# FORECAST OF ATLANTIC SEASONAL HURRICANE ACTIVITY AND LANDFALL STRIKE PROBABILITY FOR 2011

We have maintained our forecast from early April and early June and continue to call for a very active Atlantic basin hurricane season in 2011 due to an expected favorable Atlantic and neutral ENSO conditions. We anticipate a well above-average probability of United States and Caribbean major hurricane landfall.

(as of 3 August 2011)

By Philip J. Klotzbach[1] and William M. Gray[2]

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

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

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## ATLANTIC BASIN SEASONAL HURRICANE FORECAST FOR 2011

| Forecast Parameter and 1950-2000 Climatology (in parentheses) | Issue Date 8 December 2010 | Issue Date 6 April 2011 | Issue Date 1 June 2011 | Observed Activity Through July 2011 | Forecast Activity After 31 July | Total Seasonal Forecast |
|---|---|---|---|---|---|---|
| Named Storms (NS) (9.6) | 17 | 16 | 16 | 4 | 12 | 16 |
| Named Storm Days (NSD) (49.1) | 85 | 80 | 80 | 10 | 70 | 80 |
| Hurricanes (H) (5.9) | 9 | 9 | 9 | 0 | 9 | 9 |
| Hurricane Days (HD) (24.5) | 40 | 35 | 35 | 0 | 35 | 35 |
| Major Hurricanes (MH) (2.3) | 5 | 5 | 5 | 0 | 5 | 5 |
| Major Hurricane Days (MHD) (5.0) | 10 | 10 | 10 | 0 | 10 | 10 |
| Accumulated Cyclone Energy (ACE) (96.1) | 165 | 160 | 160 | 8 | 152 | 160 |
| Net Tropical Cyclone Activity (NTC) (100%) | 180 | 175 | 175 | 10 | 165 | 175 |

## POST-31 JULY PROBABILITIES FOR AT LEAST ONE MAJOR (CATEGORY 3-4-5) HURRICANE LANDFALL ON EACH OF THE FOLLOWING UNITED STATES COASTAL AREAS:

1) Entire U.S. coastline - 70% (full-season average for last century is 52%)

2) U.S. East Coast Including Peninsula Florida - 46% (full-season average for last century is 31%)

3) Gulf Coast from the Florida Panhandle westward to Brownsville - 45% (full-season average for last century is 30%)

## POST-31 JULY PROBABILITIES FOR AT LEAST ONE MAJOR (CATEGORY 3-4-5) HURRICANE TRACKING INTO THE CARIBBEAN (10-20°N, 60-88°W)

1) 59% (full-season average for last century is 42%)

## POST-31 JULY HURRICANE IMPACT PROBABILITIES FOR 2011 (NUMBERS IN PARENTHESES ARE LONG-PERIOD FULL SEASON AVERAGES)

| State | Hurricane | Major Hurricane |
|---|---|---|
| Texas | 48% (33%) | 19% (12%) |
| Louisiana | 45% (30%) | 19% (12%) |
| Mississippi | 17% (11%) | 7% (4%) |
| Alabama | 24% (16%) | 4% (3%) |
| Florida | 69% (51%) | 32% (21%) |
| Georgia | 18% (11%) | 2% (1%) |
| South Carolina | 27% (17%) | 6% (4%) |
| North Carolina | 42% (28%) | 12% (8%) |
| Virginia | 10% (6%) | 1% (1%) |
| Maryland | 2% (1%) | <1% (<1%) |
| Delaware | 2% (1%) | <1% (<1%) |
| New Jersey | 2% (1%) | <1% (<1%) |
| New York | 12% (8%) | 5% (3%) |
| Connecticut | 11% (7%) | 3% (2%) |
| Rhode Island | 9% (6%) | 4% (3%) |
| Massachusetts | 11% (7%) | 3% (2%) |
| New Hampshire | 2% (1%) | <1% (<1%) |
| Maine | 6% (4%) | <1% (<1%) |

## POST-31 JULY PROBABILITIES OF HURRICANES AND MAJOR HURRICANES TRACKING WITHIN 100 MILES OF EACH ISLAND OR LANDMASS FOR 2011 (NUMBERS IN PARENTHESES ARE LONG-PERIOD FULL SEASON AVERAGES)

| Island/Landmass | Hurricane within 100 Miles | Major Hurricane within 100 Miles |
|---|---|---|
| Bahamas, The | 70% (51%) | 44% (30%) |
| Cuba | 70% (52%) | 42% (28%) |
| Haiti | 41% (27%) | 20% (13%) |
| Jamaica | 38% (25%) | 18% (11%) |
| Mexico | 75% (57%) | 35% (23%) |
| Puerto Rico | 43% (29%) | 20% (13%) |
| Turks and Caicos | 37% (24%) | 15% (9%) |
| US Virgin Islands | 44% (30%) | 19% (12%) |

**Please also visit the Landfalling Probability Webpage at http://www.e-transit.org/hurricane for landfall probabilities for 11 U.S. coastal regions and 205 coastal and near-coastal counties from Brownsville, Texas to Eastport, Maine as well as probabilities for every island in the Caribbean. We suggest that all coastal residents visit the Landfall Probability Webpage for their individual location probabilities.**

# ABSTRACT

Information obtained through July 2011 indicates that the 2011 Atlantic hurricane season will be much more active than the average 1950-2000 season. We estimate that 2011 will have about 9 hurricanes (average is 5.9), 16 named storms (average is 9.6), 80 named storm days (average is 49.1), 35 hurricane days (average is 24.5), 5 major (Category 3-4-5) hurricanes (average is 2.3) and 10 major hurricane days (average is 5.0). The probability of U.S. major hurricane landfall and Caribbean major hurricane activity is estimated to be well above its long-period average. We expect Atlantic basin Net Tropical Cyclone (NTC) activity in 2011 to be approximately 175 percent of the long-term average season. We have maintained our seasonal forecast from early April and early June.

This forecast was based on a newly-developed extended-range early August statistical prediction scheme developed over the previous 30 years and then tested over the remainder of the previous century. Our older statistical forecast model that has been utilized for the past few years was also considered. Analog predictors were also utilized.

The ENSO-related warming trend in the tropical Pacific has abated, and we are reasonably confident that we will have near-neutral conditions for the remainder of this year's hurricane season. The combination of the neutral tropical Pacific along with continued warm sea surface temperature anomalies and unusually low sea level pressure anomalies in the tropical Atlantic will likely lead to a very active Atlantic basin hurricane season.

We are also now issuing a separate hurricane forecast for activity in the Caribbean Basin. This forecast is based on a statistical prediction scheme that utilizes 60 years of past data. This model is also predicting a very active season for the Caribbean.

# Why issue forecasts for seasonal hurricane activity?

We are frequently asked this question. Our answer is that it is possible to say something about the probability of the coming year's hurricane activity which is superior to climatology. The Atlantic basin has the largest year-to-year variability of any of the global tropical cyclone basins. People are curious to know how active the upcoming season is likely to be, particularly if you can show hindcast skill improvement over climatology for many past years.

Everyone should realize that it is impossible to precisely predict this season's hurricane activity in early August. There is, however, much curiosity as to how global ocean and atmosphere features are presently arranged as regards to the probability of an active or inactive hurricane season for the coming year. Our new early August statistical forecast methodology shows strong evidence over 29 past years that improvement over climatology can be attained. We utilize this newly-developed model along with an older August statistical model developed on over one century's worth of data when issuing this year's forecast. **We would never issue a seasonal hurricane forecast unless we had a statistical model constructed over a long hindcast period which showed significant skill over climatology.**

We issue these forecasts to satisfy the curiosity of the general public and to bring attention to the hurricane problem. There is a general interest in knowing what the odds are for an active or inactive season. One must remember that our forecasts are based on the premise that those global oceanic and atmospheric conditions which preceded comparatively active or inactive hurricane seasons in the past provide meaningful information about similar trends in future seasons. This is not always true for individual seasons. It is also important that the reader appreciate that these seasonal forecasts are based on statistical schemes which, owing to their intrinsically probabilistic nature, will fail in some years. Moreover, these forecasts do not specifically predict where within the Atlantic basin these storms will strike. The probability of landfall for any one location along the coast is very low and reflects the fact that, in any one season, most U.S. coastal areas will not feel the effects of a hurricane no matter how active the individual season is.

## Notice of Author Changes

### By William Gray

The order of the authorship of these forecasts was reversed in 2006 from Gray and Klotzbach to Klotzbach and Gray. After 22 years (1984-2005) of making these forecasts, it was appropriate that I step back and have Phil Klotzbach assume the primary responsibility for our project's seasonal forecasts. Phil has been a member of my research project for the last eleven years and was second author on these forecasts from 2001-2005. I have greatly profited and enjoyed our close personal and working relationship. Phil has an office next to my office, and we talk nearly every day.

Phil is now devoting much more time to the improvement of these forecasts than I am. I am now giving more of my efforts to the global warming issue and in synthesizing my projects' many years of hurricane and typhoon studies.

Phil Klotzbach is an outstanding young scientist with a superb academic record. I have been amazed at how far he has come in his knowledge of hurricane prediction since joining my project in 2000. I foresee an outstanding future for him in the hurricane field. The success of the last three years of seasonal forecasts is an example. He is currently developing new seasonal and two-week forecast innovations that are improving our forecasts. Phil was awarded his Ph.D. degree in 2007. He is spending most of his time working towards better understanding and improving these Atlantic basin hurricane forecasts.

## Acknowledgment

This year's forecasts are funded by private and personal funds. We thank the GeoGraphics Laboratory at Bridgewater State College (MA) for their assistance in developing the United States Landfalling Hurricane Probability Webpage (available online at http://www.e-transit.org/hurricane).

The second author gratefully acknowledges the valuable input to his CSU seasonal forecast research project over many years by former graduate students and now colleagues Chris Landsea, John Knaff and Eric Blake. We also thank Professors Paul Mielke and Ken Berry of Colorado State University for much statistical analysis and advice over many years. We thank Bill Thorson for technical advice and assistance.

# 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.

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

# 1 Introduction

This is the 28th year in which the CSU Tropical Meteorology Project has made forecasts of the upcoming season's Atlantic basin hurricane activity. Our research team has shown that a sizable portion of the year-to-year variability of Atlantic tropical cyclone (TC) activity can be hindcast with skill exceeding climatology. This year's August forecast is based on a new statistical methodology derived from 29 years of past data along with our earlier August forecast scheme developed on over 100 years of past data. Qualitative adjustments are added to accommodate additional processes which may not be explicitly represented by our statistical analyses. These evolving forecast techniques are based on a variety of climate-related global and regional predictors previously shown to be related to the forthcoming seasonal Atlantic basin TC activity and landfall probability. We believe that seasonal forecasts must be based on methods that show significant hindcast skill in application to long periods of prior data. It is only through hindcast skill that one can demonstrate that seasonal forecast skill is possible. This is a valid methodology provided that the atmosphere continues to behave in the future as it has in the past.

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

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

## 1.1 2011 Atlantic Basin Activity through July

The 2011 Atlantic basin hurricane season had approximately average tropical cyclone activity, based on the ACE index, during June and July.

<u>Arlene</u> formed late on June 28 in the southwestern Gulf of Mexico. 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.

Bret formed near the northwestern Bahamas on July 18. It intensified to a tropical storm early on July 19 while drifting slowly due to weak steering currents. It slowly strengthened while battling both dry air entrainment and moderate levels of vertical wind shear. The system reached its maximum intensity of 55 knots later that day, before beginning to weaken due to continued strong northerly shear on the system. It moved northeastward while maintaining intensity until later on July 20 when it began to succumb to the effects of strong vertical shear and dry air entrainment. It was downgraded to a tropical depression early on July 22 and was declared a remnant low later that day.

Cindy developed from an area of low pressure northeast of Bermuda on July 20. It moved rapidly northeastward while intensifying to its maximum intensity of 50 knots on July 21. Cindy began to weaken late on July 21, as the system encountered significantly cooler SSTs. As Cindy continued moving northeastward, the combination of cold SSTs and northerly shear decimated the system, and it was declared post-tropical late on July 22.

