pielke et al. 2008). In the last 100 years, approximately 30% of all major hurricanes that form in the

Atlantic basin make United States landfall. Over the period from 1995-2011, we have had a total of 64 major hurricanes. Of these 64 major hurricanes, only 10 have made United States landfall as major hurricanes (16%), or approximately half of what we would expect given the long-term average. When we exclude the two very active major hurricane landfall years of 2004-2005 (7 major hurricanes making U.S. landfall out of 13 total major hurricanes that formed in the Atlantic basin), only three of the 51 major hurricanes that formed in the Atlantic basin from 1995-2003 and 2006-2011 have made U.S. landfall. This string of good luck can be extended further back into the past. For example, from 1941-1969, we averaged nearly one major hurricane landfall per year (Figure 20), compared with only 0.4 major hurricane landfalls per year from 1970-2011 (excluding 2004-2005) (Figure 21).

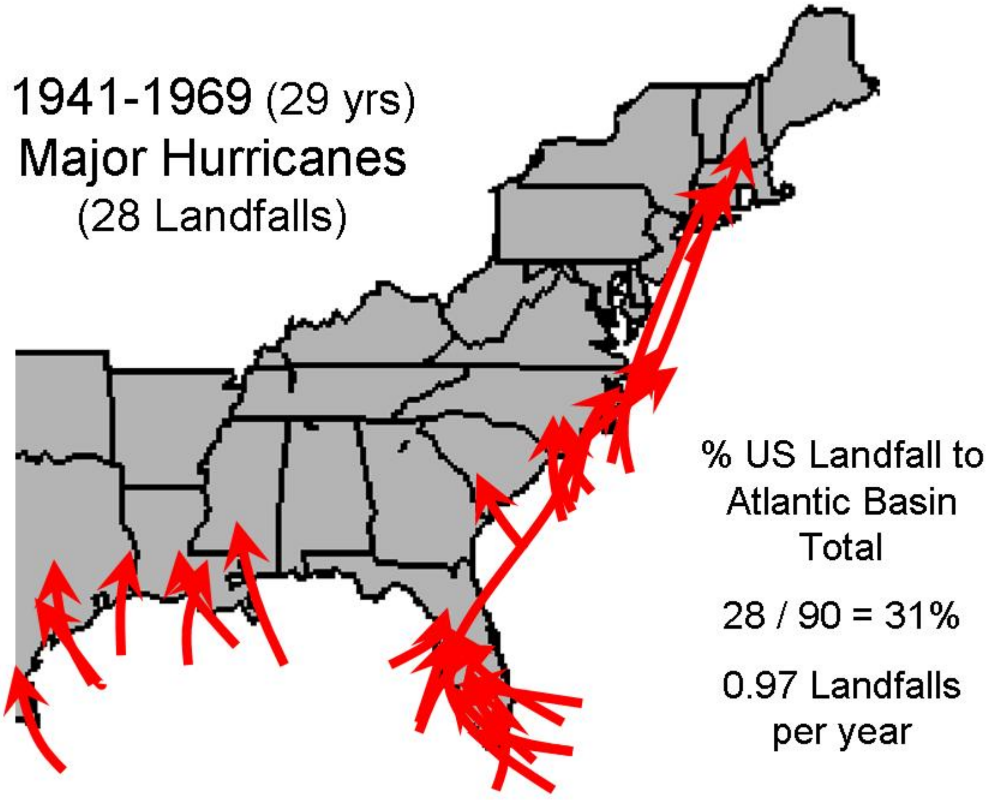

Figure 20: United States major hurricane landfalls from 1941-1969.

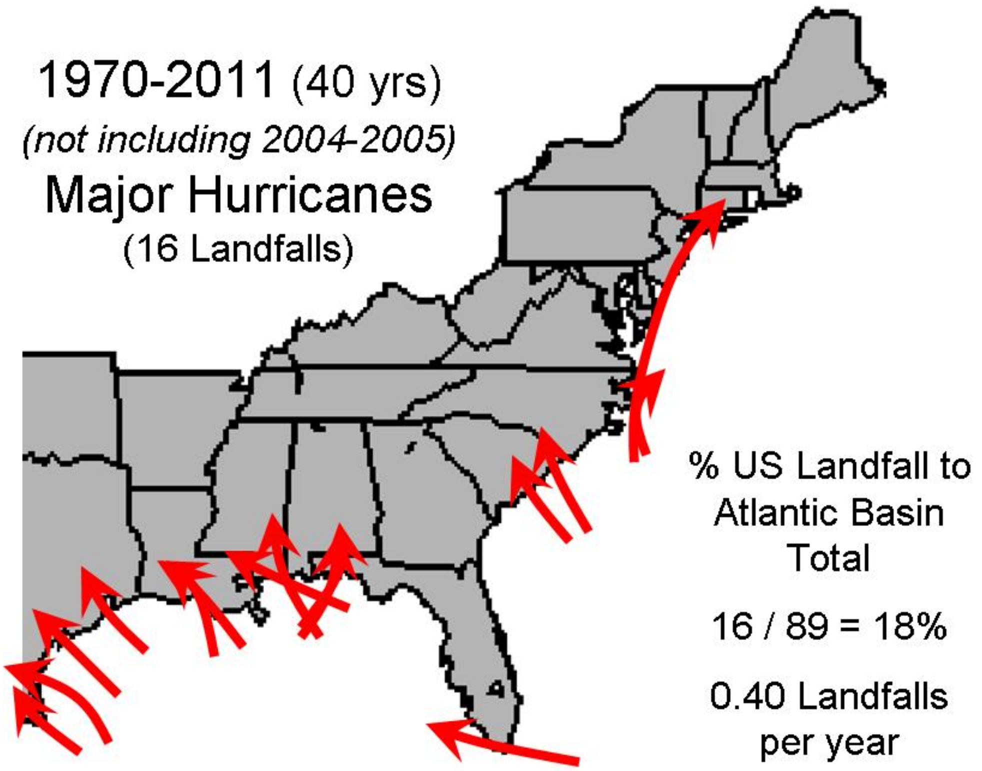

Figure 21: United States major hurricane landfalls from 1970-2011 (excluding 2004-2005).

This string of good luck has been even more remarkable for the Florida Peninsula and the East Coast. From 1995-2011, only four major hurricanes out of 64 (6%) that formed in the Atlantic basin have made landfall along the Florida Peninsula/East Coast. The 20th century average is that approximately 18% of all major hurricanes that form in the Atlantic basin make Florida Peninsula/East Coast landfall. There has been a three times reduction in the number of major hurricanes making Florida Peninsula/East Coast landfall during the most recent active period when compared with the 20th century average.

More impressive signals can be seen if one excludes the 2004-2005 hurricane seasons, when three major hurricanes made landfall along the Florida Peninsula and East Coast. From 1941-1969 and 2004-2005, 24 major hurricanes made landfall along the Florida Peninsula/East Coast over 31 years, or 0.77 major hurricane landfalls per year (Figure 22). This compares with the 1970-2011 (excluding 2004-2005) average when only 0.13 major hurricane landfalls per year occurred (or approximately six times fewer landfalls per year during the more recent period) (Figure 23).

This dearth in United States major hurricane landfalls in more recent years has resulted in much lower damages being sustained along the coastline than would be expected given the heightened amounts of basinwide activity that have been experienced since 1995.

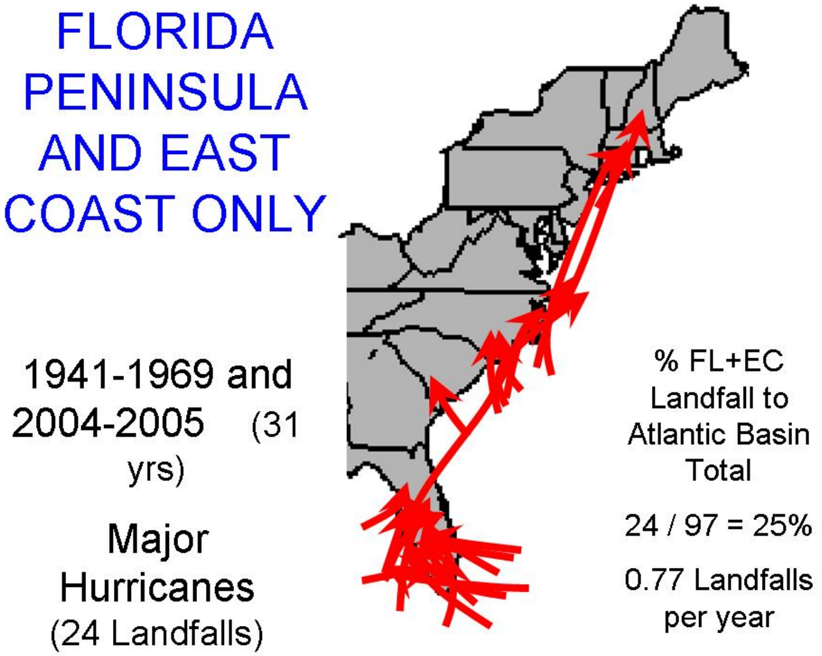

Figure 22: Florida Peninsula and East Coast major hurricane landfalls from 1941-1969 and 2004-2005.

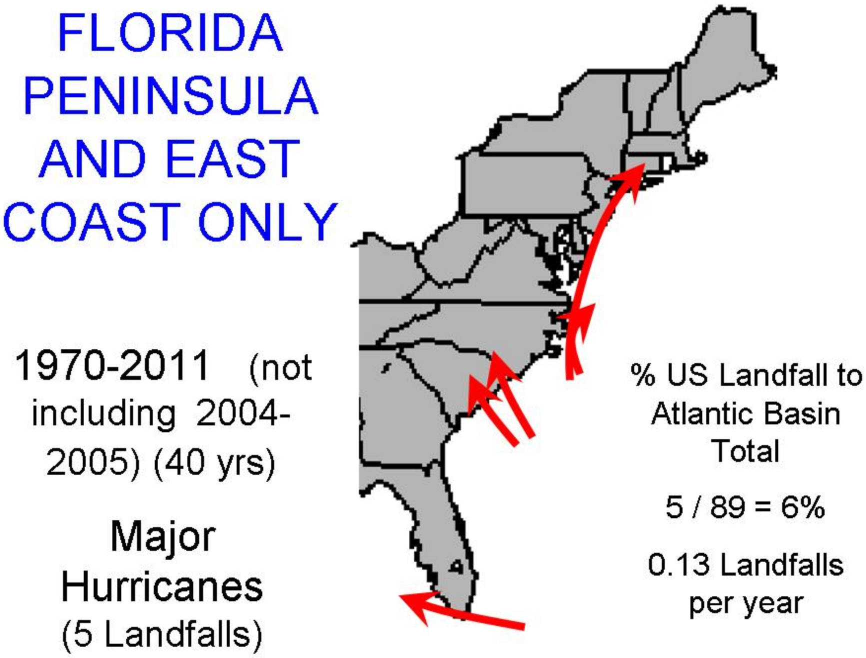

Figure 23: Florida Peninsula and East Coast major hurricane landfalls from 1970-2011 (excluding 2004-2005).

US Especially Fortunate over the Past Six Years

The U.S. has been especially lucky over the past six years in that no major hurricanes have made landfall. Following the very active landfalling seasons of 2004-2005, when seven of 13 major hurricanes made U.S. landfall, none of the nineteen major hurricanes forming in the Atlantic basin in the past six years have impacted the U.S. coastline. The last 100-year climatology indicates that approximately 30% of all major hurricanes that form in the Atlantic basin make U.S. landfall as major hurricanes.

The primary reason why we believe that the U.S. has been so fortunate is due to mid-level steering currents that have in recent years tended to steer storms away from the U.S. Figure 24 displays the August-September 500-mb U.S. and western Atlantic upper-level height field for 2006-2011 minus the height field for 2004-2005. Note the anomalous troughing along the U.S. East Coast in 2006-2011 compared to 2004-2005. This pattern caused the major hurricanes forming during the past six years to recurve before they could hit the U.S. coastline. This anomalous trough is part of a larger mid-latitude ridge/trough wave pattern that has tended to be in place over the past six years (Figure 25).

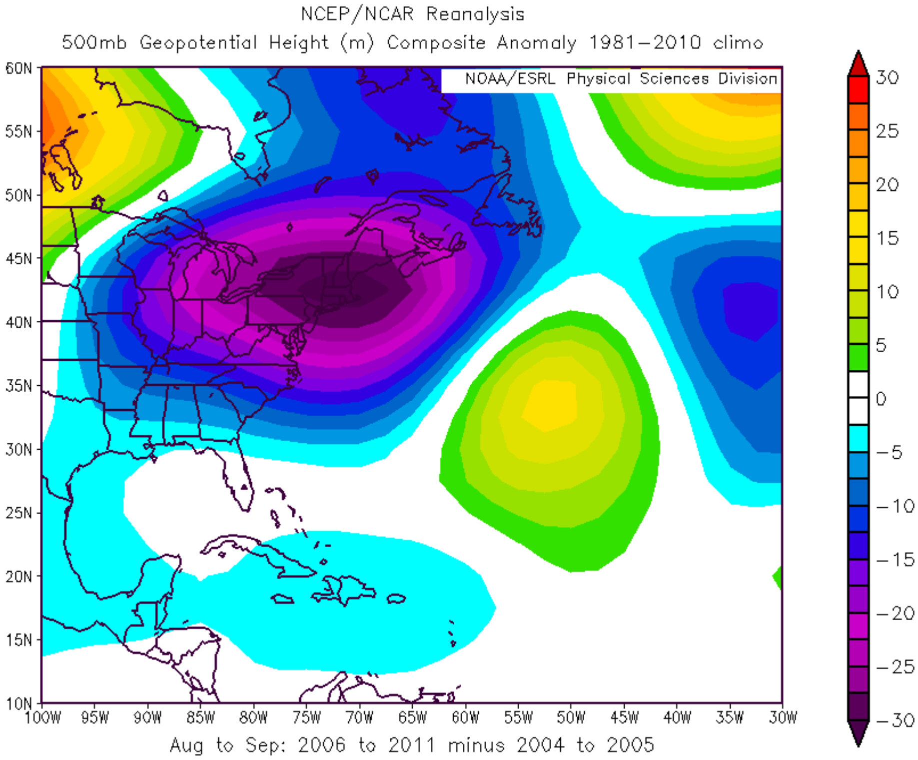

Figure 24: Average 500-mb height pattern difference of 2006-2011 minus 2004-2005. Note the anomalous troughing that has prevailed along the U.S. East Coast, causing systems to recurve before they could impact the U.S. mainland.