Don formed from a tropical wave in the southern Gulf of Mexico on July 27. It moved slowly northwestward underneath a ridge. Don slowly strengthened, but moderate northerly shear and dry air to its west prevented much intensification. As Don neared the southern Texas coast, it weakened dramatically, limping ashore as a tropical depression near Baffin Bay on July 30 and becoming a remnant low later that day. The system's rapid weakening prevented much of its beneficial rainfall from reaching drought-stricken Texas. No damage or fatalities were reported.

Table 1 records observed Atlantic basin tropical cyclone activity through 31 July, while tracks through 31 July are displayed in Figure 1.

Table 1: Observed 2011 Atlantic basin tropical cyclone activity through July.

| Highest Category | Name | Dates | Peak Sustained Winds (kts)/lowest SLP (mb) | NSD | HD | MHD | ACE | NTC |
|---|---|---|---|---|---|---|---|---|
| TS | Arlene | June 29 – June 30 | 55 kt/993 mb | 2.00 | | | 1.6 | 2.4 |
| TS | Bret | July 18 – July 21 | 55 kt/996 mb | 4.00 | | | 2.9 | 3.1 |
| TS | Cindy | July 20 – July 22 | 50 kt/1002 mb | 1.75 | | | 1.8 | 2.3 |
| TS | Don | July 27 – July 30 | 45 kt/998 mb | 2.25 | | | 1.5 | 2.5 |
| | | | | | | | | |
| Totals | 4 | | | 10.00 | | | 7.9 | 10.3 |

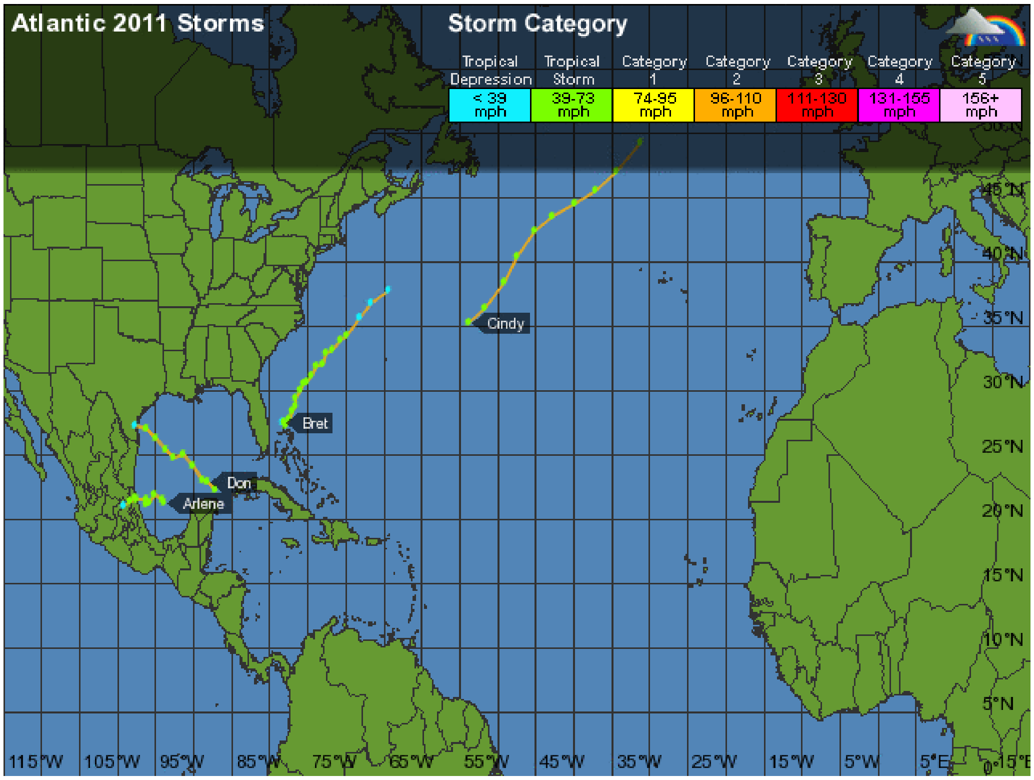


Figure 1: 2011 Atlantic basin hurricane tracks through July. Figure courtesy of Weather Underground (http://www.weatherunderground.com).

## 2 1 August Forecast Scheme as Discussed by Klotzbach in 2007 Publication

We devised a new 1 August statistical seasonal forecast scheme for the prediction of Net Tropical Cyclone (NTC) activity several years ago as documented in Klotzbach (2007). This scheme was developed on NCEP/NCAR reanalysis data from 1949-1989. It was then tested on independent data from 1990-2005 to insure that the forecast showed similar skill in this later period. As a rule, predictors were only added to the scheme if they explained an additional three percent of the variance of NTC in both the dependent period (1949-1989) and the independent period (1990-2005). The forecast scheme was also tested on independent data from 1900-1948. It showed comparable skill during this period. Over the 1900-1948 period, the scheme explained 51% of the variance in NTC activity, and over the more recent period from 1949-2010 the scheme explained 50% of the variance.

The pool of four June-July predictors for the early August forecast is given and defined in Table 2. The location of each of these predictors is shown in Figure 2. Strong statistical relationships can be extracted via combinations of these predictive parameters (which are available by the end of July), and quite skillful Atlantic basin forecasts of

NTC activity for the season can be made if the atmosphere and ocean continue to behave in the future as they have in the recent past.

This scheme only predicts Net Tropical Cyclone (NTC) activity, and the other seasonal predictors are then derived from this NTC prediction. These other seasonal predictors are calculated by taking the observed historical relationships between themselves and NTC. Relationships between NTC and other seasonal metrics such as named storms, named storm days and hurricane days were derived by breaking up the observed hurricane statistics from 1950-2007 into six groups based on NTC ranking. Equations for converting NTC to other seasonal parameters were then calculated by fitting a least squared regression equation to the observed data. These equations are listed below. Figure 3 illustrates predictions for various seasonal parameters given NTC values of 150, 100 and 50, respectively. Utilizing this approach gives slightly lower root mean squared errors and seems more physically appropriate than simply adjusting each seasonal parameter by a uniform NTC factor.

Named Storms = 5.0 + (0.049 * NTC)
Named Storm Days = 10.5 + (0.375 * NTC)
Hurricanes = 2.2 + (0.036 * NTC)
Hurricane Days = -0.6 + (0.231 * NTC)
Major Hurricanes = -0.7 + (0.031 * NTC)
Major Hurricane Days = -3.8 + (0.092 * NTC)
Accumulated Cyclone Energy = -6.6 + (0.978 * NTC)

Table 2: Listing of 1 August 2011 predictors for this year's hurricane activity using the Klotzbach (2007) statistical model. A plus (+) means that positive deviations of the parameter indicate increased hurricane activity this year, and a minus (-) means that positive deviations of the parameter indicate decreased hurricane activity this year. The combination of these four predictors calls for an above-average hurricane season.

| Predictor | Values for 2011 Forecast | Effect on 2011 Hurricane Season |
|---|---|---|
| 1) June-July SST (20-40°N, 15-35°W) (+) | -0.5 SD | Slightly Suppress |
| 2) June-July SLP (10-25°N, 10-60°W) (-) | -1.6 SD | **Strongly Enhance** |
| 3) June-July SST (5°S-5°N, 90-150°W) (-) | 0.2 SD | Neutral |
| 4) Pre-1 August Named Storm Days – South of 23.5°N, East of 75°W (+) | 0 NSD | Slightly Suppress |

**Post-31 July Seasonal Forecast Predictors**

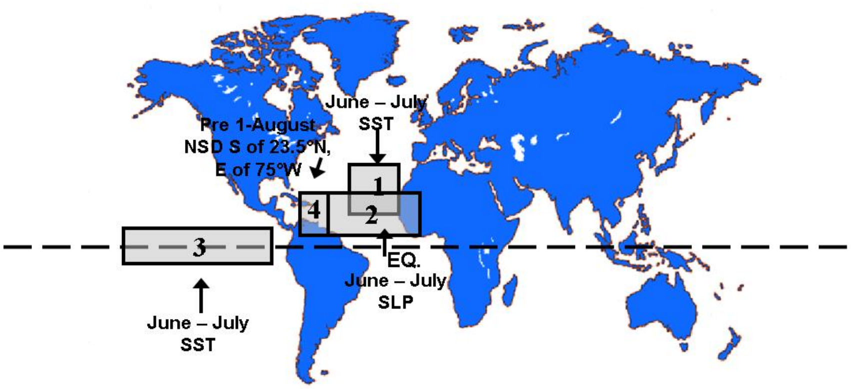


Figure 2: Location of predictors for the post-31 July forecast for the 2011 hurricane season from the Klotzbach (2007) model.

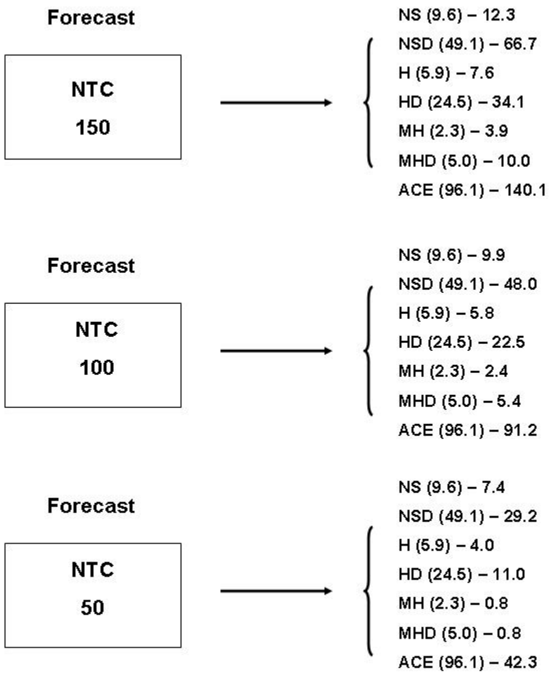


Figure 3: Schematic showing how predictions of 150, 100 and 50 NTC units, respectively, would be converted into predictions for other seasonal parameters. Numbers in parentheses are the climatological averages.

Table 3 shows our statistical forecast based on the Klotzbach (2007) scheme for the 2011 hurricane season and the comparison of this forecast with climatology (average season from 1950-2000). Our statistical forecast is calling for somewhat above-average activity this year.

Table 3: Post-31 July statistical forecast for 2011.

| Predictands and Climatology (1950-2000 – Post-31 July Average) | Klotzbach (2007) Statistical Forecast |
|---|---|
| Named Storms (NS) – 8.4 | 10.7 |
| Named Storm Days (NSD) – 44.9 | 53.0 |
| Hurricanes (H) – 5.4 | 6.1 |
| Hurricane Days (HD) – 23.4 | 23.8 |
| Major Hurricanes (MH) – 2.1 | 2.6 |
| Major Hurricane Days (MHD) – 4.9 | 6.0 |
| Accumulated Cyclone Energy Index (ACE) – 90 | 99 |
| Net Tropical Cyclone Activity (NTC) – 93 | 108 |

Table 4 displays our early August hindcasts for 1949-2005 using the new statistical scheme, along with real-time forecasts from the statistical model for 2006-2010, while Figure 4 displays observations versus NTC hindcasts/forecasts. Our early August model has correctly predicted above- or below-average post-31 July NTC in 52 out of 62 years (84%). These hindcasts have had a smaller error than climatology in 47 out of 62 years (76%). Our average hindcast errors have been 29 NTC units, compared with 44 NTC units had we used only climatology. This new scheme is also well-tuned to the multi-decadal active hurricane periods from 1950-1969 and 1995-2010 versus the inactive hurricane period from 1970-1994 (Table 5).