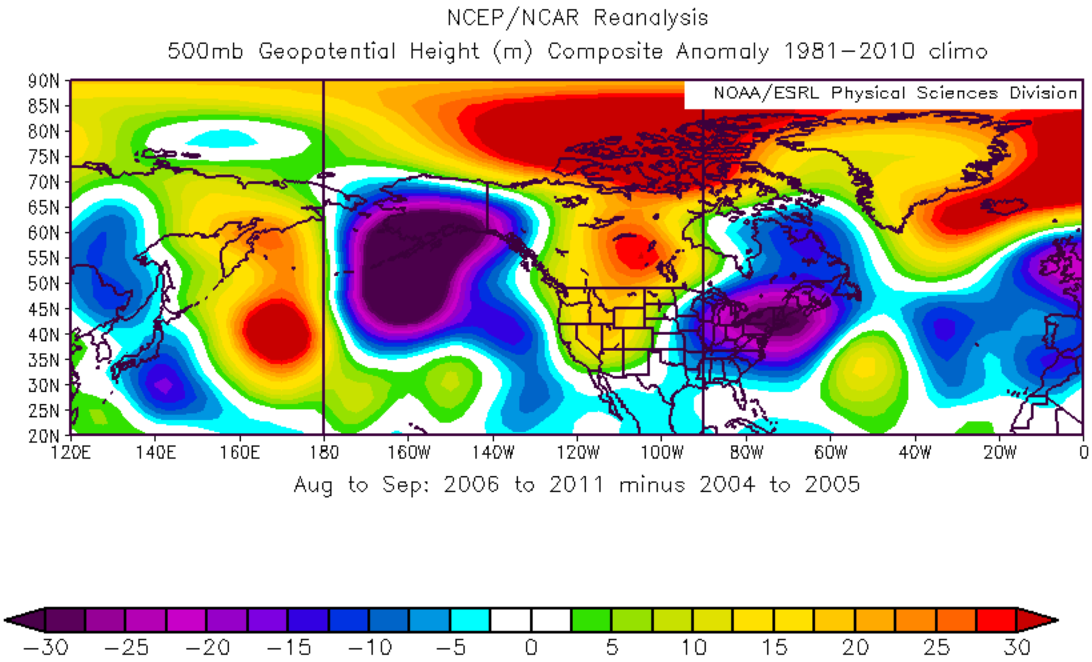

Figure 25: Average 500-mb August-September height pattern difference of 2006-2011 minus 2004-2005 for most of the Northern Hemisphere. Note the anomalous ridge/trough pattern differences that extend all the way from eastern Asia to western Europe.

6 Verification of Individual 2011 Lead Time Forecasts

Table 4 is a comparison of our forecasts for 2011 for four different lead times along with this year's observations. While our forecasts correctly anticipated an above-average season, the overall levels of activity (137% NTC versus 175% NTC) were less than predicted by all of our seasonal forecasts.

Table 4: Verification of our 2011 seasonal hurricane predictions.

Forecast Parameter and 1950-2000 Climatology (in parentheses)	8 Dec 2010	Update 6 April 2011	Update 1 June 2011	Update 3 Aug 2011	Observed 2011 Total
Named Storms (NS) (9.6)	17	16	16	16	19
Named Storm Days (NSD) (49.1)	85	80	80	80	90.50
Hurricanes (H) (5.9)	9	9	9	9	7
Hurricane Days (HD) (24.5)	40	35	35	35	25
Major Hurricanes (MH) (2.3)	5	5	5	5	3
Major Hurricane Days (MHD) (5.0)	10	10	10	10	4.50
Accumulated Cyclone Energy (ACE) (96.2)	165	160	160	160	125
Net Tropical Cyclone Activity (NTC) (100%)	180	175	175	175	137

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 developed over 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. Eighteen of 32 (56%) predictions for the 2011 hurricane season were within one standard deviation of observed values, while the remainder of the predictions were within two standard deviations. This year's seasonal forecasts were judged to be somewhat of an over-prediction.

Table 5: Verification of our 2011 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. 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 6.8-11.2, which with rounding would be 7-11.

Forecast Parameter and 1950-2000 Climatology (in parentheses)	8 Dec 2010	Update 6 April 2011	Update 1 June 2011	Update 3 Aug 2011	Observed 2011 Total
Named Storms (NS) (9.6)	**17** (±4.4)	**16** (±4.0)	**16** (±3.8)	**16** (±2.3)	19
Named Storm Days (NSD) (49.1)	**85** (±23.9)	**80** ±(19.4)	**80** (±18.3)	**80** (±17.4)	90.50
Hurricanes (H) (5.9)	**9** (±2.5)	**9** (±2.2)	**9** (±2.1)	**9** (±1.6)	7
Hurricane Days (HD) (24.5)	**40** (±12.4)	**35** (±9.5)	**35** (±9.0)	**35** (±8.6)	25
Major Hurricanes (MH) (2.3)	**5** (±1.5)	**5** (±1.4)	**5** (±1.2)	**5** (±0.9)	3
Major Hurricane Days (MHD) (5.0)	**10** (±4.7)	**10** (±4.4)	**10** (±4.5)	**10** (±3.5)	4.50
Accumulated Cyclone Energy (ACE) (96.2)	**165** (±50)	**160** (±39)	**160** (±39)	**160** (±36)	125
Net Tropical Cyclone Activity (NTC) (100%)	**180** (±49)	**175** (±41)	**175** (±37)	**175** (±34)	137

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 December of the previous year. 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 (1999-2011).

Tropical Cyclone Parameter	Early December	Early April	Early June	Early August
NS	10/13	11/13	11/13	10/13
NSD	10/13	11/13	11/13	11/13
H	9/13	11/13	11/13	11/13
HD	8/13	9/13	10/13	11/13
MH	8/13	9/13	11/13	11/13
MHD	8/13	9/13	11/13	11/13
NTC	8/13	9/13	10/13	11/13
Total	**61/91 (67%)**	**69/91 (76%)**	**75/91 (82%)**	**76/91 (84%)**

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, especially for the early December lead time, 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 1984-2010.

6.2 Verification of Two-Week Forecasts

This is the third 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 2011 hurricane season and shows their verification. The first four forecasts and the last forecast either verified in the correct category or missed by one ACE unit. The fifth forecast was a significant under-prediction. This was due to Ophelia and Philippe lasting much longer and becoming much more intense than predicted by the global models. No new TCs formed during the two-week period.

Table 8: Two-week forecast verification for 2011. Forecasts that verified in the correct category are highlighted in blue, forecasts that missed by one category are highlighted in green, while forecasts that missed by two categories are highlighted in red.

Forecast Period	Predicted ACE	Observed ACE
8/3 – 8/16	**Average (5-9)**	**4**
8/17 – 8/30	**Above-Average (19 or More)**	**23**
8/31 – 9/13	**Above-Average (37 or More)**	**38**
9/14 – 9/27	**Below-Average (15 or Less)**	**12**
9/28 – 10/11	**Below-Average (8 or Less)**	**26 (BUST!)**
10/12 – 10/25	**Average (5 – 9)**	**4**

As was the case over the past two years, one of the primary challenges with the two-week forecasts this year was that we were largely dependent on the MJO for skill, especially during the second week portion of the forecast. Expect for one high-amplitude MJO event that developed in the early part of October, the remainder of the August-October period was characterized by weak MJO activity (Figure 23). We were therefore largely dependent on global model genesis forecasts and storms that existed on the initial forecast date for our forecasts this year.

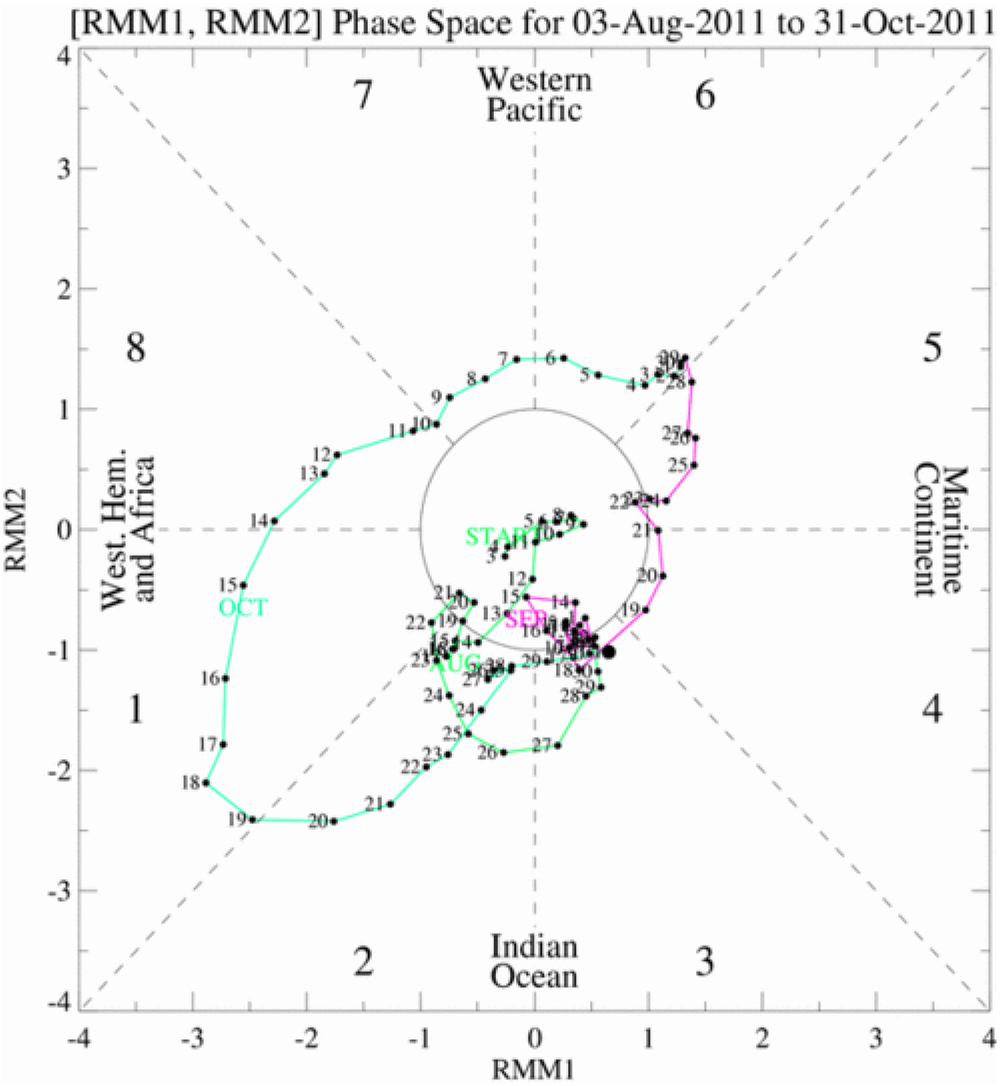

Figure 23: Propagation of the Madden-Julian Oscillation (MJO) based on the Wheeler-Hendon classification scheme over the period from August 3 to October 31. Note that coherent eastward propagation of the MJO during this timeframe was virtually non-existent until the latter part of September when a coherent MJO developed and propagated from the Indian Ocean all the way around the globe before diminishing in magnitude toward the end of October. The Maritime Continent refers to Indonesia and the surrounding islands. RMM stands for Real-Time Multivariate MJO.

6.3 Verification of Caribbean Basin Forecasts

This is the second year that we have issued a specific seasonal forecast for the Caribbean basin, defined as 10-20°N, 60-88°W (Figure 24). The models that were developed for this Caribbean forecast indicated that approximately 45% of the variance in Accumulated Cyclone Energy (ACE) generated in the Caribbean basin could be explained by the early June forecast, increasing to approximately 50% of the variance by early August. This is the first year that we issued a late-season (October-November) forecast for the Caribbean basin.