Table 4: Observed versus hindcast post-31 July NTC for 1949-2010 using the scheme detailed in Klotzbach (2007). Average errors for hindcast NTC and climatological NTC predictions are given without respect to sign. Red bold-faced years in the "Hindcast NTC" column are years that we did not go the right way, while red bold-faced years in the "Hindcast improvement over Climatology" column are years that we did not beat climatology. The hindcast went the right way with regards to an above- or below-average season in 52 out of 62 years (84%), while hindcast improvement over climatology occurred in 47 out of 62 years (76%). Note that since 1977, this forecast scheme has beaten climatology in all but four years.

| Year | Observed NTC | Hindcast NTC | Observed minus Hindcast | Observed minus Climatology | Hindcast improvement over Climatology |
|---|---|---|---|---|---|
| 1949 | 117 | 139 | -21 | 24 | 3 |
| 1950 | 247 | 129 | 118 | 154 | 36 |
| 1951 | 127 | 142 | -15 | 34 | 19 |
| 1952 | 101 | 145 | -44 | 8 | **-36** |
| 1953 | 125 | 121 | 4 | 32 | 28 |
| 1954 | 115 | 118 | -3 | 22 | 19 |
| 1955 | 205 | 179 | 27 | 112 | 86 |
| 1956 | 60 | 89 | -29 | -33 | 4 |
| 1957 | 67 | **101** | -33 | -26 | **-8** |
| 1958 | 142 | 113 | 29 | 49 | 20 |
| 1959 | 73 | **105** | -32 | -20 | **-12** |
| 1960 | 79 | **169** | -90 | -14 | **-76** |
| 1961 | 209 | 159 | 50 | 116 | 66 |
| 1962 | 41 | **117** | -76 | -52 | **-24** |
| 1963 | 116 | 107 | 10 | 23 | 14 |
| 1964 | 179 | 137 | 42 | 86 | 44 |
| 1965 | 83 | 60 | 23 | -10 | **-14** |
| 1966 | 96 | 163 | -66 | 3 | **-63** |
| 1967 | 102 | 101 | 1 | 9 | 8 |
| 1968 | 32 | 81 | -49 | -61 | 12 |
| 1969 | 179 | 122 | 57 | 86 | 29 |
| 1970 | 56 | 85 | -29 | -37 | 8 |
| 1971 | 89 | 61 | 27 | -4 | **-23** |
| 1972 | 26 | 26 | -1 | -67 | 67 |
| 1973 | 43 | **103** | -60 | -50 | **-10** |
| 1974 | 78 | 75 | 3 | -15 | 11 |
| 1975 | 82 | **114** | -32 | -11 | **-21** |
| 1976 | 81 | 61 | 20 | -12 | **-8** |
| 1977 | 47 | 89 | -41 | -46 | 4 |
| 1978 | 80 | 76 | 4 | -13 | 8 |
| 1979 | 86 | 87 | -1 | -7 | 6 |
| 1980 | 130 | 103 | 28 | 37 | 10 |
| 1981 | 108 | 104 | 4 | 15 | 11 |
| 1982 | 30 | 30 | 0 | -63 | 63 |
| 1983 | 31 | 43 | -13 | -62 | 50 |
| 1984 | 80 | 80 | 1 | -13 | 12 |
| 1985 | 97 | 95 | 3 | 4 | 2 |
| 1986 | 28 | 39 | -11 | -65 | 54 |
| 1987 | 46 | 88 | -42 | -47 | 5 |
| 1988 | 117 | 133 | -16 | 24 | 8 |
| 1989 | 123 | 152 | -29 | 30 | 1 |
| 1990 | 90 | **131** | -41 | -3 | **-38** |
| 1991 | 55 | 75 | -19 | -38 | 18 |
| 1992 | 65 | 49 | 16 | -28 | 13 |
| 1993 | 50 | 43 | 6 | -43 | 37 |
| 1994 | 33 | 50 | -17 | -60 | 43 |
| 1995 | 205 | 203 | 2 | 112 | 110 |
| 1996 | 163 | 133 | 31 | 70 | 40 |
| 1997 | 33 | 46 | -13 | -60 | 47 |
| 1998 | 166 | 145 | 21 | 73 | 52 |
| 1999 | 178 | 126 | 52 | 85 | 33 |
| 2000 | 134 | 98 | 36 | 41 | 5 |
| 2001 | 133 | 117 | 16 | 40 | 24 |
| 2002 | 81 | 38 | 43 | -12 | **-31** |
| 2003 | 155 | 138 | 17 | 62 | 45 |
| 2004 | 232 | 118 | 114 | 139 | 25 |
| 2005 | 204 | 184 | 20 | 111 | 91 |
| 2006 | 77 | 92 | -15 | -16 | 1 |
| 2007 | 92 | **105** | -12 | -1 | **-12** |
| 2008 | 125 | 191 | -66 | 32 | **-34** |
| 2009 | 69 | 87 | -19 | -24 | 6 |
| 2010 | 189 | 127 | 62 | 96 | 34 |
| **Average** | **105** | **105** | **\|29\|** | **\|44\|** | **+15** |

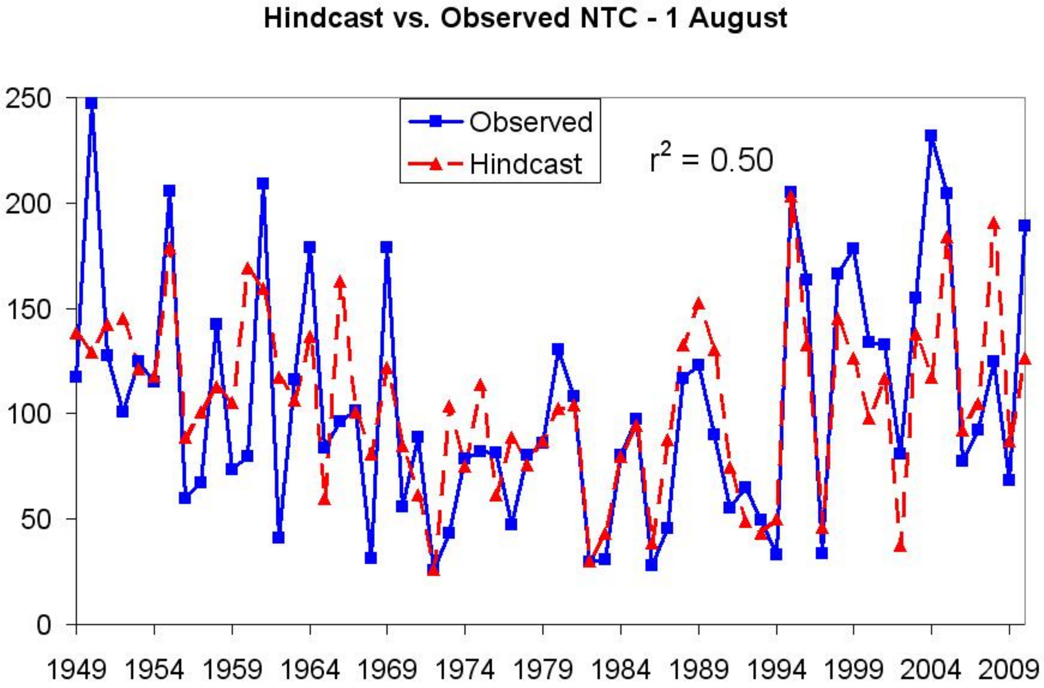


Figure 4: Observed versus hindcast values of post-31 July NTC for 1949-2010 using the Klotzbach (2007) statistical scheme.

Table 5: Observed versus hindcast average post-31 July NTC for active vs. inactive multi-decadal periods.

| ***Years*** | ***Average Observed NTC*** | ***Average Hindcast NTC*** |
|---|---|---|
| 1949-1969 (Active) | 119 | 124 |
| 1970-1994 (Inactive) | 70 | 80 |
| 1995-2010 (Active) | 140 | 122 |

## 2.1 Physical Associations among Predictors Listed in Table 2

The locations and brief descriptions of the four predictors from our August statistical forecast detailed in Klotzbach (2007) are now discussed. It should be noted that all forecast parameters correlate significantly with physical features during August through October that are known to be favorable for elevated levels of hurricane activity. For each of these predictors, we display a four-panel figure showing linear correlations between values of each predictor and August-October values of SST, sea level pressure, 925 mb zonal wind, and 200 mb zonal wind, respectively.

### Predictor 1. June-July SST in the Northeastern Subtropical Atlantic (+)

(20°-40°N, 15-35°W)

Warm sea surface temperatures in this area in June-July correlate very strongly with anomalously warm SSTs in the tropical Atlantic throughout the upcoming hurricane season (Figure 5). Anomalously warm SSTs are important for development and intensification of tropical cyclones by infusing more latent heat into the system (Goldenberg and Shapiro 1998). In addition, associated with anomalously warm June-July SSTS are weaker trade winds. Weaker trade winds cause less evaporation and upwelling of cooler sub-surface water which feeds back into keeping the tropical Atlantic warm. In addition, weaker trade winds imply that there is less vertical wind shear across the tropical Atlantic. Weak wind shear is favorable for tropical cyclone development and intensification (Gray 1968, Gray 1984a, Goldenberg and Shapiro 1996, Knaff et al. 2004). Lastly, there is a strong positive correlation (~0.5) between anomalously warm June-July SSTs in the subtropical northeastern Atlantic and low sea level pressures in the tropical Atlantic and Caribbean during August-October. Low sea level pressures imply decreased subsidence and enhanced mid-level moisture. Both of these conditions are favorable for tropical cyclogenesis and intensification (Knaff 1997).

### Predictor 2. June-July SLP in the Tropical Atlantic (-)

(10-25°N, 10-60°W)

Low sea level pressure in the tropical Atlantic in June-July implies that early summer conditions in the tropical Atlantic are favorable for an active TC season with increased vertical motion, decreased stability and enhanced mid-level moisture. There is a strong auto-correlation ($r > 0.5$) between June-July sea level pressure anomalies and August-October sea level pressure anomalies in the tropical Atlantic (Figure 6). Low sea level pressure in the tropical Atlantic also correlates quite strongly ($r > 0.5$) with reduced trade winds (weaker easterlies) and anomalous easterly upper-level winds (weaker westerlies). The combination of these two features implies weaker vertical wind shear and therefore more favorable conditions for tropical cyclone development in the Atlantic (Gray 1968, Gray 1984a, Goldenberg and Shapiro 1996).

### Predictor 3. June-July Nino3 Index (-)

(5°S-5°N, 90-150°W)

Cool SSTs in the Nino3 region during June-July imply that a La Niña event is currently present. In general, positive or negative anomalies in the Nino3 region during the early summer persist throughout the remainder of the summer and fall (Figure 7). El Niño conditions shift the center of the Walker Circulation eastward which causes increased convection over the central and eastern tropical Pacific. This increased convection in the central and eastern Pacific manifests itself in anomalous upper-level westerlies across the Caribbean and tropical Atlantic, thereby increasing vertical wind shear and reducing Atlantic basin hurricane activity. The relationship between ENSO and Atlantic hurricane activity has been well-documented in the literature (e.g., Gray 1984a, Goldenberg and Shapiro 1996, Elsner 2003, Bell and Chelliah 2006).

### Predictor 4. Named Storm Days South of 23.5°N, East of 75°W (+)

Most years do not have named storm formations in June and July from easterly wave propagation westward from Africa into the MDR; however, if tropical formations do occur, it indicates that a very active hurricane season is likely. For example, the seven years with the most named storm days in the deep tropics in June and July (since 1949) were 1966, 1969, 1995, 1996, 1998, 2005, and 2008. All seven of these seasons were very active.

When storms form in the deep tropics in the early part of the hurricane season, it indicates that conditions are already very favorable for TC development. In general, the start of the hurricane season is restricted by thermodynamics (warm SSTs, unstable lapse rates), and therefore deep tropical activity early in the hurricane season implies that the thermodynamics are already quite favorable for TC development (Figure 8). Also, this predictor’s correlation with seasonal NTC is 0.52 over the 1950-2007 period, and when tested on independent data (1900-1948), the correlation actually improves to 0.63, which gives us increased confidence in its use as a seasonal predictor.