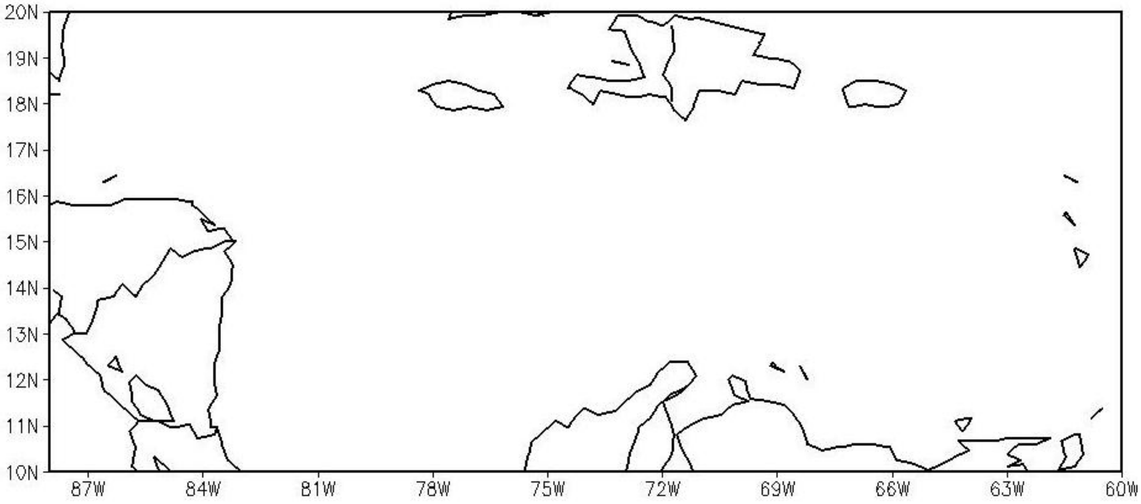

Figure 24: The Caribbean basin as defined for these forecasts.

Real-time forecasts issued in 2011 called for a very active Caribbean. The primary reason why these forecasts called for so much activity was due to anomalously weak trade winds across the region, indicating enhanced pre-existing low-level vorticity across the region as well as the development of a moderate La Niña event. The average annual Caribbean ACE over the period from 1949-2008 was 15, while the early June and early August models predicted an ACE of 46 and 37, respectively. Overall conditions were generally quite favorable for storm formation in the Caribbean, as indicated by the real-time genesis potential produced by the Cooperative Institute for Research in the Atmosphere (CIRA) (Figure 25). Despite these favorable conditions, observed ACE in the Caribbean was actually below average (10 ACE units). One hypothesis for why the season was not as active in the Caribbean as was predicted is due to the fact that steering currents were organized as such to direct systems developing in the MDR to track northeastward and recurve, instead of causing them to track westward into the Caribbean.

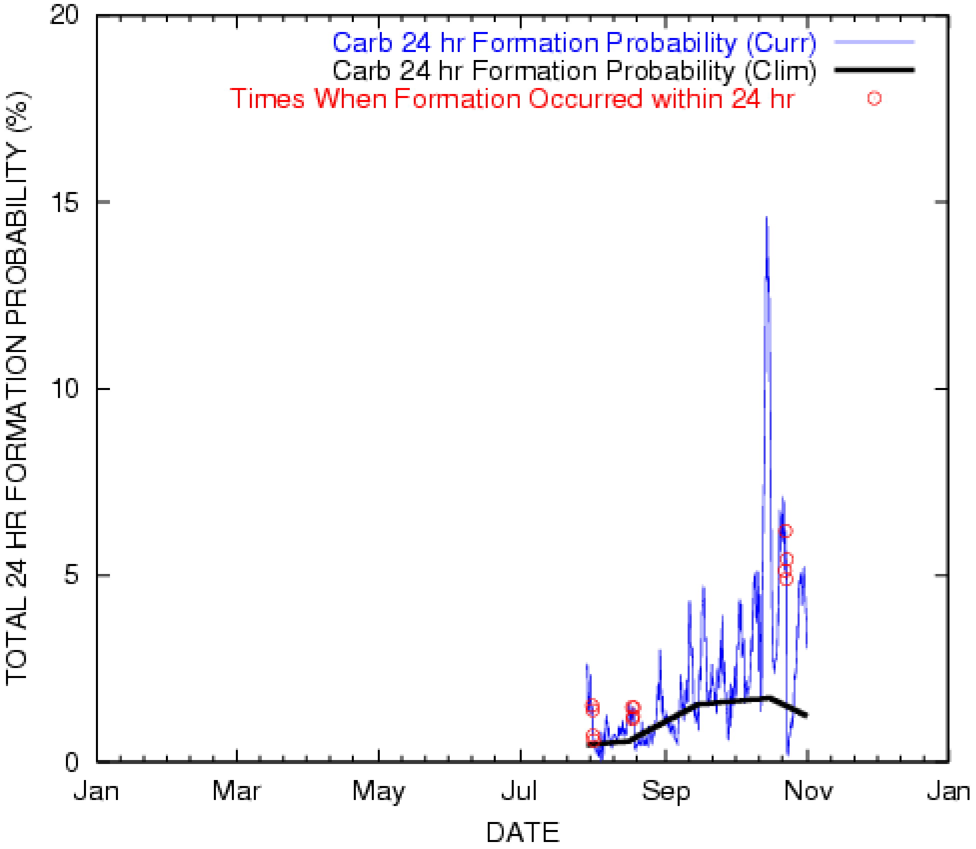

Figure 25: Caribbean real-time genesis parameter. Note that, in general, the 2011 real-time genesis parameter well exceeded climatology. Figure courtesy of CIRA.

Our October-November Caribbean basin forecast for hurricane days and ACE in the Caribbean verified quite well. This model effectively uses two predictors: 1) the state of ENSO, and 2) the size of the Atlantic Warm Pool. Both of these predictors were quite favorable for an active end of the season in the Caribbean. Hurricane Rina formed in late October in the Caribbean, becoming a strong Category 2 hurricane before dissipating over the Yucatan Peninsula. 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)	3.5	3.0
Accumulated Cyclone Energy Index (6.3)	16	9

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 (relative to climatology) can be forecast with statistical skill. 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 2011.

Landfall probabilities for the 2011 hurricane season were estimated to be well above their long-period averages due to the forecasts of a very active season. The 2011 hurricane season was relatively quiet from a U.S. landfall perspective, with only one Category 1 hurricane (Irene) and one tropical storm (Lee) making U.S. landfall this year. Average U.S. landfalling statistics since 1900 are that 3.5 named storms, 1.8 hurricanes and 0.7 major hurricanes make U.S. landfall per year. Two tropical cyclones passed through the Caribbean (10-20°N, 60-88°W) during 2011. Harvey was at tropical-storm strength, while Rina reached Category 2 hurricane strength. We attribute this season's lack of expected landfall activity primarily due to the strong semi-stationary upper-level trough over the U.S. East Coast which was present for most of this season.

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 26). 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.

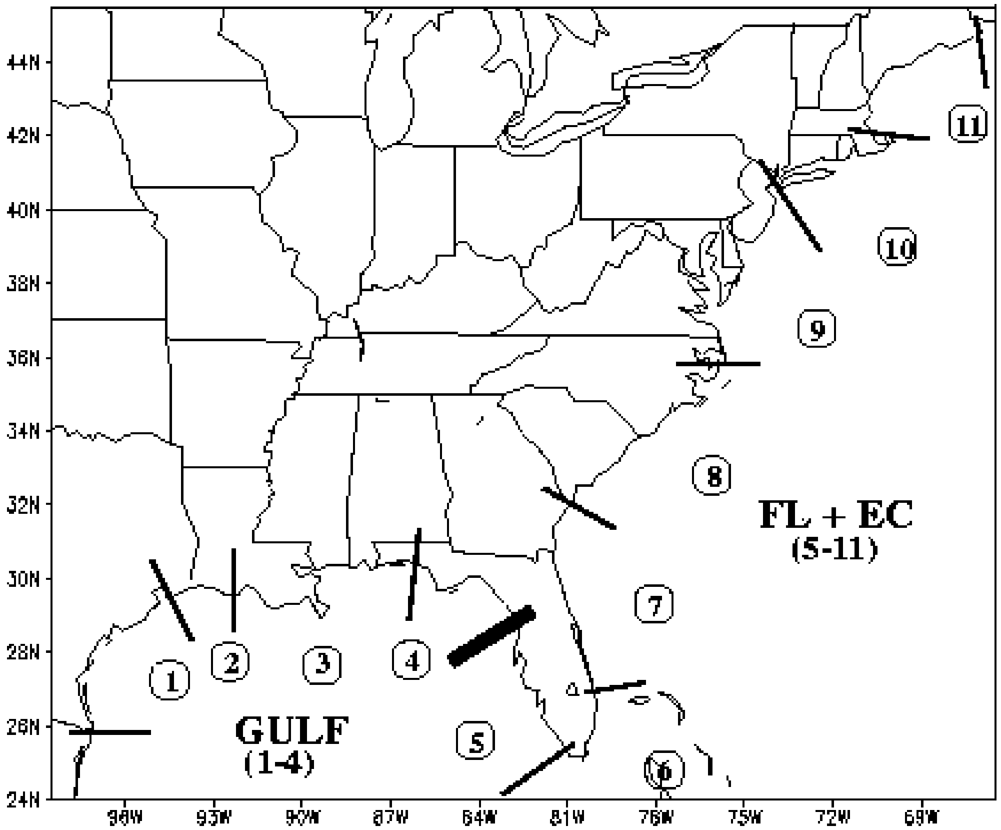

Figure 26: Location of the 11 coastal regions for which separate hurricane landfall probability estimates are made. These subdivisions were determined by the historical frequency of landfalling major hurricanes.

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 2011 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				
	8 Dec.	6 Apr.	1 June	3 August	Observed Number
TS	94%	94%	94%	92% (80%)	1
HUR (Cat 1-2)	87%	86%	86%	85% (68%)	1
HUR (Cat 3-4-5)	73%	72%	72%	70% (52%)	0
All HUR	96%	96%	96%	95% (84%)	1
Named Storms	99%	99%	99%	99% (97%)	2

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

	Forecast Date				
	8 Dec.	6 Apr.	1 June	3 August	Observed Number
TS	79%	79%	79%	77% (59%)	1
HUR (Cat 1-2)	63%	62%	62%	60% (42%)	0
HUR (Cat 3-4-5)	48%	47%	47%	45% (30%)	0
All HUR	81%	80%	80%	78% (61%)	0
Named Storms	96%	96%	96%	95% (83%)	1

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

	Forecast Date				
	8 Dec.	6 Apr.	1 June	3 August	Observed Number
TS	72%	71%	71%	68% (51%)	0
HUR (Cat 1-2)	65%	64%	64%	62% (45%)	1
HUR (Cat 3-4-5)	49%	48%	48%	46% (31%)	0
All HUR	82%	81%	81%	79% (62%)	1
Named Storms	95%	94%	94%	93% (81%)	1

(d) Caribbean (10-20°N, 60-88°W)

Forecast Date

	8 Dec.	6 Apr.	1 June	3 August	Observed Number
TS	95%	95%	95%	94% (82%)	1
HUR (Cat 1-2)	78%	77%	77%	75% (57%)	1
HUR (Cat 3-4-5)	62%	61%	61%	59% (42%)	0
All HUR	92%	91%	91%	90% (75%)	1
Named Storms	99%	99%	99%	99% (96%)	2

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 flow patterns that dictate 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 62 (1950-2011) 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 62-year period from 1950-2011.

	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 31 Observed NTC years ≥ 100	54	29	12	65	36	14	119	65	26	129	72	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 & 1997 (12 years)	37	17	5	27	14	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 2011 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 2011 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 2011 seasonal hurricane forecasts. In our early December 2010 forecast for 2011, we believed that the development of El Niño was unlikely. We became somewhat concerned about El Niño development in early April as the tropical Pacific warmed rapidly, however, we became more confident that neutral conditions would prevail with our early June forecast. By early August, we were quite confident that an El Niño event was unlikely. After a brief transition to neutral conditions during the months of June and July, ENSO transitioned back to a weak La Niña event for the peak months of the hurricane season. The following are several quotes from our 2011 forecasts regarding ENSO this year:

(8 December 2010) –

"One of the important questions for the upcoming hurricane season is whether El Niño will re-develop for the 2011 hurricane season. At this point, we think that this is a very unlikely scenario, given the current upper ocean heat content structure across the tropical Pacific."

(6 April 2011) –

"Based on this information, our best estimate is that we will likely experience neutral ENSO conditions during the 2011 hurricane season. Since we expect to continue to see a warm tropical Atlantic (discussed in detail in the next section), we believe that ENSO will not be a significant detrimental factor for this year's hurricane season."

(1 June 2011) –

"While the moderation of tropical Pacific SSTs have continued over the past couple of months, we do not expect to see a transition to El Niño conditions during the next several months."

(3 August 2011) –

"After significant warming during the late winter and early spring, it appears that neutral conditions are likely to persist for the next several months. The upper-ocean heat content in the central and eastern tropical Pacific is typically a good indicator of future trends in ENSO. Following dramatic warming during the January-March time period, the upper ocean heat content has leveled off and begun

to decrease, which indicates to us that the potential for a transition to El Niño has been greatly reduced.”

Our definition of weak, moderate and strong La Niña events for the August-October period is based on the August-October-averaged Nino 3.4 index. When this index is between minus 0.5-1.0°C, we define it as a weak La Niña event, when the index is between minus 1.0-1.5°C, we define it as a moderate La Niña event, and when the index is less than minus 1.5°C, we define it as a strong La Niña event. The August-October-averaged Nino 3.4 index in 2011 was approximately -0.7°C, or a weak La Niña event.

A moderate-to-strong La Niña occurred during the winter of 2010/2011, with a transition to neutral conditions during the spring months. The transition from a strong La Niña to neutral conditions was quite rapid. The warming in the tropical eastern and central Pacific came to an abrupt end during the early part of the summer, with ENSO reverting back to a weak La Niña by late August. Table 13 displays temperatures in the various Nino regions as observed in January, April, July and October of this year, respectively. The October – January and October-April anomalies are also provided. While we have reverted back to La Niña conditions, the current cold event appears to be of a somewhat lesser magnitude than what was experienced last winter.

Table 13: January anomalies, April anomalies, July anomalies, October anomalies and October-January and October-April anomalies in the Nino 1+2, Nino 3, Nino 3.4 and Nino 4 regions.

Region	January 2011 Anomaly (ºC)	April 2011 Anomaly (ºC)	July 2011 Anomaly (ºC)	October 2011 Anomaly (ºC)	October 2011 minus January 2011 Anomaly (°C)	October 2011 minus April 2011 Anomaly (°C)
Nino 1+2	-0.4	0.2	0.5	-0.6	-0.2	-0.8
Nino 3	-1.3	-0.3	0.0	-1.0	+0.3	-0.7
Nino 3.4	-1.6	-0.8	-0.3	-1.0	+0.6	-0.2
Nino 4	-1.6	-0.6	-0.3	-0.7	+0.9	-0.1

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 27 displays the low-level wind anomalies across the tropical Pacific from mid April to mid October. Other than one westerly wind burst in the middle of May and additional westerly anomalies over the past few weeks associated with an amplified MJO event, easterly anomalies predominated over the six-month period.

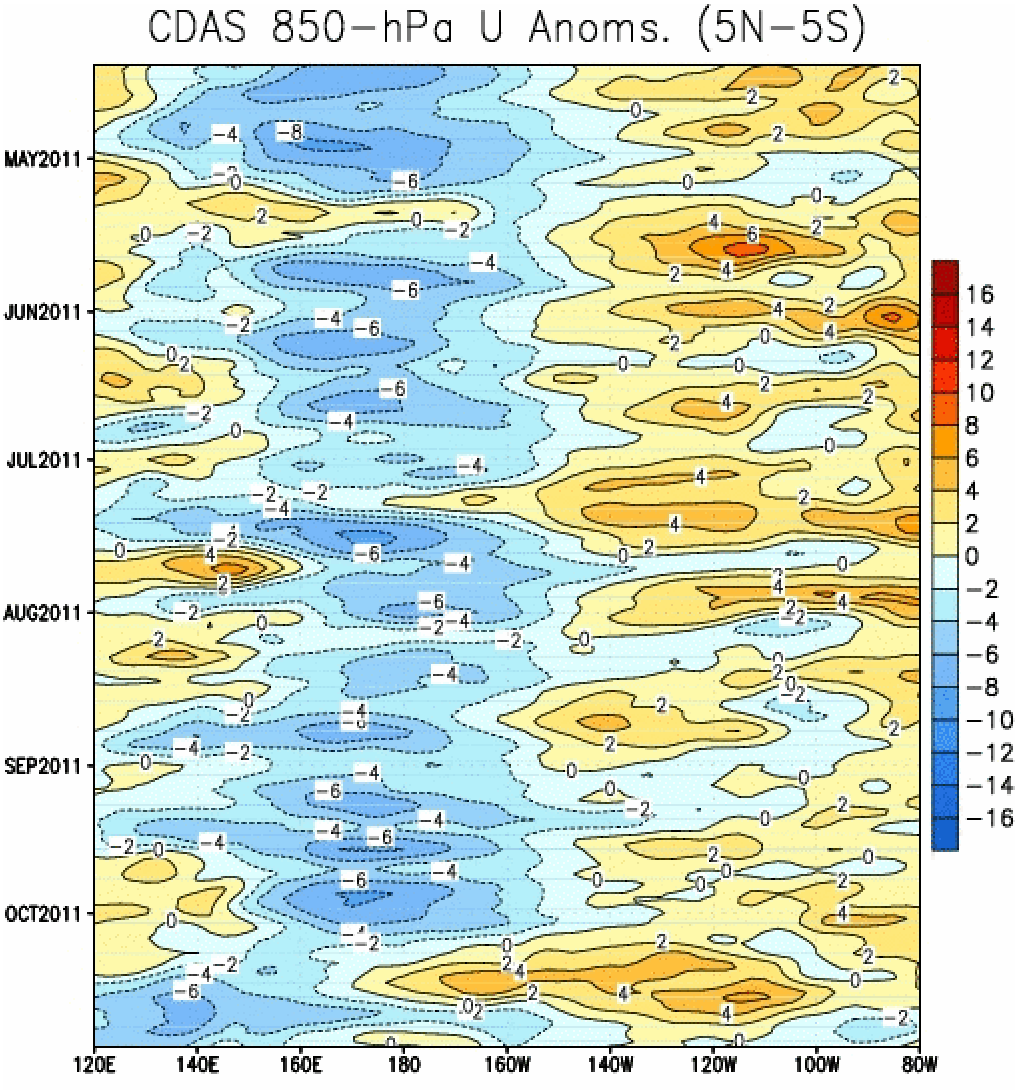

Figure 27: Equatorial wind anomalies in the Indo/Pacific sector. Note the persistence of anomalous easterlies (e.g., stronger trades) near the International Date Line. Figure courtesy of the Climate Prediction Center.

8.2 Intra-Seasonal Variability

Similar to the past two years, the peak months of the 2011 hurricane season were generally characterized by weak intra-seasonal variability, except for some heightened MJO activity during October. In contrast, 2008 was associated with considerable intra-seasonal variability. In part due to the weak MJO activity, strong clustering of Atlantic basin TC formation was not observed during the 2011 hurricane season.

8.3 Atlantic SST

The tropical Atlantic was characterized by above-normal SSTs during the 2011 hurricane season; however, positive anomalies were much less than was observed in 2010. Positive SST anomalies in the Main Development Region (MDR) cooled considerably from February – March, likely due to a strongly positive North Atlantic Oscillation (NAO) that prevailed during the second half of the winter into the first part of the spring of 2011 (Figure 28). A positive NAO is associated with stronger-than-normal trade winds across the tropical Atlantic. Strong trades drive enhanced mixing and upwelling and consequently force anomalous cooling (Figure 29). Figure 30 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.

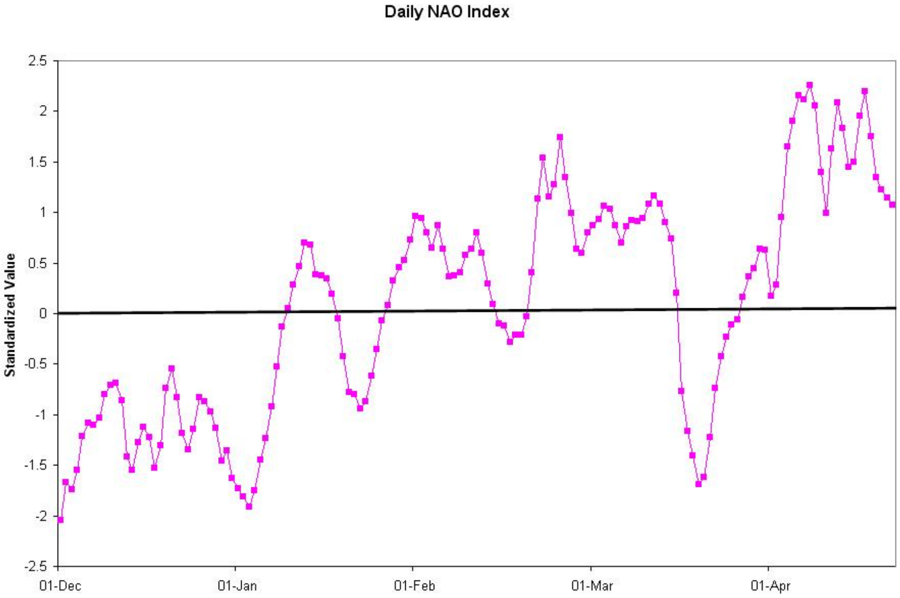

Figure 28: 1 December 2010 – 30 April 2011 daily NAO anomaly. Note the transition to predominately positive values that took place in late January.

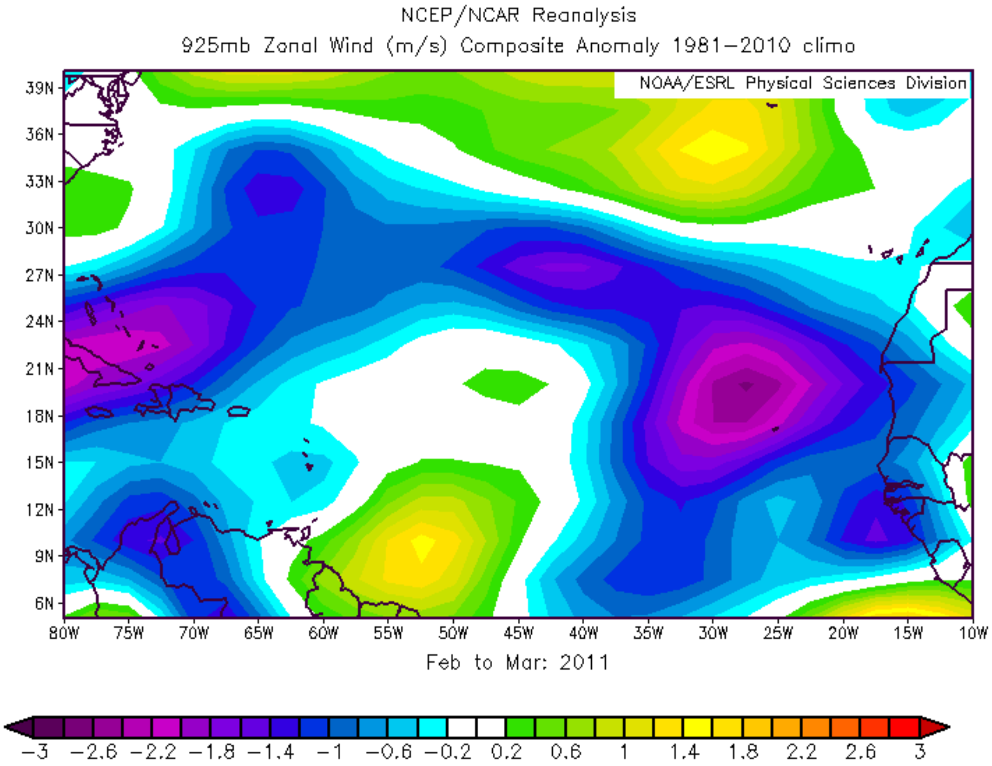

Figure 29: February-March 925-mb zonal wind anomalies across the tropical and subtropical Atlantic. Note the significant easterly anomalies (e.g., stronger trades) throughout most of the sub-tropical Atlantic.

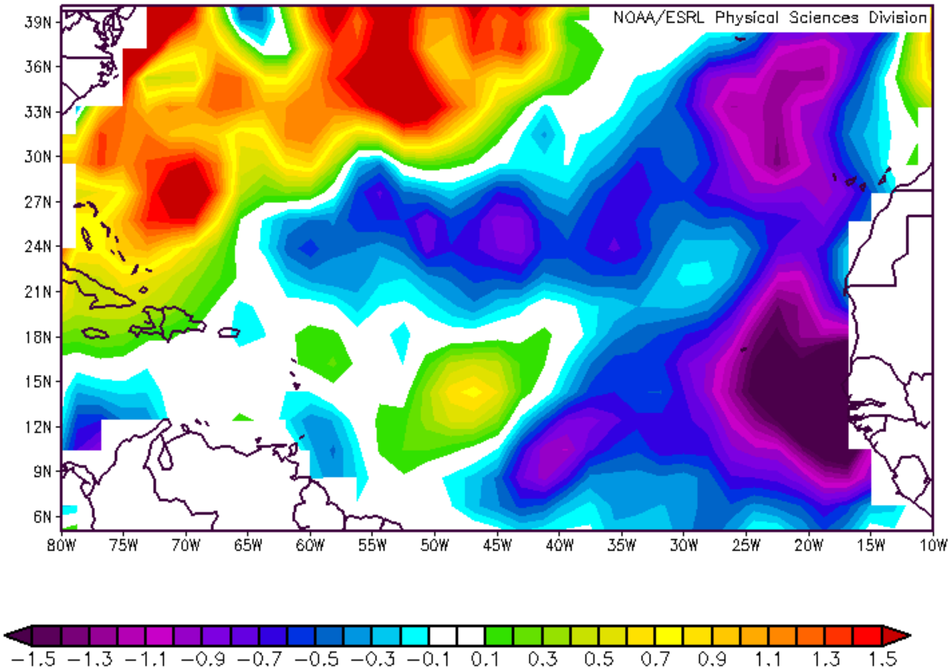

Figure 30: Late May 2011 – late January 2011 SST anomaly change.

These anomalous SST changes are one reason why the Atlantic TC season likely did not live up to expectations. Figure 31 displays the anomalous SST pattern observed in July 2011. A strong cool anomaly was located in the northeastern subtropical Atlantic, which along with continued warm anomalies in the tropical Atlantic created a stronger-than-normal SST gradient, which drove enhanced baroclinicity and the development of cold lows during the peak months of the hurricane season. These cold lows are typically associated with increased vertical shear and enhanced dry air intrusions from the mid-latitudes into the deep tropics. Both of these factors came into play during the 2011 hurricane season.