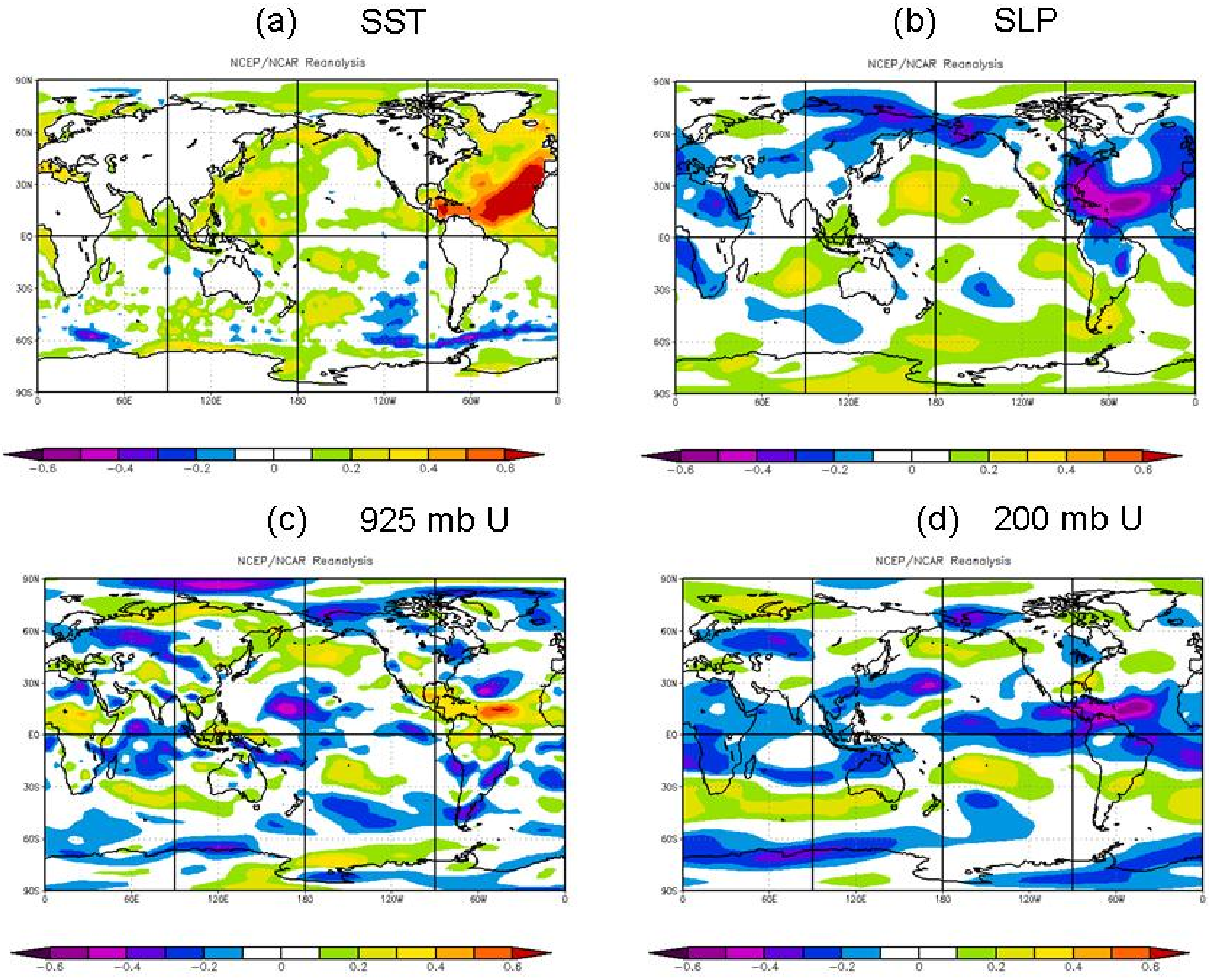


Figure 5: Linear correlations between June-July SST in the subtropical eastern Atlantic (Predictor 1) and August-October sea surface temperature (panel a), August-October sea level pressure (panel b), August-October 925 mb zonal wind (panel c) and August-October 200 mb zonal wind (panel d).

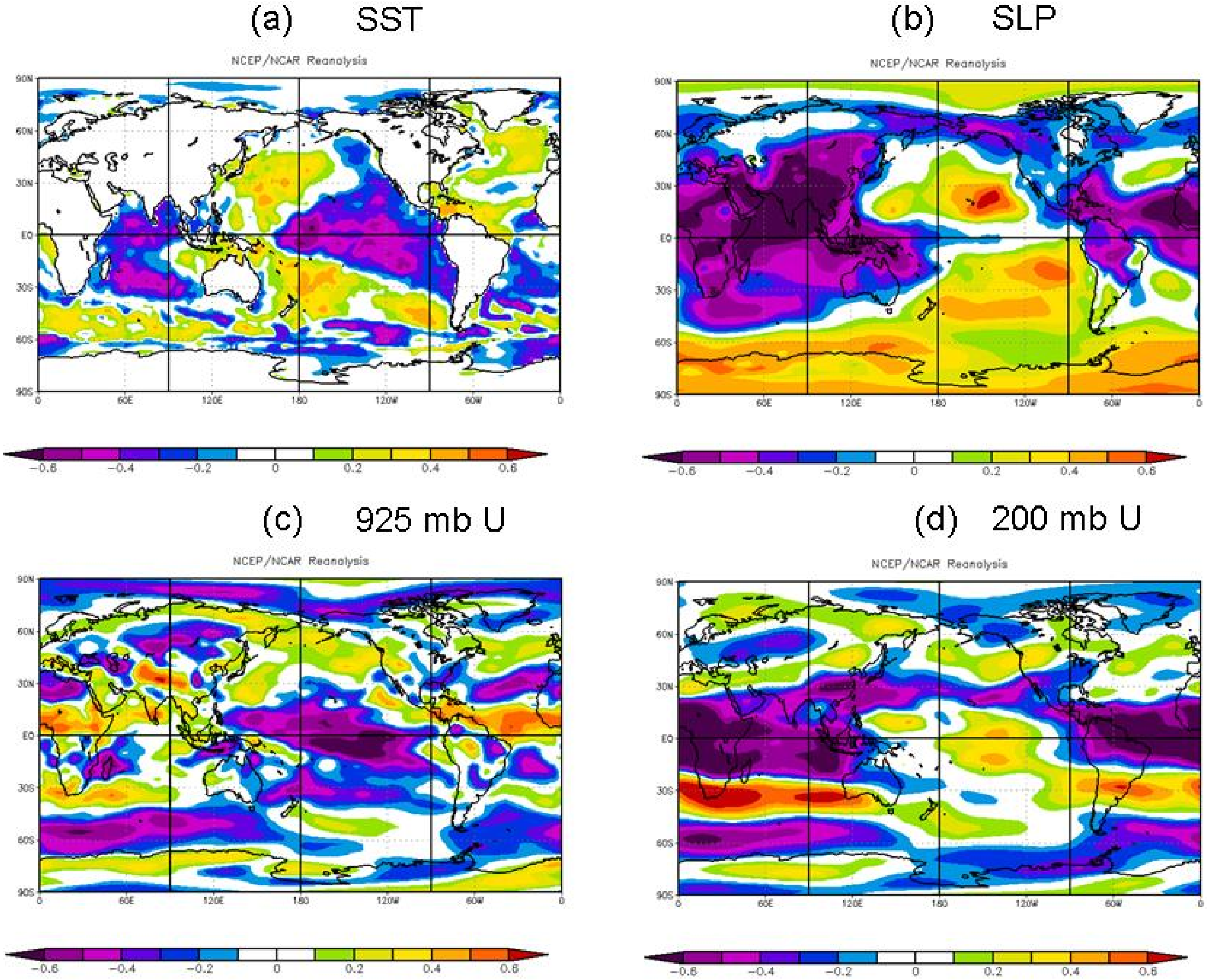
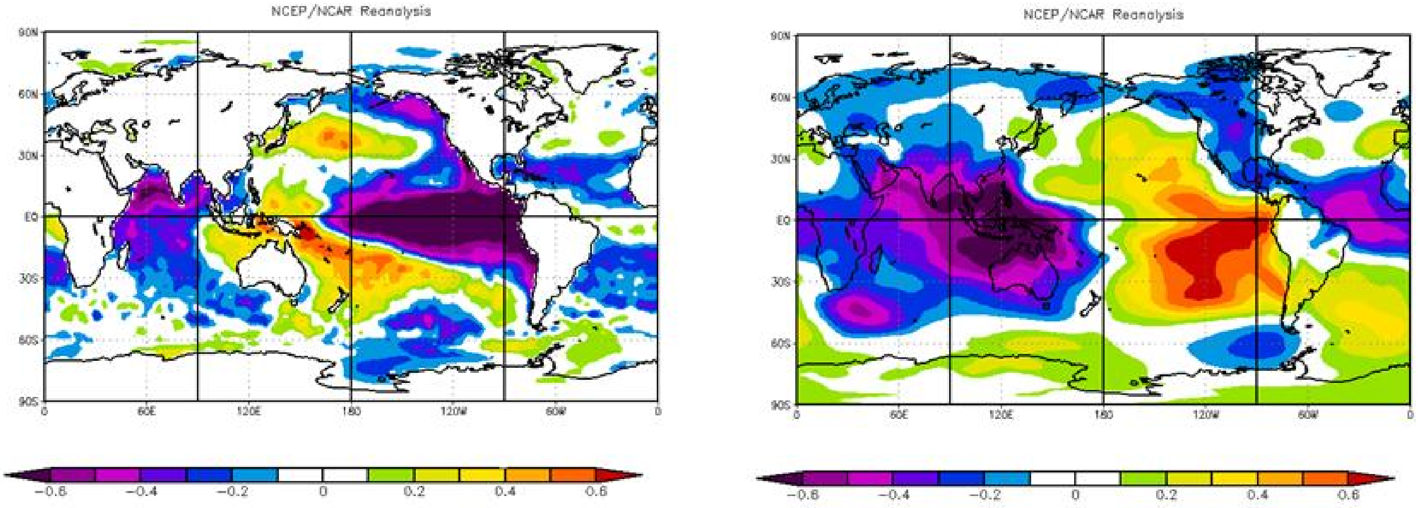


Figure 6: Linear correlations between June-July SLP in the tropical Atlantic (Predictor 2) and August-October sea surface temperature (panel a), August-October sea level pressure (panel b), August-October 925 mb zonal wind (panel c) and August-October 200 mb zonal wind (panel d). Sea level pressure values have been multiplied by -1 to allow for easy comparison with Figure 5.

(a) SST

(b) SLP



(c) 925 mb U

(d) 200 mb U

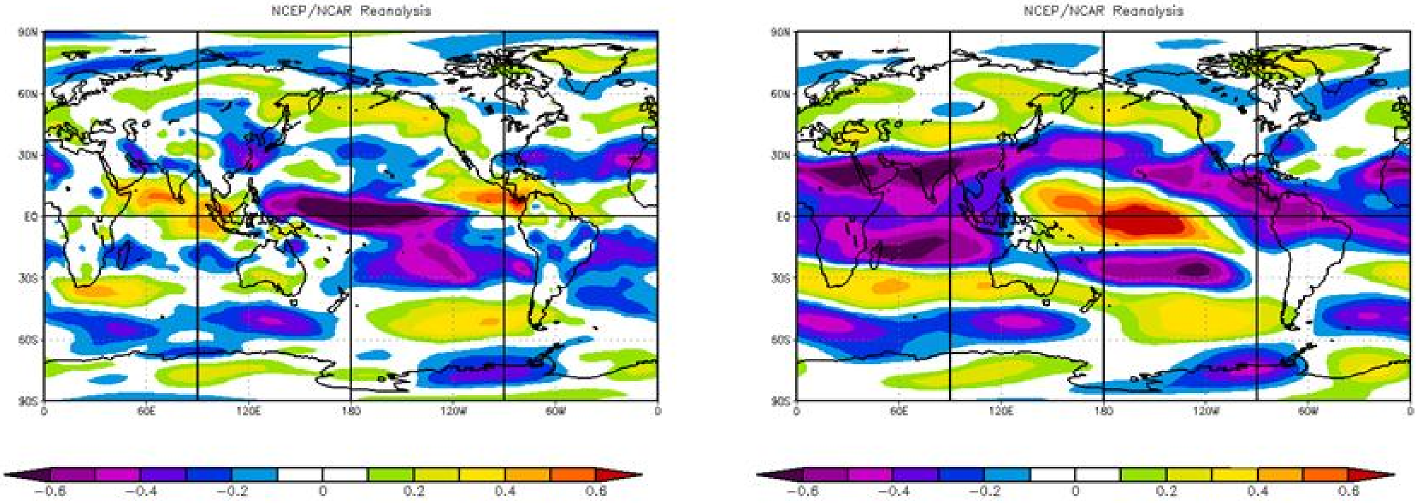


Figure 7: Linear correlations between <u>June-July Nino 3</u> (Predictor 3) and August-October sea surface temperature (panel a), August-October sea level pressure (panel b), August-October 925 mb zonal wind (panel c) and August-October 200 mb zonal wind (panel d). Sea surface temperature values have been multiplied by -1 to allow for easy comparison with Figure 5.