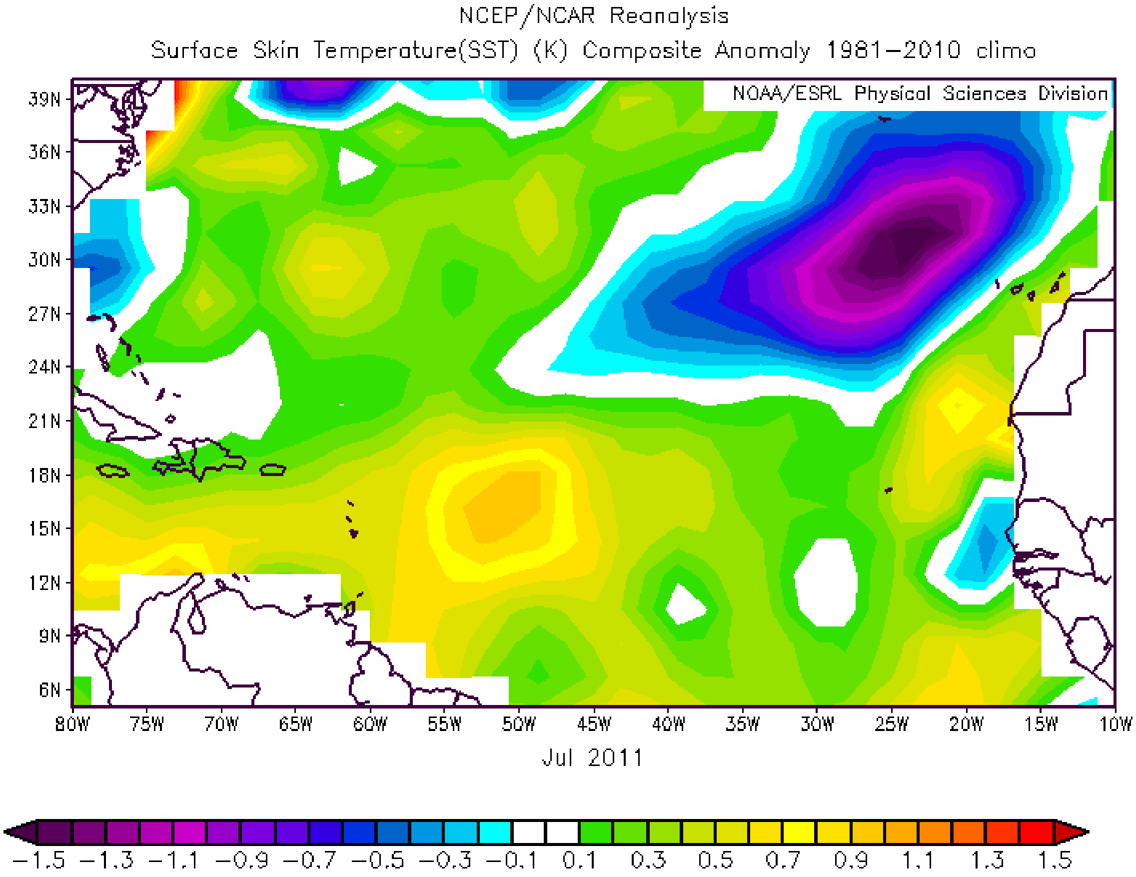

Figure 31: SST anomaly pattern observed across the tropical and subtropical Atlantic in July 2011.

We are well-aware that this SST anomaly pattern is typically associated with less active hurricane seasons, and one of the predictors in our early August statistical forecast model takes this into account. However, an error in calculating the predictor's value caused us to over-estimate these SST anomalies in July. Consequently, our early August statistical model gave us a somewhat higher value (by about 30 NTC units) than what it gave when the final July values were released.

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 2011 Atlantic hurricane season was characterized by below-normal sea level pressures. Figure 32 displays August-October 2011 tropical and sub-tropical sea level pressure anomalies in the North Atlantic.

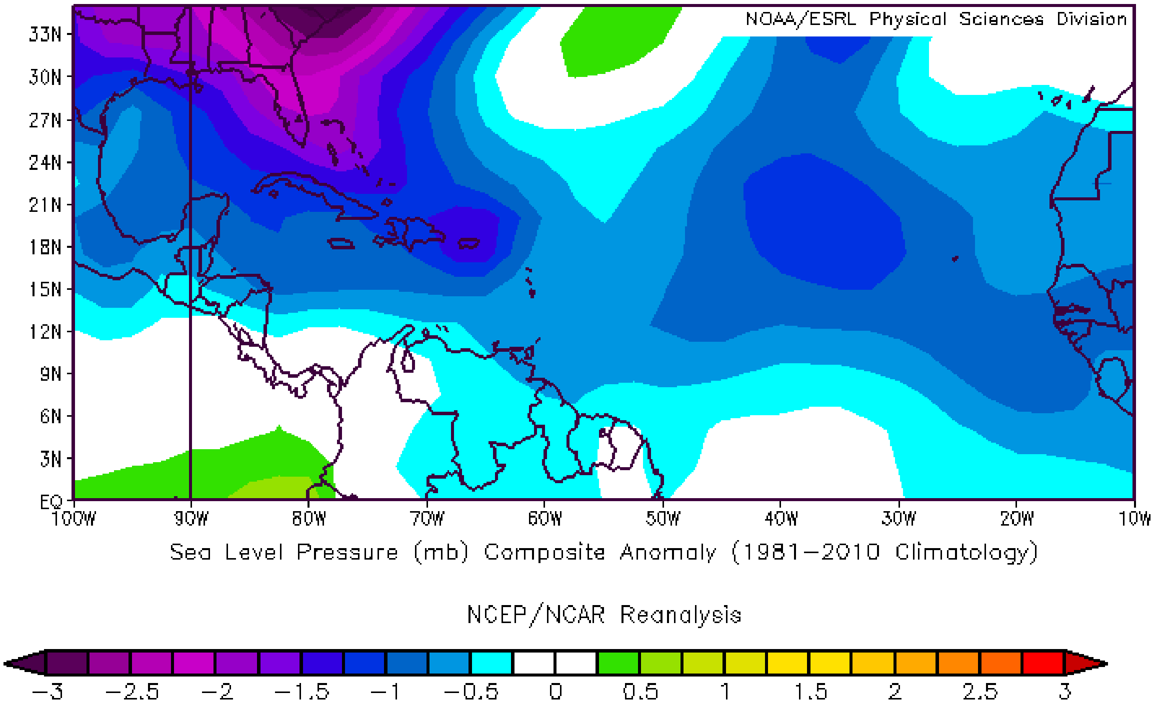

Figure 32: August-October 2011 tropical and sub-tropical North Atlantic sea level pressure anomalies. Sea level pressure anomalies were below-average across the tropical Atlantic.

8.5 Tropical Atlantic Vertical Wind Shear

Tropical Atlantic vertical wind shear was higher in 2011 than it was in 2010 (Figure 33). Shear was slightly stronger than average across the eastern tropical Atlantic and below-average in the central tropical Atlantic, which likely explains why TCs typically did not intensify into hurricanes until they reached the central part of the Atlantic. Vertical shear was below-average across the Caribbean, but steering currents (discussed in Section 8.7) were such as to direct most TCs toward the northeast and prevent them from moving into the generally favorable conditions that were present in the Caribbean. Vertical shear was much above-average in the Gulf of Mexico and across the remainder of the subtropical Atlantic (area highlighted in blue in Figure 33), which prevented most systems that formed in the tropical Atlantic from intensifying as they moved northward.

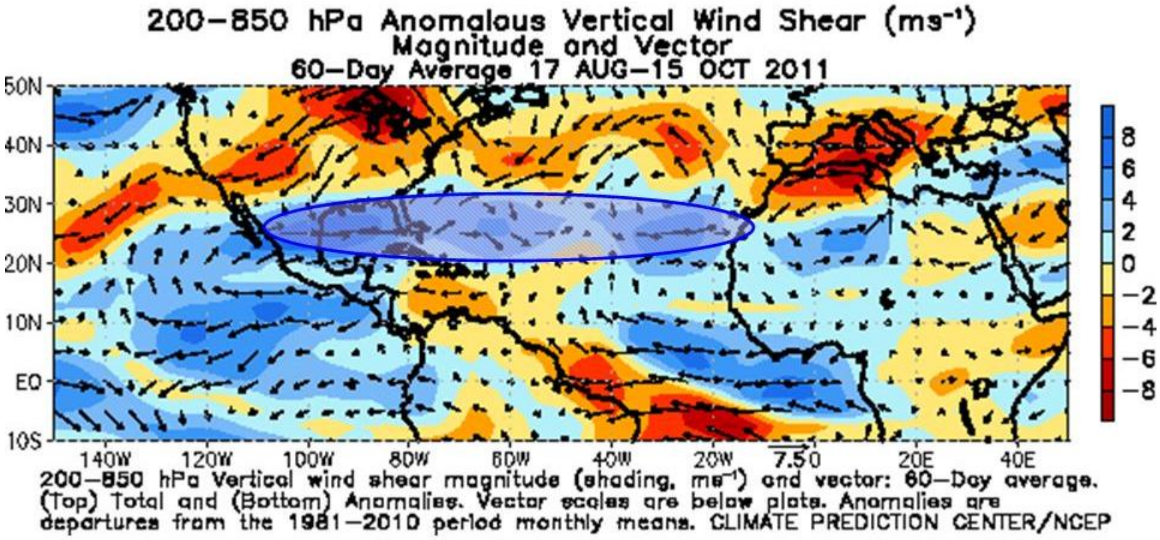

Figure 33: Anomalous vertical wind shear as observed across the Atlantic from August 17 – October 15, 2011. Vertical wind shear was slightly above-average in the tropical Atlantic and below average in the Caribbean. Note the anomalously strong vertical shear that dominated throughout the entire subtropical Atlantic (as highlighted by the blue ellipse).

8.6 Tropical Atlantic Moisture

One of the other factors that prevented as much as activity as was predicted in 2011 was the drier-than-normal mid-level air that predominated across the tropical Atlantic. The tropical Atlantic and the Gulf of Mexico were quite dry this year, while the Caribbean was slightly driver than normal. Drier middle levels inhibit deep convection by enhancing entrainment of dry air in the mid-levels of the atmosphere. Vertical instability is also reduced (Figure 34). The combination of these factors created an environment in the MDR that was much less conducive for hurricane formation than was present in 2010.

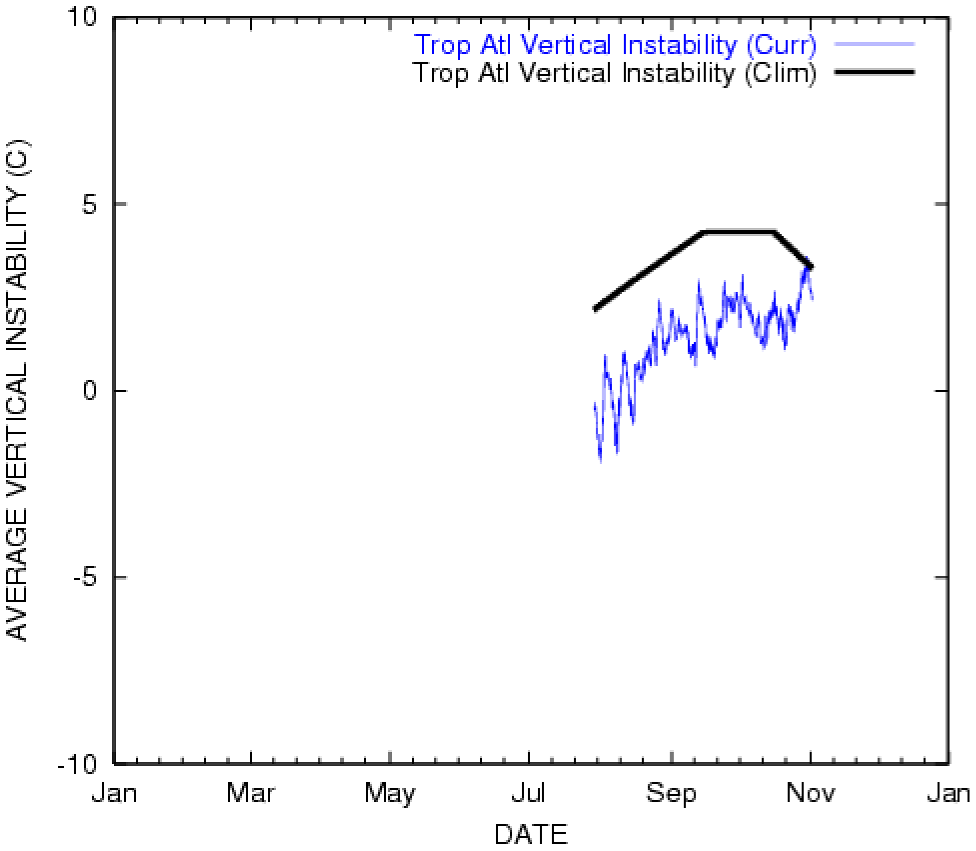

Figure 34: Vertical instability as observed in the tropical Atlantic from August-October. Note that the instability was below climatology for the entire three-month period, indicating a more stable atmosphere.

8.7 Steering Currents

As was the case last year, most tropical cyclones that formed in the MDR this year recurved before impacting the United States coastline (with the notable exception of Hurricane Irene). The United States has now gone six 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 35).