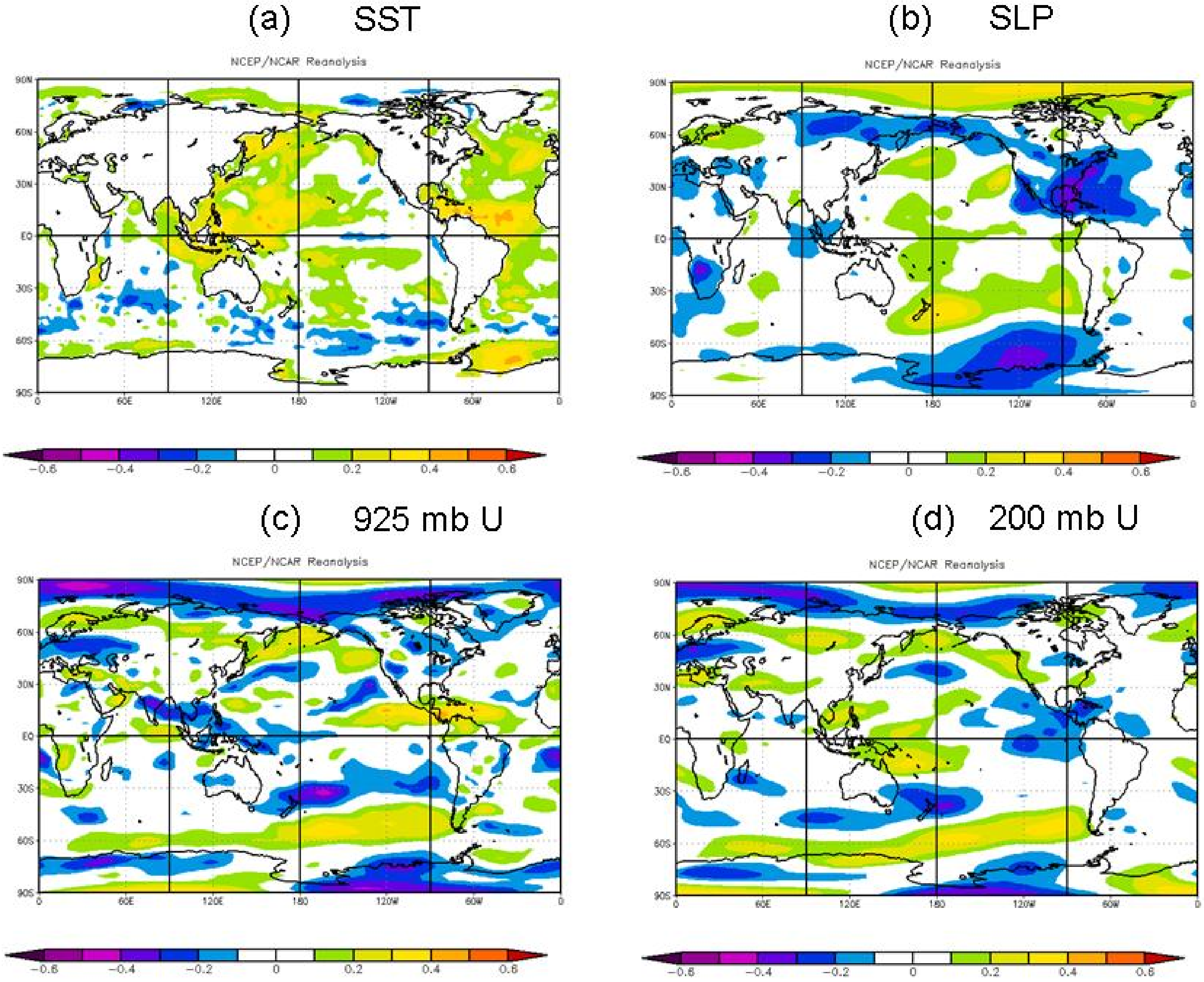


Figure 8: Linear correlations between June-July NSD in the tropics (Predictor 4) and August-October sea surface temperature (panel a), August-October sea level pressure (panel b), August-October 925 mb zonal wind (panel c) and August-October 200 mb zonal wind (panel d).

## 3 Newly-Developed 1 August Forecast Scheme

We have recently devised a new 1 August statistical seasonal forecast scheme for the prediction of Net Tropical Cyclone (NTC) activity. This model uses a total of three predictors, two selected from large-scale climate datasets, with the third being a dynamical model forecast for ENSO from the European Centre for Medium Range Weather Forecasts (ECMWF). Full documentation of the scheme will be available in a forthcoming paper (Klotzbach 2011, manuscript accepted for publication in *Geophys. Res. Lett.*). The major components of the forecast scheme are discussed in the next few paragraphs.

The pool of three predictors for this new early August statistical forecast scheme is given and defined in Table 6. The location of each of these predictors is shown in Figure 9. Skillful forecasts can be issued for post-31 July NTC based upon hindcast results over the period from 1982-2010. When these three predictors are combined, they correlate at 0.85 with observed NTC using a drop-one cross validation approach over the period from 1982-2010 (Figure 10). Other parameters (e.g., named storms, major hurricanes) are calculated from NTC using the same methodology outlined in Section 2.

Table 6: Listing of 1 August 2011 predictors for this year's hurricane activity using the new statistical model. A plus (+) means that positive deviations of the parameter indicate increased hurricane activity this year, and a minus (-) means that positive deviations of the parameter indicate decreased hurricane activity this year. The combination of these three predictors calls for an above-average hurricane season.

| Predictor | Values for 2011 Forecast | Effect on 2011 Hurricane Season |
|---|---|---|
| 1) June-July SST (20-50°N, 15-35°W) (+) | +0.2 SD | Slightly Enhance |
| 2) July Surface U (10-17.5°N, 40-80°W) (+) | +0.8 SD | **Enhance** |
| 3) ECMWF Forecast for September Nino 3 (Issued on 1 July) (-) | -0.3 SD | Slightly Enhance |

**Post-31 July Seasonal Forecast Predictors**

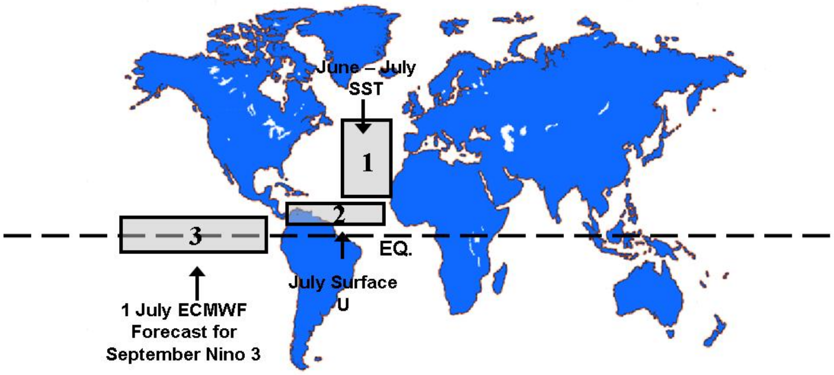


Figure 9: Location of predictors for the post-31 July forecast for the 2011 hurricane season from the new statistical model.

Table 7 shows our statistical forecast for the 2011 hurricane season from the new statistical model and the comparison of this forecast with climatology (average season from 1950-2000). Our statistical forecast is calling for above-average activity this year.

Table 7: Post-31 July statistical forecast for 2011 from the new statistical model.

| Predictands and Climatology (1950-2000 – Post-31 July Average) | Klotzbach (2011) Statistical Forecast |
|---|---|
| Named Storms (NS) – 8.4 | 12.4 |
| Named Storm Days (NSD) – 44.9 | 65.5 |
| Hurricanes (H) – 5.4 | 7.4 |
| Hurricane Days (HD) – 23.4 | 31.2 |
| Major Hurricanes (MH) – 2.1 | 3.5 |
| Major Hurricane Days (MHD) – 4.9 | 8.8 |
| Accumulated Cyclone Energy Index (ACE) – 90 | 130 |
| Net Tropical Cyclone Activity (NTC) – 93 | 140 |

Table 8 displays our early August cross-validated hindcasts for 1982-2010 using the new statistical scheme, while Figure 10 displays observations versus NTC cross-validated hindcasts. Our early August model has correctly predicted above- or below-average post-31 July NTC in 24 out of 29 years (83%). These hindcasts have had a smaller error than climatology in 21 out of 29 years (72%). Our average hindcast errors have been 25 NTC units, compared with 50 NTC units had we used only climatology.

Table 8: Observed versus hindcast post-31 July NTC for 1982-2010 using the new statistical scheme. Average errors for hindcast NTC and climatological NTC predictions are given without respect to sign. Red bold-faced years in the "Hindcast NTC" column are years that we did not go the right way, while red bold-faced years in the "Hindcast improvement over Climatology" column are years that we did not beat climatology. The hindcast went the right way with regards to an above- or below-average season in 24 out of 29 years (83%), while hindcast improvement over climatology occurred in 21 out of 29 years (72%).

| Year | Observed NTC | Hindcast NTC | Observed minus Hindcast | Observed minus Climatology | Hindcast improvement over Climatology |
|---|---|---|---|---|---|
| 1982 | 30 | 7 | 23 | -63 | 41 |
| 1983 | 31 | 29 | 2 | -62 | 61 |
| 1984 | 80 | 81 | 0 | -13 | 12 |
| 1985 | 97 | **92** | 5 | 4 | **-1** |
| 1986 | 28 | 48 | -20 | -65 | 45 |
| 1987 | 46 | 65 | -19 | -47 | 28 |
| 1988 | 117 | 168 | -51 | 24 | **-27** |
| 1989 | 123 | 161 | -38 | 30 | **-8** |
| 1990 | 90 | **121** | -30 | -3 | **-28** |
| 1991 | 55 | 79 | -23 | -38 | 14 |
| 1992 | 65 | 84 | -19 | -28 | 9 |
| 1993 | 50 | 80 | -30 | -43 | 13 |
| 1994 | 33 | 29 | 3 | -60 | 57 |
| 1995 | 205 | 193 | 12 | 112 | 100 |
| 1996 | 163 | 113 | 50 | 70 | 20 |
| 1997 | 33 | 49 | -16 | -60 | 44 |
| 1998 | 166 | 169 | -3 | 73 | 70 |
| 1999 | 178 | 161 | 17 | 85 | 68 |
| 2000 | 134 | **93** | 41 | 41 | 0 |
| 2001 | 133 | 131 | 2 | 40 | 38 |
| 2002 | 81 | 43 | 38 | -12 | **-26** |
| 2003 | 155 | 115 | 40 | 62 | 22 |
| 2004 | 232 | 152 | 80 | 139 | 59 |
| 2005 | 204 | 184 | 20 | 111 | 91 |
| 2006 | 77 | **108** | -30 | -16 | **-15** |
| 2007 | 92 | **123** | -31 | -1 | **-30** |
| 2008 | 125 | 181 | -56 | 32 | **-24** |
| 2009 | 69 | 59 | 10 | -24 | 15 |
| 2010 | 187 | 168 | 19 | 94 | 75 |
| **Average** | **106** | **106** | **\|25\|** | **\|50\|** | **+25** |

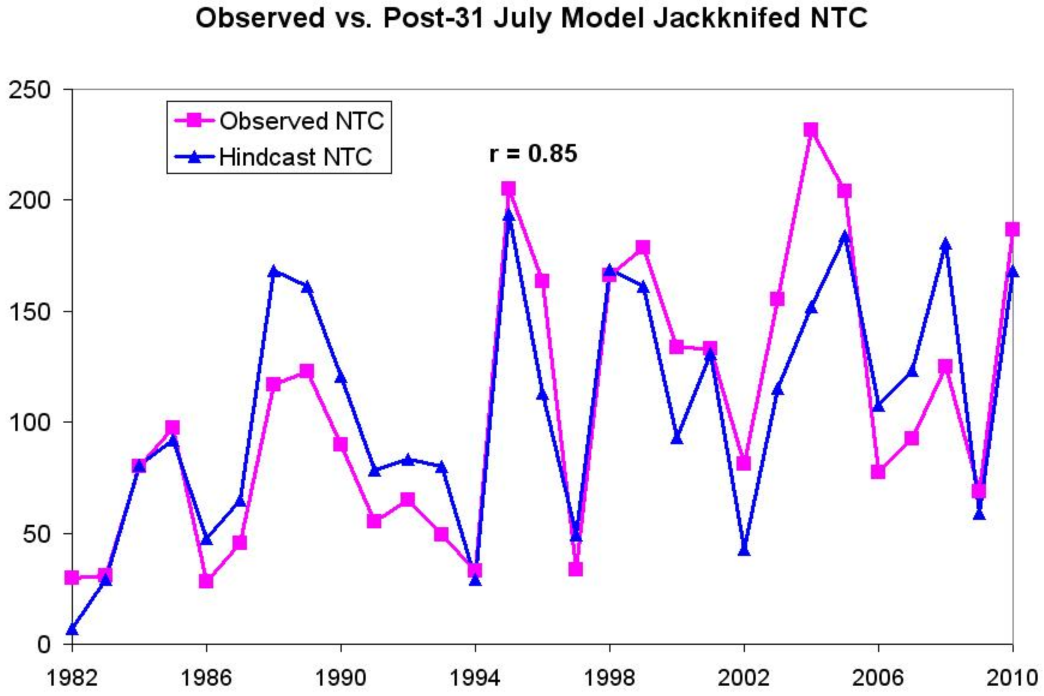


Figure 10: Observed versus hindcast values of post-31 July NTC for 1982-2010 using the new statistical scheme.

## 3.2 Physical Associations among Predictors Listed in Table 6

The locations and brief descriptions of the three predictors for our new August statistical forecast are now discussed. It should be noted that all forecast parameters correlate significantly with physical features during August through October that are known to be favorable for elevated levels of TC activity. For each of these predictors, we display a four-panel figure showing linear correlations between values of each predictor and August-October values of SST, sea level pressure, 850 mb zonal wind, and 200 mb zonal wind, respectively.

Predictor 1. June-July SST in the Northeastern Subtropical Atlantic (+)

(20°-50°N, 15-35°W)

A similar predictor was utilized in the previous August seasonal forecast model (Klotzbach 2007). Anomalously warm SSTs in the subtropical North Atlantic are associated with a positive phase of the Atlantic Meridional Mode (AMM), a northward-shifted Intertropical Convergence Zone, and consequently, reduced trade wind strength (Kossin and Vimont 2007). Weaker trade winds are associated with less mixing and upwelling, which results in warmer tropical Atlantic SSTs during the August-October period. This strong relationship between Predictor 1 and August-October tropical

Atlantic SSTs is demonstrated by the correlation of 0.70 between the two parameters (Figure 11).

### Predictor 2. July Surface U in the Tropical Atlantic (-)

(10-17.5°N, 40-80°W)

Low-level trade wind flow has been utilized as a predictor in seasonal forecasting systems for the Atlantic basin (Lea and Saunders 2004). When the trades are weaker-than-normal, SSTs across the tropical Atlantic tend to be elevated, and consequently a large-than-normal Atlantic Warm Pool (AWP) is typically observed (Wang and Lee 2007) (Figure 12). A larger AWP also correlates with reduced vertical shear across the tropical Atlantic. Predictor 2 has a -0.72 correlation with August-October-averaged 200-850-mb zonal shear.

### Predictor 3. ECMWF 1 July Forecast for the Nino3 Index (-)

(5°S-5°N, 90-150°W)

The relationship between ENSO and Atlantic TCs has been well-documented for over more than 25 years (e.g., Gray 1984, Tang and Neelin 2004, Klotzbach 2011). When El Niño is underway in the tropical Pacific during the Atlantic hurricane season, the Walker Circulation tends to weaken and shift eastward, imparting increased upper-level westerly wind anomalies, consequently increasing the shear across the tropical Atlantic (Gray 1984). In addition, anomalous sinking and drying take place across the tropical Atlantic in El Niño years, creating a more stable atmosphere which is less conducive for TC formation (Tang and Neelin 2004). ECMWF's seasonal forecast system 3 (Stockdale et al. 2011) has shown significant skill at predicting ENSO events several months in the future. According to hindcast data from 1982-2010 provided by F. Vitart (2011, personal communication), a Nino 3 forecast from the ECMWF system 3 model initialized on 1 July correlates with the observed September Nino 3 at 0.90. As would be expected given this discussion, Predictor 3 has a significant correlation with August-October-averaged 200-850-mb zonal shear across the tropical Atlantic (Figure 13).

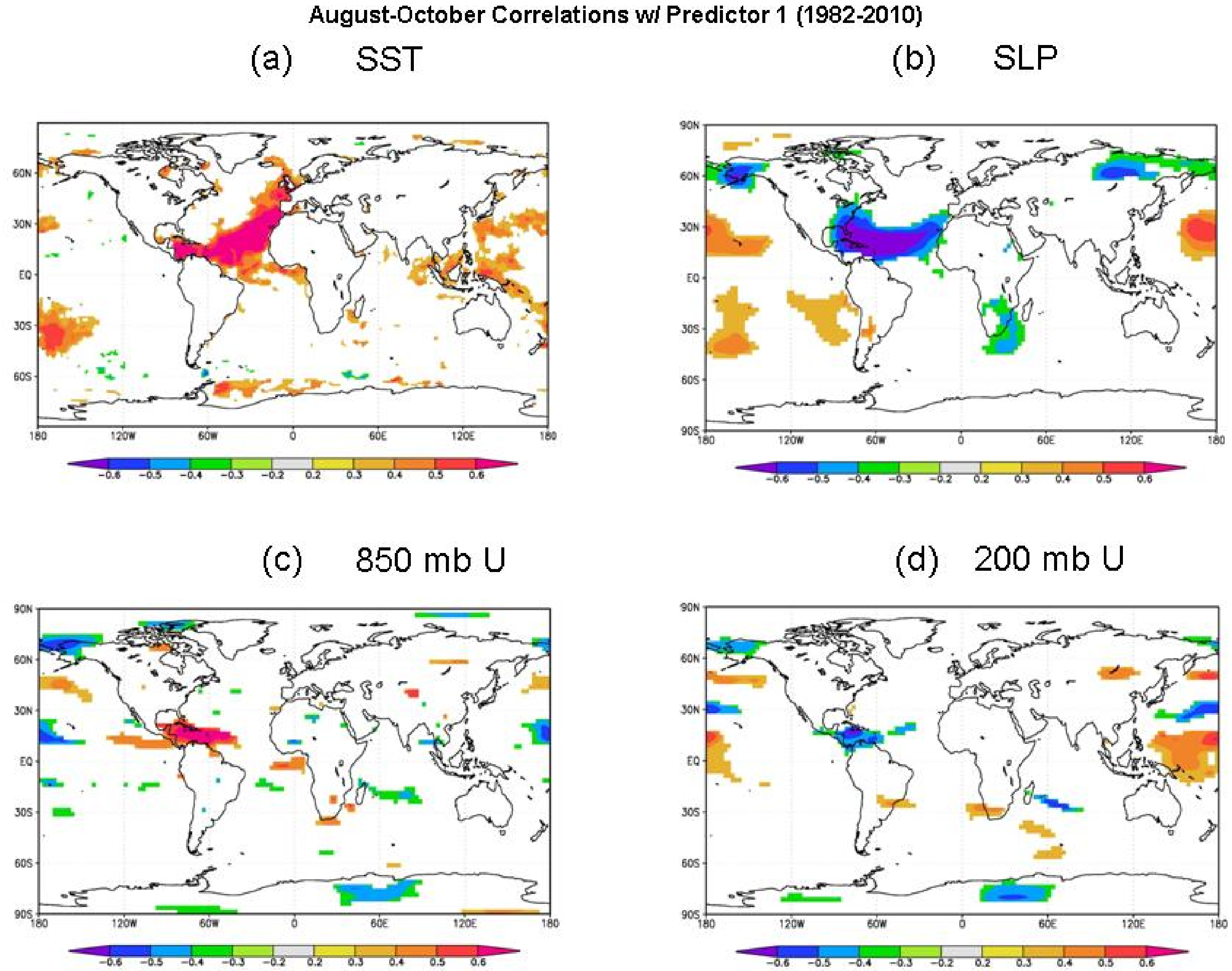


Figure 11: Linear correlations between June-July SST in the subtropical eastern Atlantic (Predictor 1) and August-October sea surface temperature (panel a), August-October sea level pressure (panel b), August-October 850 mb zonal wind (panel c) and August-October 200 mb zonal wind (panel d).