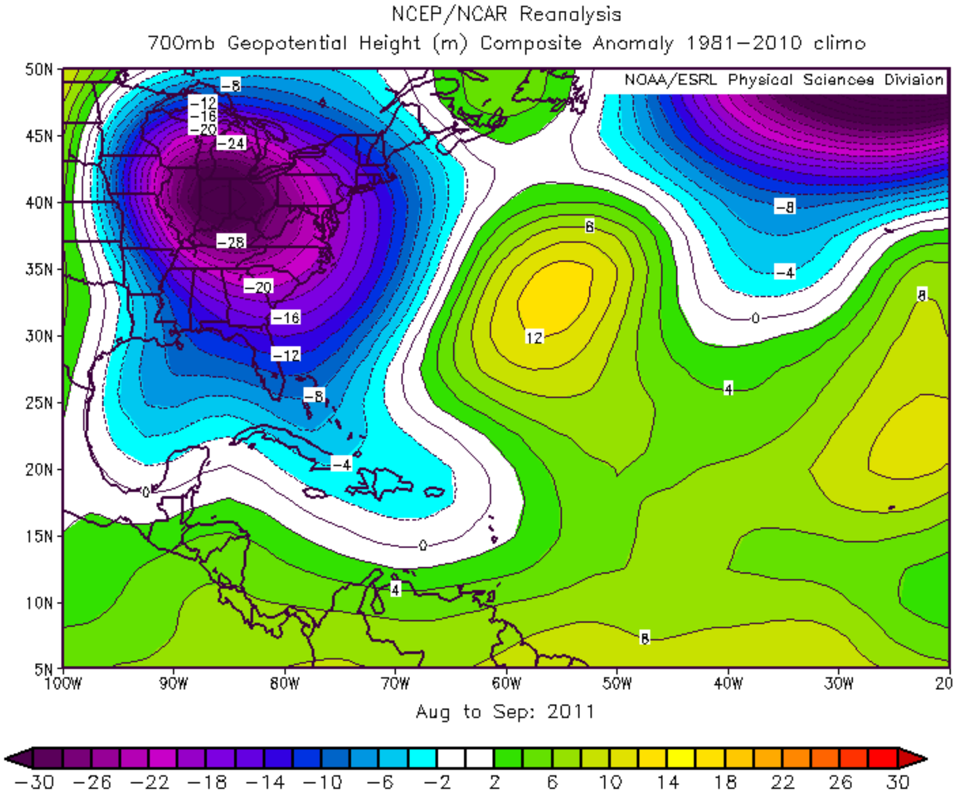

Figure 35: 700-mb height anomalies in the central and western part of the Atlantic in August-September 2011. Anomalous troughing dominated along the East Coast of the United States, thereby imparting steering currents that helped cause most TCs to recurve before making US landfall.

8.8 Indian Ocean Dipole (IOD)

One other large-scale phenomena that may have helped contribute to a somewhat less active than forecast Atlantic basin was a positive Indian Ocean Dipole (IOD) event. The IOD is a measure of an SST gradient between the western tropical Indian Ocean and the eastern tropical Indian Ocean, where a positive IOD indicates an anomalously strong gradient between the western and eastern portions of the basin. Typically, positive IOD events are observed in El Niño years, when anomalously cool SSTs are observed in the western tropical Pacific, extending into the eastern tropical Indian Ocean. However, positive IOD events do occasionally develop in La Niña years, with the last example of this being in 2007. A similar positive IOD developed in 2011, with anomalously warm SSTs in the Arabian Sea and anomalously cool SSTs in the Bay of Bengal.

When a positive IOD occurs, the typically enhanced convective signal in the western tropical Pacific is reduced. Associated with this reduction in convection is a weaker-than-normal response to La Niña in the Walker Circulation. Figure 36 displays the anomalous near-equatorial OLR for the past year. Note that the coherent OLR anomaly pattern typically observed with La Niña (and clearly evident during the winter of 2010/2011) was not very pronounced during the peak of this year's hurricane season. Consequently, the anomalous upper level easterlies in the tropical Atlantic associated with a La Niña event were largely confined to the Caribbean, while vertical shear in the MDR was slightly stronger than normal.

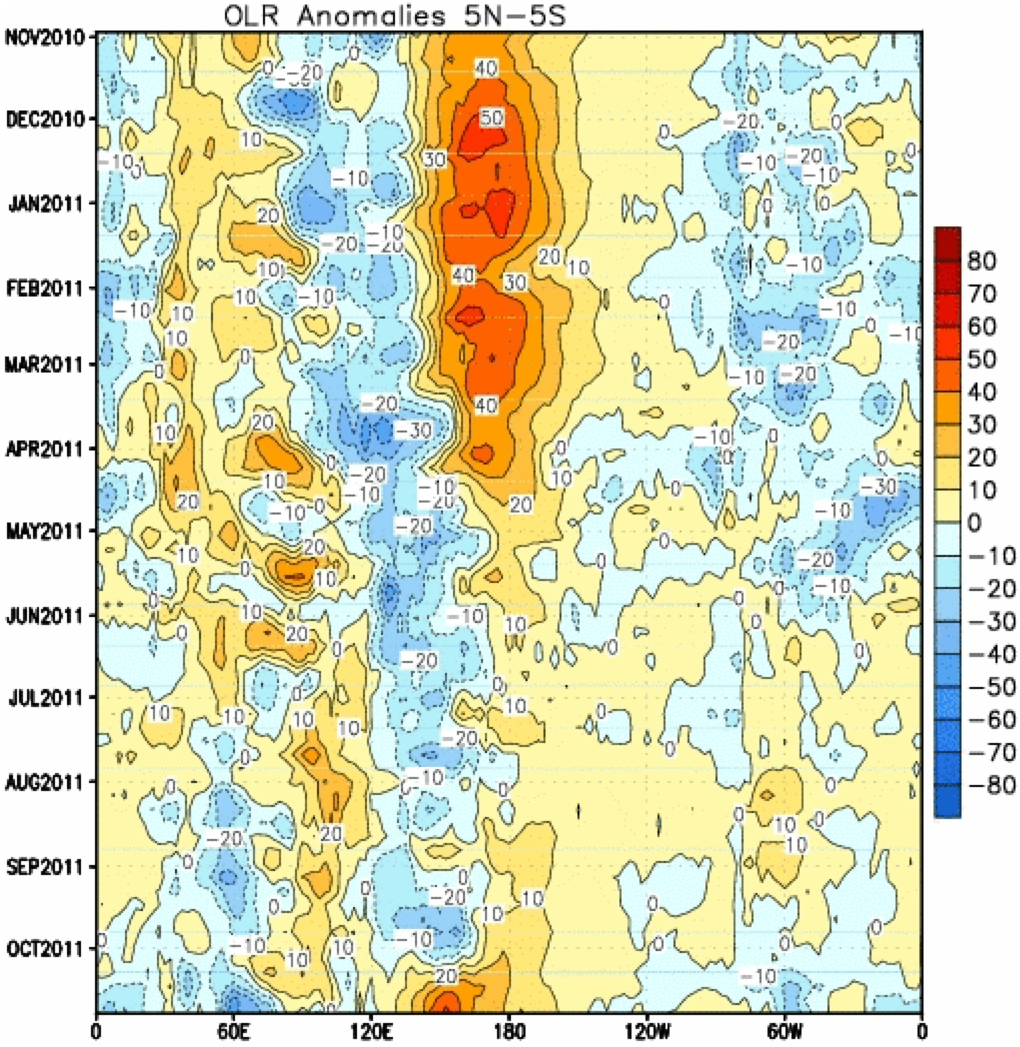

Figure 36: Near-equatorial OLR anomalies over the past year. Note the mixed OLR anomaly signal during the August-October period. The recent pronounced OLR signal is associated with an MJO event.

8.8 Atlantic Multi-Decadal Oscillation (AMO)

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 37). 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 – 10-20°N; 20-70°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 37). 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 37 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 modest temporary weakening during 2011. We observed that the NAO went strongly positive during the second half of the winter of 2010/2011 extending into the early spring. This helped cause the Atlantic gyre to become stronger, the eastern Atlantic SST to become cooler, and Atlantic tropospheric westerly vertical wind shear to increase across the Atlantic sub-tropics (20°N-30°N). This unexpected weakening of the

AMO/THC is one of the reasons why we likely over-estimated major hurricane activity this year.

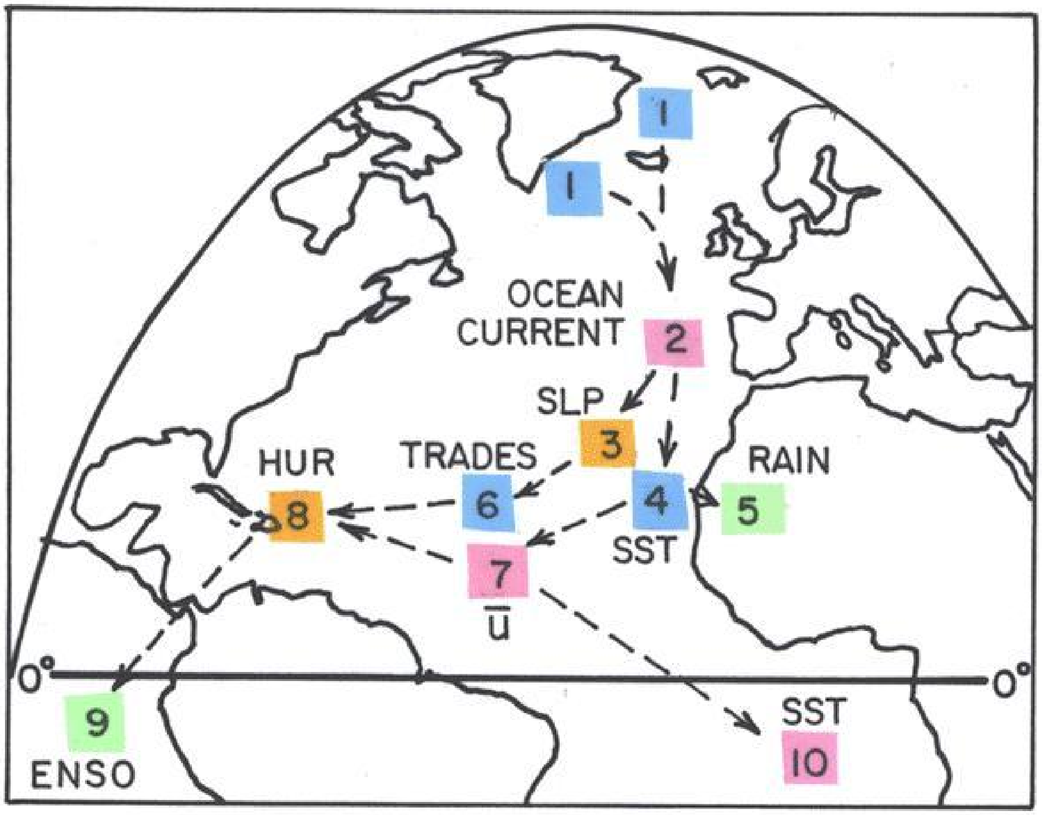

Figure 37: Schematic showing the large number of parameters that are closely related to the AMO or THC.

8.9 Summary

The 2011 Atlantic basin hurricane season had activity at above-average levels, but not to the level that was expected in our pre-season forecasts. While anomalously warm tropical Atlantic SSTs and La Niña conditions likely provided conditions that were reasonably favorable for an active season, anomalously cool SSTs in the northeast subtropical Atlantic, anomalously dry mid levels in the tropical Atlantic and a positive Indian Ocean Dipole (IOD) event conspired to put a damper on this season's more intense tropical cyclone activity. 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 six years since the last major hurricane made U.S. landfall (Wilma – October 2005).

9 Have Atmospheric CO_2 Increases Been Responsible for the Recent Large Upswing (since 1995) in Atlantic Basin Major Hurricanes?

A. BACKGROUND

The U.S. landfall of major hurricanes Dennis, Katrina, Rita and Wilma in 2005 and the four Southeast landfalling hurricanes of 2004 – Charley, Frances, Ivan and Jeanne, raised questions about the possible role that global warming played in those two unusually destructive seasons for the U.S. In addition, three hurricanes (Dolly, Gustav and Ike) pummeled the Gulf Coast in 2008 causing considerable devastation. Some researchers have tried to link the rising CO_2 levels with SST increases during the late 20th century and say that this has brought on higher levels of hurricane intensity.

These speculations that hurricane intensity has increased due to CO_2 increases have been given much media attention; however, we believe that they are not valid, given current observational data. Gray (2011) goes into extensive detail describing why the relationship between increased CO_2 and increased hurricane activity may not be valid.

There has, however, been a large increase in Atlantic basin major hurricane activity in the last seventeen years (since 1995) in comparison with the prior 17-year period of 1978-1994 (Figure 38) as well as the prior quarter-century period of 1970-1994. It has been tempting for many who do not have a strong background of hurricane information to jump on this recent increase in major hurricane activity as strong evidence of a human influence on hurricanes. It should be noted, however, that the last 17-year active major hurricane period of 1995-2011 has not been more active than the earlier 17-year period of 1948-1964 when the Atlantic Ocean circulation conditions were similar to what has been observed during the last 17 years. These earlier active conditions occurred even though atmospheric CO_2 amounts were lower during the earlier period.

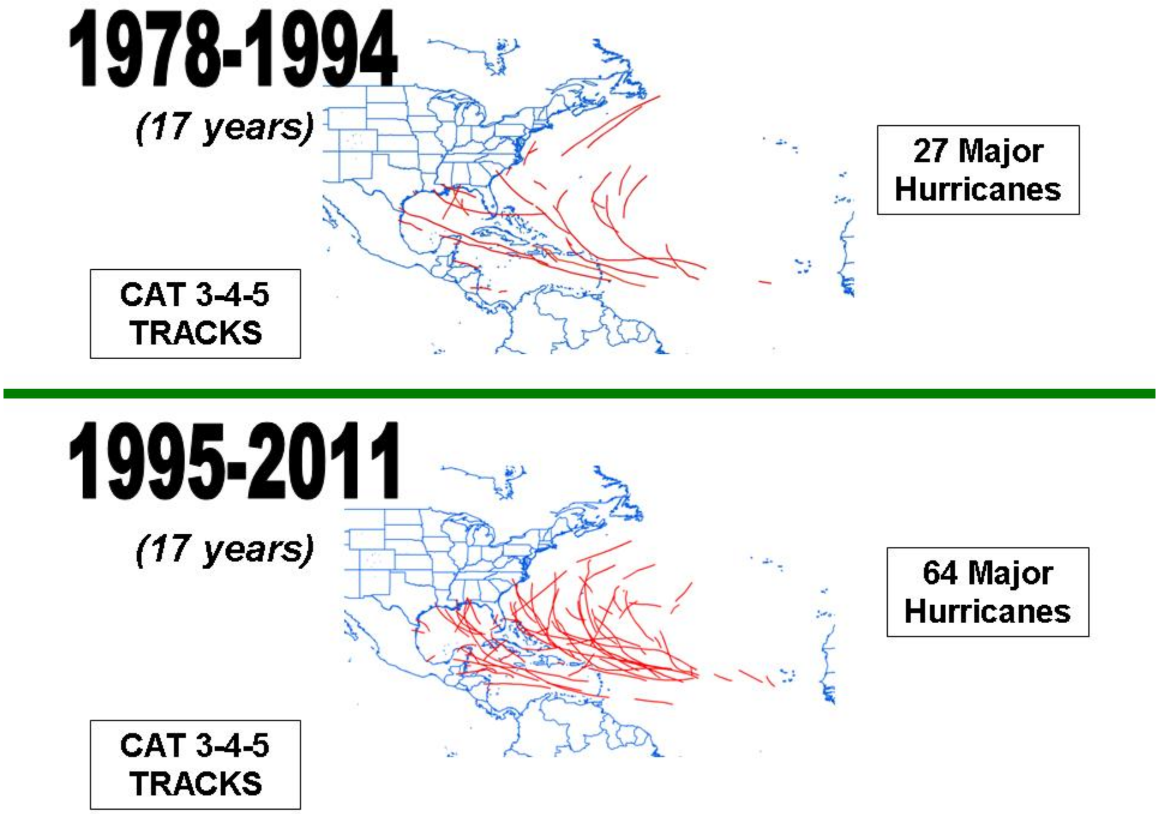

Figure 38: The tracks of major (Category 3-4-5) hurricanes during the 17-year period of 1995-2011 when the THC was strong versus the prior 17-year period of 1978-1994 when the THC was weak. Note that there were approximately 2.5 times as many major hurricanes when the THC was strong as when it was weak.

Table 14 shows how large Atlantic basin hurricane variations can be between strong and weak THC periods. Note especially how large the ratio is for major hurricane days (3.7) during strong vs. weak THC periods. Normalized U.S. hurricane damage studies by Pielke and Landsea (1998) and Pielke et al. (2008) show that landfalling major hurricanes account on average for about 80-85 percent of all hurricane-related destruction. This occurs even though these major hurricanes make up only 20-25 percent of named storms. This would give a general potential destructive difference of 3.7 * 4.25 or about 15 to 1.

Although global surface temperatures increased during the late 20th century, there is no reliable data to indicate increased hurricane frequency or intensity in any of the globe's other tropical cyclone basins since 1972. Global Accumulated Cyclone Energy (ACE), 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, shows significant year-to-year and decadal variability over the past forty years but no increasing trend (Figure 39). Similarly, Klotzbach (2006) found no significant change in global TC activity during the period from 1986-2005.

Table 14: Comparison of Atlantic annual basin hurricane activity in two 17-year periods when the Atlantic Ocean THC (or AMO) was strong versus an intermediate period (1970-1994) when the THC was weak.

	THC	SST (10-15°N; 70-40°W)	Avg. CO$_2$ ppm	NS	NSD	H	HD	MH	MHD	ACE	NTC
1948-1964 (17 years)	Strong	27.93	319	10.0	54.0	6.5	29.9	3.8	9.4	120	133
1970-1994 (25 years)	Weak	27.60	345	9.3	41.9	5.0	16.0	1.5	2.5	68	75
1995-2011 (17 years)	Strong	28.02	373	14.9	75.5	7.8	31.9	3.8	9.1	140	153
Annual Ratio Strong/Weak THC		Δ 0.35°C	~ 0	1.3	1.5	1.4	1.9	2.5	3.7	1.9	1.9

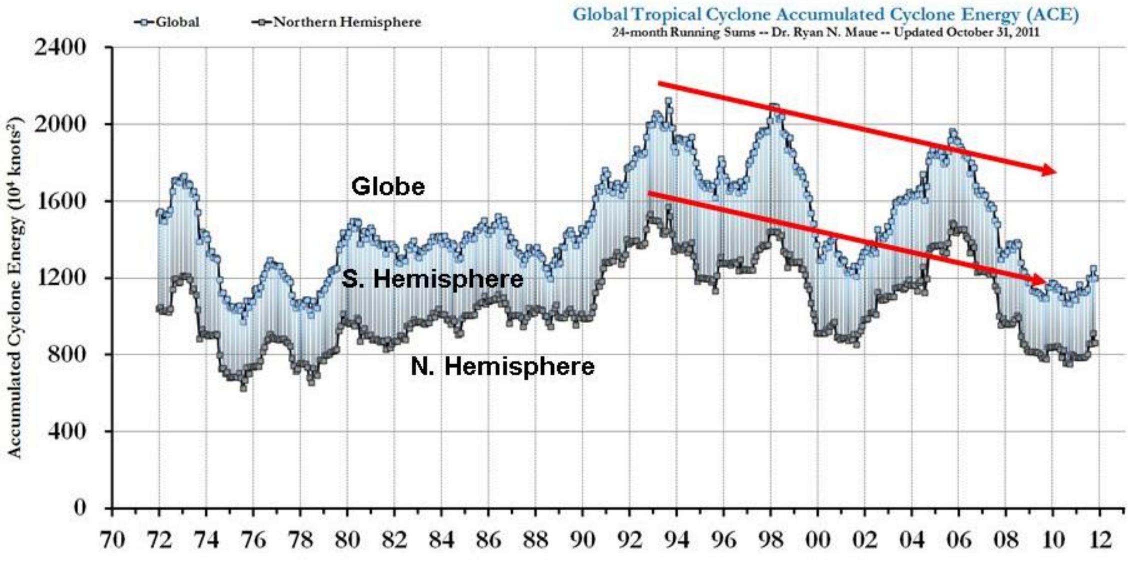

Figure 39: Northern Hemisphere and global Accumulated Cyclone Energy (ACE) over the period from December 1971-October 2011. Figure has been adapted from Ryan Maue.

Causes of the Upswing in Atlantic Major Hurricane Activity since 1995. The Atlantic Ocean has a strong multi-decadal signal in its hurricane activity which is likely due to multi-decadal variations in the strength of the THC (Figure 40). The oceanic and atmospheric response to the THC is often referred to as the Atlantic Multi-decadal Oscillation (AMO). We use the THC and AMO interchangeably throughout the remainder of this discussion. The strength of the THC can never be directly measured, but it can be diagnosed, as we have done, from the magnitude of the SST anomaly

(SSTA) in the North Atlantic (Figure 41) combined with the sea level pressure anomaly (SLPA) in the Atlantic between the latitude of the equator and 50°N (Klotzbach and Gray 2008).

The THC (or AMO) is strong when there is an above-average poleward advection of warm low-latitude waters to the high latitudes of the North Atlantic. This water can then sink to deep levels when it reaches the far North Atlantic in a process known as deep water formation. The water then moves southward at deep levels in the ocean. The amount of North Atlantic water that sinks is proportional to the water's density which is determined by its salinity content as well as its temperature. Salty water is denser than fresh water especially at water temperatures near freezing. There is a strong association between North Atlantic SSTA and North Atlantic salinity (Figure 42). High salinity implies higher rates of North Atlantic deep water formation (or subsidence) and thus a stronger flow of upper level warm water from lower latitudes as replacement. See the papers by Gray et al. (1999), Goldenberg et al. (2001), and Grossmann and Klotzbach (2009) for more discussion.

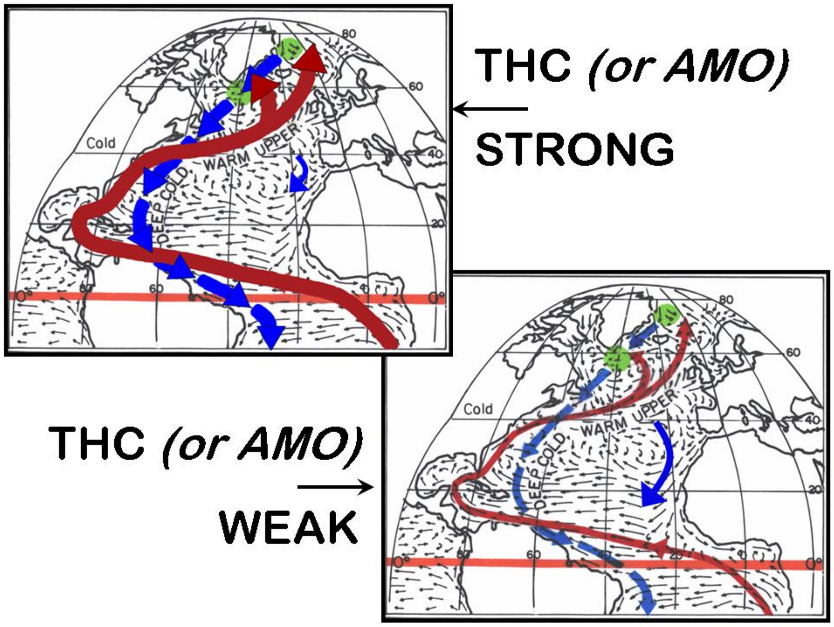

Figure 40: Illustration of strong (top) and weak (bottom) phases of the THC or AMO.

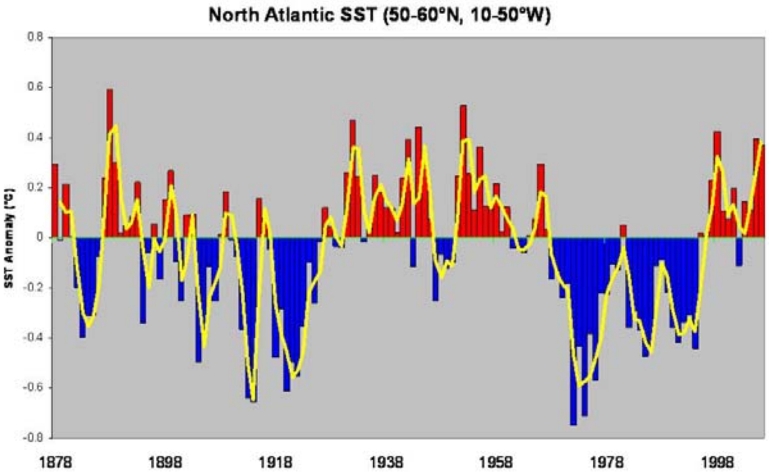

Figure 41: Long-period portrayal (1878-2006) of North Atlantic sea surface temperature anomalies (SSTA). The red (warm) periods are when the THC (or AMO) is stronger than average and the blue periods are when the THC (or AMO) is weaker than average.

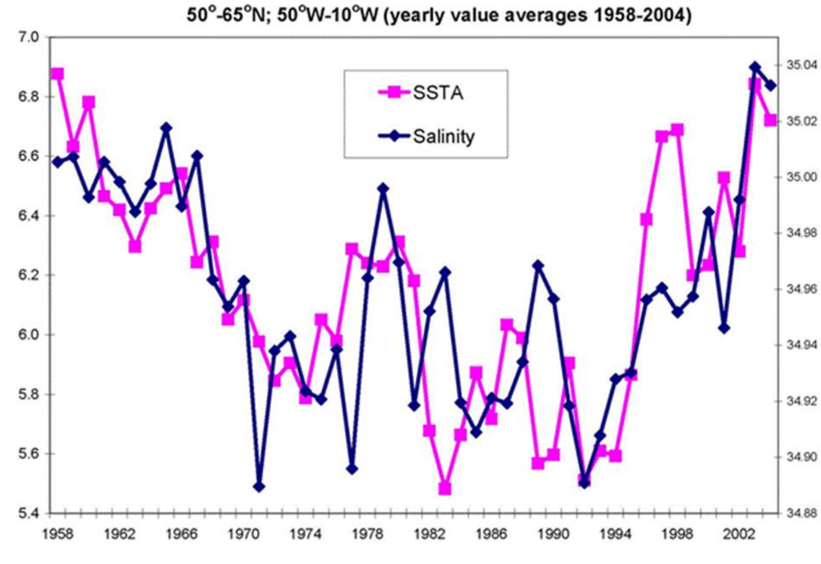

Figure 42: Illustration of the strong association of yearly average North Atlantic SSTA and North Atlantic salinity content between 1958 and 2004.