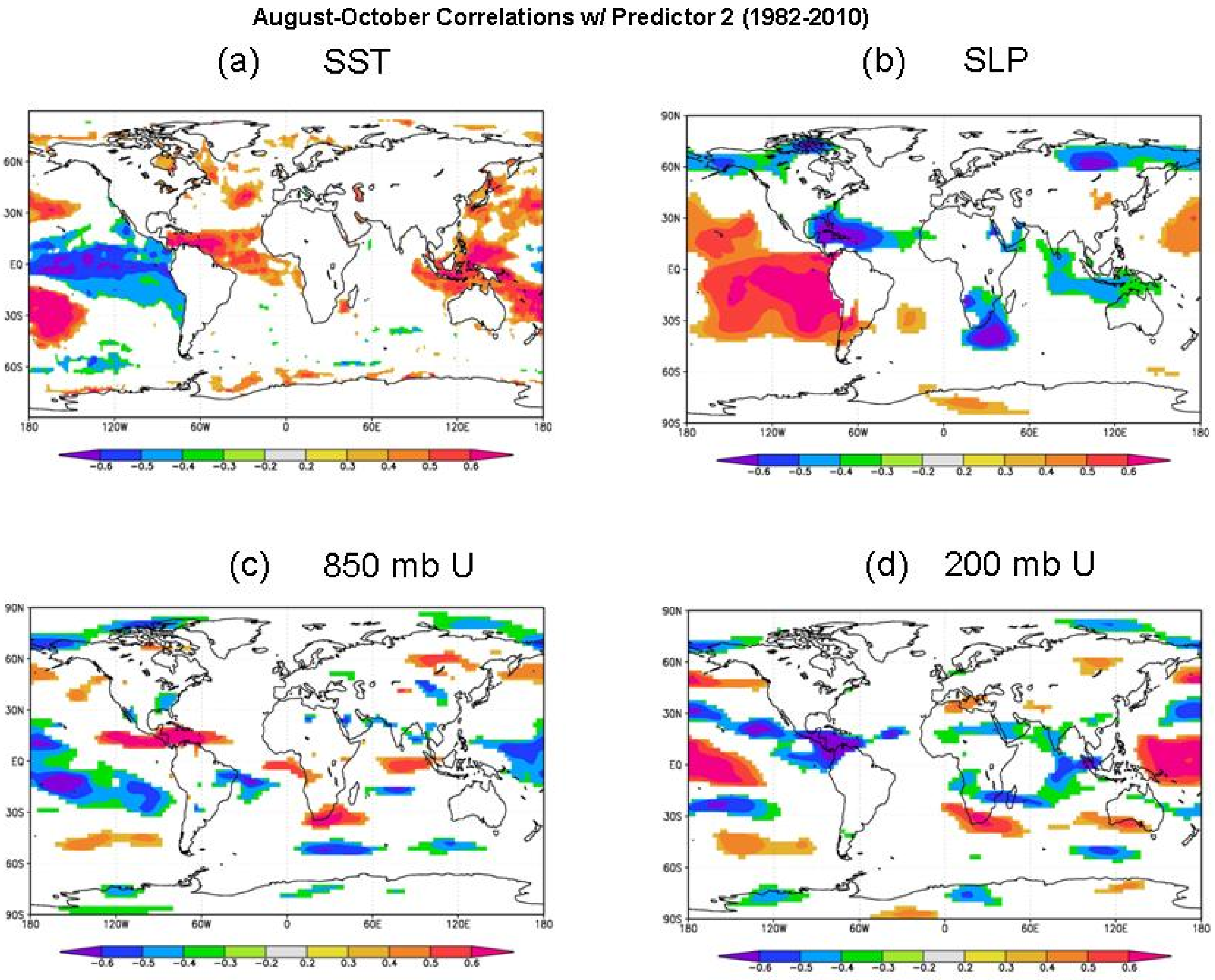
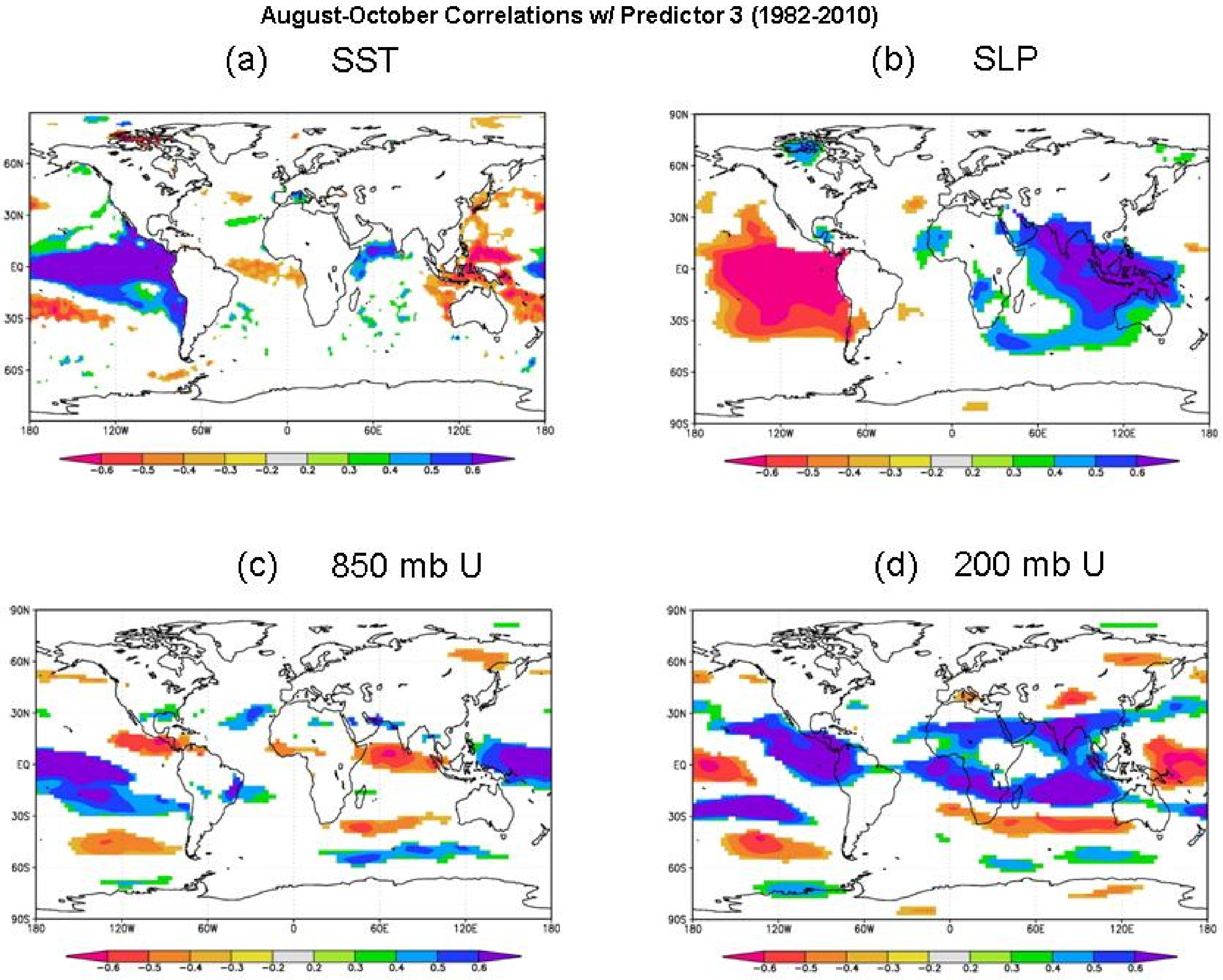


Figure 12: Linear correlations between July Surface U in the tropical Atlantic (Predictor 2) and August-October sea surface temperature (panel a), August-October sea level pressure (panel b), August-October 850 mb zonal wind (panel c) and August-October 200 mb zonal wind (panel d).



August-October Correlations w/ Predictor 3 (1982-2010)

(a) SST

(b) SLP

(c) 850 mb U

(d) 200 mb U

Figure 13: Linear correlations between <u>June-July Nino 3</u> (Predictor 3) and August-October sea surface temperature (panel a), August-October sea level pressure (panel b), August-October 925 mb zonal wind (panel c) and August-October 200 mb zonal wind (panel d). The color scale has been reversed so that the correlations match up with those in Figures 11 and 12.

Table 9 summarizes the statistical model output from both forecasts. Both models call for an active season, increasing our confidence that an active season is likely in store.

Table 9: Summary of output from both the Klotzbach (2007) and Klotzbach (2011) statistical models for post-31 July tropical cyclone activity.

| Predictands and Climatology (1950-2000 – Post-31 July Average) | Klotzbach (2007) | Klotzbach (2011) |
|---|---|---|
| Named Storms (NS) – 8.4 | 10.7 | 12.4 |
| Named Storm Days (NSD) – 44.9 | 53.0 | 65.5 |
| Hurricanes (H) – 5.4 | 6.1 | 7.4 |
| Hurricane Days (HD) – 23.4 | 23.8 | 31.2 |
| Major Hurricanes (MH) – 2.1 | 2.6 | 3.5 |
| Major Hurricane Days (MHD) – 4.9 | 6.0 | 8.8 |
| Accumulated Cyclone Energy Index (ACE) – 90 | 99 | 130 |
| Net Tropical Cyclone Activity (NTC) – 93 | 108 | 140 |

## 4 Forecast Uncertainty

One of the questions that we are asked regarding our seasonal hurricane predictions is the degree of uncertainty that is involved. Obviously, our predictions are our best estimate, but there is with all forecasts an uncertainty as to how well they will verify.

Table 10 provides our post-31 July forecast, with error bars (based on one standard deviation of absolute errors) as calculated from hindcasts/forecasts of the Klotzbach (2007) scheme over the 1990-2009 period, using equations developed over the 1950-1989 period. We typically expect to see 2/3 of our forecasts verify within one standard deviation of observed values, with 95% of forecasts verifying within two standard deviations of observed values.

Table 10: Model hindcast error and our 2011 hurricane forecast. Uncertainty ranges are given in one standard deviation (SD) increments.

| Parameter | Hindcast Error (SD) | Post-31 July 2011 Forecast | Uncertainty Range – 1 SD (67% of Forecasts Likely in this Range) |
|---|---|---|---|
| Named Storms (NS) | 2.3 | 12 | 9.7 – 14.3 |
| Named Storm Days (NSD) | 17.4 | 70 | 52.6 – 87.4 |
| Hurricanes (H) | 1.6 | 9 | 7.4 – 10.6 |
| Hurricane Days (HD) | 8.6 | 35 | 26.4 – 43.6 |
| Major Hurricanes (MH) | 0.9 | 5 | 4.1 – 5.9 |
| Major Hurricane Days (MHD) | 3.5 | 10 | 6.5 – 13.5 |
| Accumulated Cyclone Energy (ACE) | 36 | 152 | 116 – 188 |
| Net Tropical Cyclone (NTC) Activity | 34 | 165 | 131 - 199 |

# 5 Caribbean Forecast Methodology

We developed a forecast for the Caribbean that we issued for the first time last year. We find that predictors for the Caribbean are somewhat different than those used for the entire Atlantic basin. We intend to explore additional region-specific forecasts in the future, such as forecasts for the Gulf of Mexico or the higher latitude Atlantic.

We define the Caribbean to extend from 10-20°N, 60-88°W. This model attempts to predict seasonal levels of Accumulated Cyclone Energy (ACE) generated in the Caribbean. Through a combination of three predictors discussed in detail below, we can issue a forecast that shows significant levels of hindcast skill.

## 5.1 Caribbean Statistical Forecast Scheme

We have found that using three July predictors, we can obtain early August hindcasts that show considerable skill at predicting post-31 July ACE in the Caribbean over the sixty-year development period from 1949-2008.

This new scheme was created by evaluating three July predictors using least-squared regression. By definition, least-squared regression tends to be conservative, and therefore, predicting large outlier events can be quite challenging. In order to help adjust for this challenge, the hindcasts from the linear regression model were adjusted to the final hindcast in the following manner:

The standardized value of each hindcast was calculated. These hindcasts were then adjusted to the final hindcast by multiplying by the standard deviation of the observations. Since the standard deviation of the observations is larger than the standard deviation of the hindcasts, this aids in the forecast of outlying events. Any hindcasts that resulted in a negative ACE prediction were assigned a final ACE value of 0.

Our statistical scheme shows significant hindcast skill, explaining 54% of the variance over the 1949-2010 period. Table 11 displays our early August hindcasts for 1949-2008 using the new statistical scheme, while Figure 14 displays observations versus post-31 July ACE hindcasts. The forecasts for 2009 and 2010 are also displayed. Our early August hindcasts have correctly predicted above- or below-average seasons in 52 out of 62 hindcast years (84%). These hindcasts have had a smaller error than climatology in 47 out of 62 years (76%). Our average hindcast error is 6.7 ACE units, compared with 11.6 ACE units for climatology. This scheme also shows considerable stability when broken in half, correlating at 0.70 from 1949-1979 and 0.76 from 1980-2010. This new scheme is also well-tuned to the multi-decadal active hurricane periods from 1950-1969 and 1995-2010 versus the inactive hurricane period from 1970-1994 (Table 12).

Whenever an ACE greater than 20 was hindcast (23 out of 61 years), all but three of these 23 years (87%) had observed ACE values greater than 20. In 25 of 61 years when hindcast ACE was 10 or less, only three of 25 years had observed ACE values greater than 10.

Figure 15 displays the locations of the early August predictors used in this scheme in map form. Table 13 lists the three predictors that are utilized for this year's August forecast.

Table 11: Observed versus hindcast post-31 July Caribbean ACE for 1949-2008. Real-time forecasts for 2009 and 2010 are also included. Average errors for hindcast ACE and climatological ACE predictions are given without respect to sign. Red bold-faced years in the "Hindcast ACE" column (2) are years that we did not go the right way, while red bold-faced years in the "Hindcast improvement over Climatology" column (5) are years that we did not beat climatology. The hindcast went the right way with regards to an above- or below-average season in 52 out of 62 years (84%), while hindcast improvement over climatology occurred in 47 out of 62 years (76%).