B. WHY CO_2 INCREASES ARE NOT RESPONSIBLE FOR ATLANTIC SST AND HURRICANE ACTIVITY INCREASES

Theoretical considerations do not support a close relationship between SSTs and hurricane intensity. In a global warming world, the atmosphere's upper air temperatures will warm or cool in unison with longer-period SST changes. Vertical lapse rates will thus not be significantly altered in a somewhat warmer or somewhat cooler tropical oceanic environment. We have no plausible physical reasons for believing that Atlantic hurricane frequency or intensity will significantly change if global or Atlantic Ocean temperatures were to rise by 1-2°C. Without corresponding changes in many other basic features, such as vertical wind shear or mid-level moisture, little or no additional TC activity should occur with SST increases.

Confusing Time Scales of SST Influences. A hurricane passing over a warmer body of water, such as the Gulf Stream, will often undergo some intensification. This is due to the sudden lapse rate increase which the hurricane's inner core experiences when it passes over warmer water. The warmer SSTs cause the hurricane's lower boundary layer temperature and moisture content to rise. While these low-level changes are occurring, upper tropospheric conditions are often not altered significantly. These rapidly occurring lower- and upper-level temperature differences cause the inner-core hurricane lapse rates to increase and produce more intense inner-core deep cumulus convection. This typically causes a rapid increase in hurricane intensity. Such observations have led many observers to directly associate SST increases with greater hurricane potential intensity. This is valid reasoning for day-to-day hurricane intensity change associated with hurricanes moving over warmer or colder patches of SST. But such direct reasoning does not hold for conditions occurring in an overall climatologically warmer (or cooler) tropical oceanic environment where broad-scale global and tropical rainfall conditions are not expected to significantly vary. During long-period climate change, temperature and moisture conditions rise at both lower and upper levels. Lapse rates are little affected.

Any warming-induced increase in boundary layer temperature and moisture will be (to prevent significant global rainfall alteration) largely offset by a similar but weaker change through the deep troposphere up to about 10 km height. Upper-tropospheric changes are weaker than boundary layer changes, but they occur through a much deeper layer. These weaker and deeper compensating increases in upper-level temperature and moisture are necessary to balance out the larger increases in temperature and moisture which occur in the boundary layer. Global and tropical rainfall would be altered significantly only if broad-scale lapse rates were ever altered to an appreciable degree.

Thus, we cannot automatically assume that with warmer global SSTs that we will have more intense hurricanes due to lapse-rate alterations. We should not expect that the frequency and/or intensity of major hurricanes will necessarily change as a result of changes in global or individual storm basin SSTs. Historical evidence does not support hurricanes being less intense during the late 19th century and the early part of the 20th century when SSTs were slightly lower.

C. DISCUSSION

We have no plausible physical reasons for believing that Atlantic hurricane frequency or intensity will change significantly if global ocean temperatures were to continue to rise. For instance, in the quarter-century period from 1945-1969 when the globe was undergoing a weak cooling trend, the Atlantic basin experienced 80 major (Cat 3-4-5) hurricanes and 201 major hurricane days. By contrast, in a similar 25-year period from 1970-1994 when the globe was undergoing a general warming trend, there were only 38 Atlantic major hurricanes (48% as many) and 63 major hurricane days (31% as many) (Figure 43). Atlantic SSTs and hurricane activity do not follow global mean temperature trends.

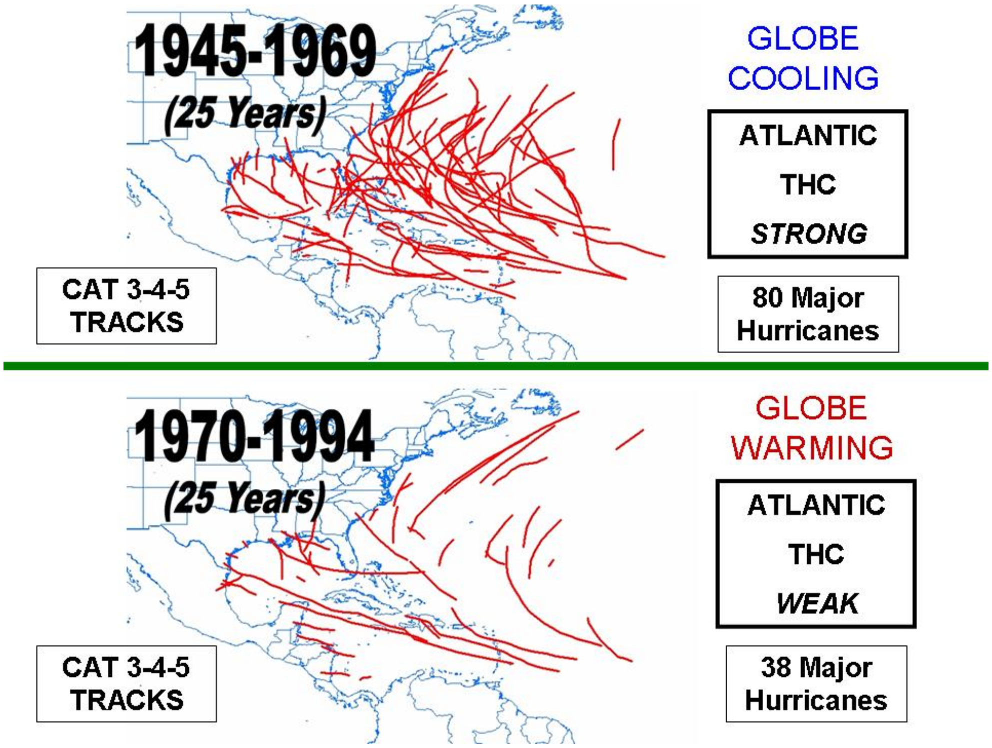

Figure 43: Tracks of major (Category 3-4-5) hurricanes during the 25-year period of 1945-1969 when the globe was undergoing a weak cooling versus the 25-year period of 1970-1994 when the globe was undergoing a modest warming. CO_2 amounts in the later period were approximately 18 percent higher than in the earlier period. Major Atlantic hurricane activity was less than half as frequent during the latter period despite warmer global temperatures.

The most reliable long-period hurricane records we have are the measurements of US landfalling TCs since 1900 (Table 15). Although global mean ocean and Atlantic SSTs have increased by about 0.4°C between two 56-year periods (1900-1955 compared with 1956-2011), the frequency of US landfall numbers actually shows a slight downward trend for the later period. This downward trend is particularly noticeable for the US East Coast and Florida Peninsula where the difference in landfall of major (Category 3-4-5) hurricanes between the 46-year period of 1920-1965 (24 landfall events) and the 46-year period of 1966-2011 (7 landfall events) has been especially large (Figure 44). For the entire United States coastline, 39 major hurricanes made landfall during the earlier 46-year period (1920-1965) compared with only 26 major hurricanes for the latter 46-year period (1966-2011). This occurred despite the fact that CO_2 averaged approximately 365 ppm during the latter period compared with 310 ppm during the earlier period.

Table 15: U.S. landfalling tropical cyclones by intensity during two 56-year periods.

YEARS	***Named Storms***	***Hurricanes***	***Major Hurricanes (Cat 3-4-5)***	***Global Temperature Increase***
1900-1955 (56 years)	213	116	45	+0.4°C
1956-2011 (56 years)	182	88	34	

We should not read too much into the four very active hurricane seasons of 2004, 2005, 2008 and 2010. The activity of these years was unusual but well within natural bounds of hurricane variation.

What made the 2004, 2005 and 2008 seasons so destructive was not the high frequency of major hurricanes but the high percentage of hurricanes that were steered over the US coastline. The US hurricane landfall events of these years were primarily a result of the favorable upper-air steering currents present during these years.

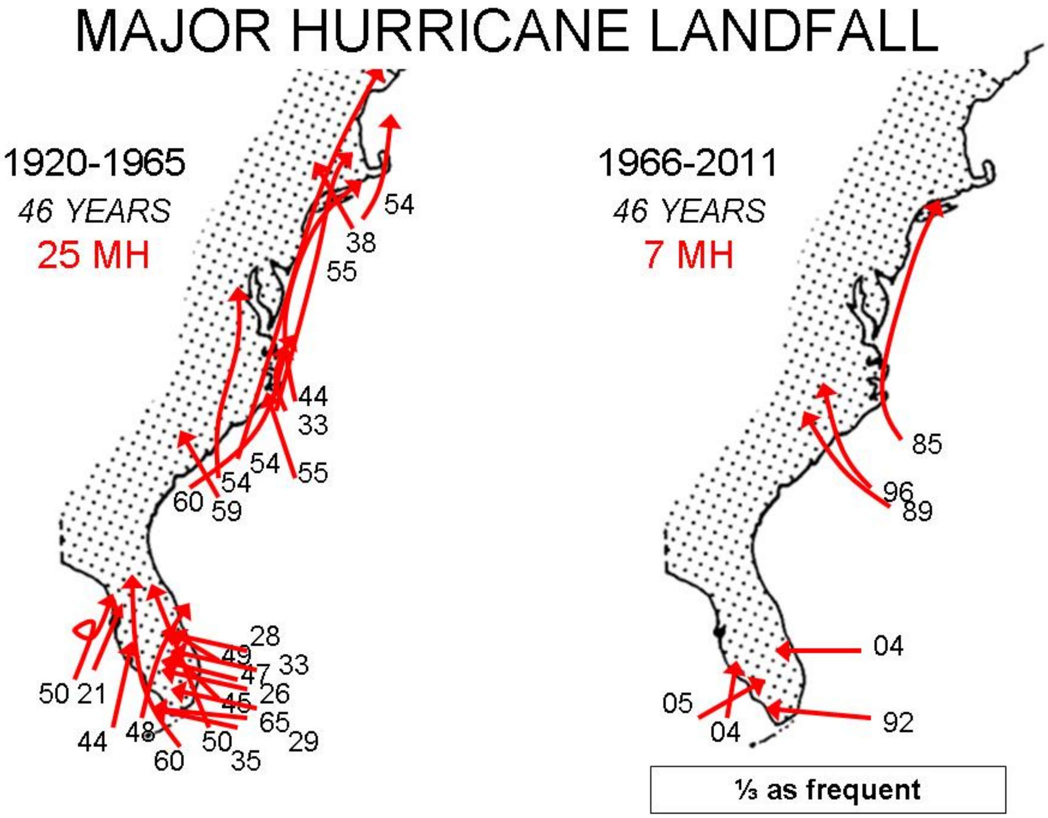

Figure 44: Contrast of tracks of East Coast and Florida Peninsula major landfalling hurricanes during the 46-year period of 1920-1965 versus the most recent 46-year period of 1966-2011.

Although 2005 had a record number of TCs (28 named storms), this should not be taken as an indication of something beyond natural processes. There have been several other years with comparable hurricane activity to 2005. For instance, 1933 had 21 named storms in a year when there was no satellite or aircraft data. Records of 1933 show all 21 named storms had tracks west of 60°W where surface observations were more plentiful. If we eliminate all of the named storms of 2005 whose tracks were entirely east of 60°W and therefore may have been missed given the technology available in 1933, we reduce the 2005 named storm total by seven (to 21) – the same number as was observed in 1933.

Utilizing the National Hurricane Center's best track database of hurricane records back to 1875, six previous seasons had more hurricane days than the 2005 season. These years were 1878, 1893, 1926, 1933, 1950 and 1995. Also, five prior seasons (1893, 1926, 1950, 1961 and 2004) had more major hurricane days. Although the 2005 hurricane season was certainly one of the most active on record, it was not as much of an outlier as many have indicated.

We believe that the Atlantic basin remains in an active hurricane cycle associated with a strong THC. This active cycle is expected to continue for another decade or two at which time we should enter a quieter Atlantic major hurricane period like we experienced during the quarter-century periods of 1970-1994 and 1901-1925. Atlantic hurricanes go through multi-decadal cycles. Cycles in Atlantic major hurricanes have been observationally traced back to the mid-19th century. Changes in the THC (or AMO) have been inferred from Greenland paleo ice-core temperature measurements going back thousands of years. These changes are natural and have nothing to do with human activity.

10 Forecasts of 2012 Hurricane Activity

We will be issuing our first forecast for the 2012 hurricane season on Wednesday, 7 December 2011. This forecast will provide a qualitative outlook for factors likely to impact the 2012 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.

11 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, and Max Mayfield, former directors of the National Hurricane Center (NHC) and the current director, Bill Read.

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13 Verification of Previous Forecasts

Table 16: Verification of the authors' early August forecasts of Atlantic named storms and hurricanes between 1984-2011. 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
Average	**11.0**	**10.8**	**6.3**	**6.1**
1984-2011 Correlation		**0.65**		**0.64**

Table 17: Summary verification of the authors' five previous years of seasonal forecasts for Atlantic TC activity between 2006-2010. Verifications of all seasonal forecasts back to 1984 are available here: http://tropical.atmos.colostate.edu/Includes/Documents/Publications/forecast_verifications.xls

2006	6 Dec. 2005	Update 4 April	Update 31 May	Update 3 August	Obs.
Hurricanes	9	9	9	7	5
Named Storms	17	17	17	15	10
Hurricane Days	45	45	45	35	21.25
Named Storm Days	85	85	85	75	52.75
Major Hurricanes	5	5	5	3	2
Major Hurricane Days	13	13	13	8	2
Net Tropical Cyclone Activity	195	195	195	140	85

2007	8 Dec. 2006	Update 3 April	Update 31 May	Update 3 August	Obs.
Hurricanes	7	9	9	8	6
Named Storms	14	17	17	15	15
Hurricane Days	35	40	40	35	12.25
Named Storm Days	70	85	85	75	37.75
Major Hurricanes	3	5	5	4	2
Major Hurricane Days	8	11	11	10	6
Net Tropical Cyclone Activity	140	185	185	160	99

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