| Year | (1) Observed ACE | (2) Hindcast ACE | (3) Observed minus Hindcast | (4) Observed minus Climatology | (5) Hindcast improvement over Climatology |
|---|---|---|---|---|---|
| 1949 | 7 | **24** | -17 | -6 | **-11** |
| 1950 | 16 | 26 | -9 | 3 | **-6** |
| 1951 | 24 | 21 | 3 | 10 | 7 |
| 1952 | 8 | 12 | -4 | -6 | 2 |
| 1953 | 4 | 9 | -4 | -9 | 4 |
| 1954 | 40 | 37 | 3 | 26 | 24 |
| 1955 | 48 | 39 | 9 | 35 | 26 |
| 1956 | 5 | 11 | -6 | -8 | 2 |
| 1957 | 0 | 9 | -9 | -13 | 5 |
| 1958 | 9 | **23** | -14 | -4 | **-10** |
| 1959 | 1 | 9 | -8 | -12 | 5 |
| 1960 | 8 | **17** | -10 | -6 | **-4** |
| 1961 | 24 | 26 | -2 | 11 | 9 |
| 1962 | 0 | 6 | -6 | -13 | 7 |
| 1963 | 28 | 27 | 1 | 15 | 14 |
| 1964 | 21 | 21 | 0 | 7 | 7 |
| 1965 | 0 | 0 | 0 | -13 | 13 |
| 1966 | 19 | 14 | 5 | 6 | 1 |
| 1967 | 27 | 21 | 6 | 14 | 8 |
| 1968 | 0 | 7 | -7 | -13 | 6 |
| 1969 | 12 | 12 | 0 | -1 | 1 |
| 1970 | 2 | **28** | -27 | -12 | **-15** |
| 1971 | 19 | **0** | 19 | 6 | **-13** |
| 1972 | 0 | 0 | 0 | -13 | 13 |
| 1973 | 0 | **17** | -17 | -13 | **-4** |
| 1974 | 18 | 21 | -3 | 5 | 2 |
| 1975 | 4 | **21** | -17 | -9 | **-8** |
| 1976 | 1 | 0 | 1 | -13 | 12 |
| 1977 | 1 | 3 | -2 | -13 | 11 |
| 1978 | 11 | 7 | 5 | -2 | **-3** |
| 1979 | 26 | 18 | 8 | 12 | 5 |
| 1980 | 21 | 26 | -5 | 8 | 2 |
| 1981 | 3 | **20** | -17 | -10 | **-7** |
| 1982 | 0 | 0 | 0 | -13 | 13 |
| 1983 | 0 | 0 | 0 | -13 | 13 |
| 1984 | 3 | 13 | -10 | -10 | 0 |
| 1985 | 1 | 5 | -4 | -12 | 8 |
| 1986 | 1 | 0 | 1 | -12 | 11 |
| 1987 | 6 | 1 | 5 | -7 | 2 |
| 1988 | 42 | 37 | 4 | 28 | 24 |
| 1989 | 16 | **10** | 6 | 3 | **-3** |
| 1990 | 6 | **15** | -10 | -8 | **-2** |
| 1991 | 0 | 0 | 0 | -13 | 13 |
| 1992 | 0 | 0 | 0 | -13 | 13 |
| 1993 | 4 | 4 | 0 | -10 | 10 |
| 1994 | 3 | 0 | 3 | -11 | 8 |
| 1995 | 23 | 26 | -3 | 10 | 7 |
| 1996 | 16 | 16 | -1 | 2 | 2 |
| 1997 | 3 | 0 | 3 | -11 | 8 |
| 1998 | 44 | 43 | 1 | 31 | 30 |
| 1999 | 24 | 34 | -10 | 11 | 1 |
| 2000 | 13 | 11 | 2 | 0 | **-2** |
| 2001 | 23 | 21 | 2 | 10 | 7 |
| 2002 | 6 | 0 | 6 | -7 | 1 |
| 2003 | 3 | 8 | -5 | -11 | 6 |
| 2004 | 51 | 17 | 34 | 37 | 3 |
| 2005 | 30 | 28 | 2 | 16 | 15 |
| 2006 | 4 | 4 | 0 | -9 | 9 |
| 2007 | 47 | 22 | 25 | 34 | 9 |
| 2008 | 21 | 34 | -13 | 8 | **-6** |
| 2009 | 4 | 10 | -6 | -9 | 3 |
| 2010 | 24 | 41 | -17 | -11 | **-6** |
| **Average** | **13** | **15** | **6.5** | **11.6** | **5.1** |

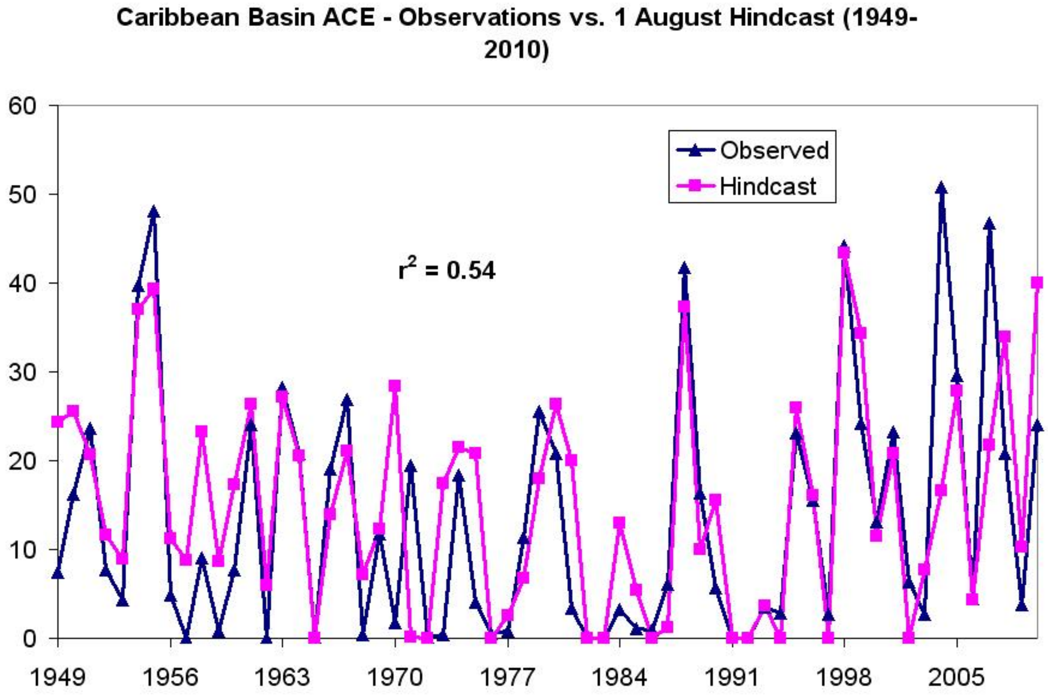


Figure 14: Observed versus hindcast values of post-31 July Caribbean Basin ACE for 1949-2010.

Table 12: Hindcast versus observed average ACE for active vs. inactive multi-decadal periods. Percentage differences from the climatological average (1949-2008) are in parentheses.

| ***Years*** | ***Average Observed ACE*** | ***Average Hindcast ACE*** |
|---|---|---|
| 1949-1969 (Active) | 14 (108%) | 18 (132%) |
| 1970-1994 (Inactive) | 8 (57%) | 10 (75%) |
| 1995-2010 (Active) | 21 (156%) | 20 (154%) |

**Post-31 July Caribbean Forecast Predictors**

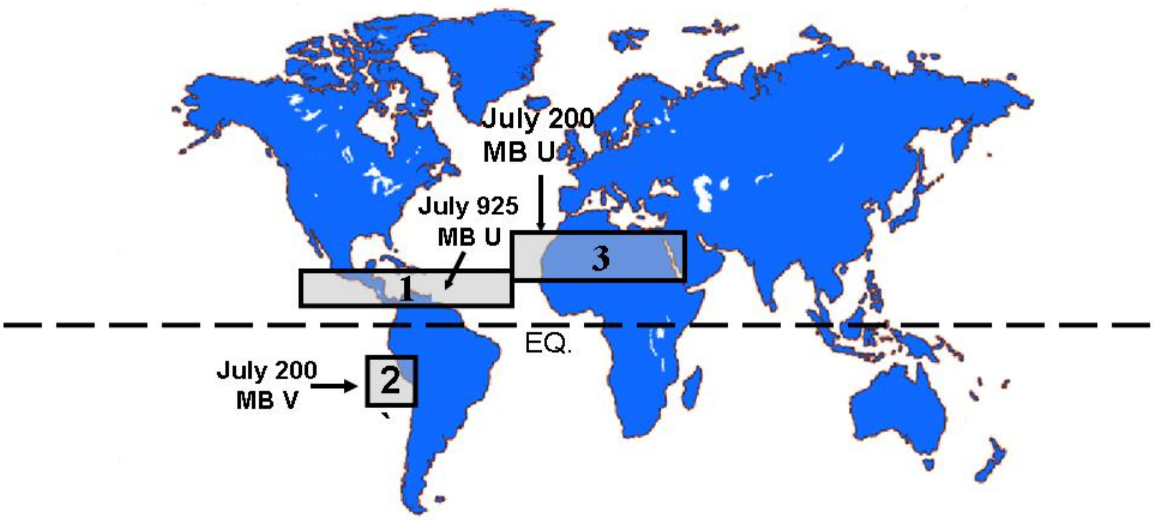


Figure 15: Location of July predictors for our post-31 July Caribbean statistical prediction for the 2011 hurricane season.

Table 13: Listing of 1 August 2011 Caribbean basin predictors for the 2011 hurricane season. A plus (+) means that positive values of the parameter indicate increased hurricane activity during the post-31 July period.

| Predictor | 2011 Forecast Values | Effect on 2011 Hurricane Season |
|---|---|---|
| 1) July 925 MB U (7.5-17.5°N, 20-120°W) (+) | 2.4 SD | **Strongly Enhance** |
| 2) July 200 MB V (10-25°S, 70-90°W) (-) | -0.3 SD | Slightly Enhance |
| 3) July 200 MB U (15-25°N, 20°W-50°E) (-) | +0.3 SD | Slightly Suppress |

The Caribbean model continues to call for a very active hurricane season in 2011. Our forecast model is calling for an ACE of 37, while the 1949-2008 average ACE for post-31 July ACE in the Caribbean is 13.

## 5.2 Physical Associations among Predictors Listed in Table 13

The locations and brief descriptions of the three July predictors for our August Caribbean statistical forecast are now discussed. It should be noted that all three forecast parameters correlate significantly with seasonal physical features that are known to be favorable for elevated levels of hurricane activity. Tables 14 and 15 display correlations between each predictor and August-October-averaged SST, sea level pressure, 200 mb zonal wind and 925 mb zonal wind in the Main Development Region (MDR) and in the Caribbean, respectively. Since many storms that generate large values of ACE in the Caribbean form in the MDR, one would expect that these predictors would correlate with physical features in both regions. Correlations that are significant at the 95% level using a two-tailed Student's t-test are highlighted in bold-faced type. Although most of Predictor 2's correlations are weak, they are generally of the sign that would be expected to enhance tropical cyclone activity in the Atlantic. This predictor also correlates significantly at the 95% level over both the 1949-1978 and 1979-2008 time period, indicating stability of the predictor-tropical cyclone relationship throughout the developmental data period.

Table 14: Correlations between early August Caribbean predictors and August-October values of Main Development Region <u>(10-20°N, 20-70°W)</u> SST, sea level pressure, 200 mb zonal wind and 925 mb zonal wind.

| Predictor | SST | SLP | 200 MB U | 925 MB U |
|---|---|---|---|---|
| 1) July 925 MB U (7.5-17.5°N, 20-120°W) (+) | **0.42** | **-0.58** | **-0.41** | **0.31** |
| 2) July 200 MB V (10-25°S, 70-90°W) (-) | -0.03 | 0.19 | 0.22 | -0.04 |
| 3) July 200 MB U (15-25°N, 20°W-50°E) (-) | 0.01 | **0.38** | **0.48** | -0.11 |

Table 15: Correlations between early August Caribbean predictors and August-October values of Caribbean <u>(10-20°N, 60-88°W)</u> SST, sea level pressure, 200 mb zonal wind and 925 mb zonal wind.

| Predictor | SST | SLP | 200 MB U | 925 MB U |
|---|---|---|---|---|
| 1) July 925 MB U (7.5-17.5°N, 20-120°W) (+) | **0.37** | **-0.53** | **-0.54** | **0.67** |
| 2) July 200 MB V (10-25°S, 70-90°W) (-) | -0.06 | 0.19 | 0.13 | -0.15 |
| 3) July 200 MB U (15-25°N, 20°W-50°E) (-) | 0.03 | **0.32** | **0.56** | **-0.29** |

As was done with our discussion of both seasonal statistical schemes for the Atlantic basin, for each of these predictors, we display a four-panel figure showing linear correlations between values of each predictor and August-October values of SST, sea level pressure, 200 mb zonal wind, and 925 mb zonal wind, respectively. In general, higher values of SSTA, lower values of SLPA, anomalous westerlies at 925 mb and anomalous easterlies at 200 mb are associated with active Caribbean basin seasons.

## <u>Predictor 1. July 925 MB U in the Tropical Atlantic/Eastern Pacific (+)</u>

### (7.5-17.5°N, 20-120°W)

Anomalously weak trade winds during the month of July across the tropical Atlantic and eastern Pacific are strongly correlated with an active hurricane season in the Caribbean (Figure 16). These weaker trades are associated with higher-than-normal pressure in the tropical eastern Pacific and lower-than-normal pressure in the tropical Atlantic, characteristic of a La Niña event in the tropical Pacific. During the months of August-October, weaker trades reduce upwelling and mixing of the tropical Atlantic, driving warmer SSTs and lower sea level pressures. In addition, weaker trades in July tend to persist from August-October, which combined with anomalous easterly winds at upper levels (characteristic of a La Niña event) reduces levels of vertical shear both in the Caribbean and in the MDR.

### Predictor 2. July 200 MB V off the west coast of South America (-)

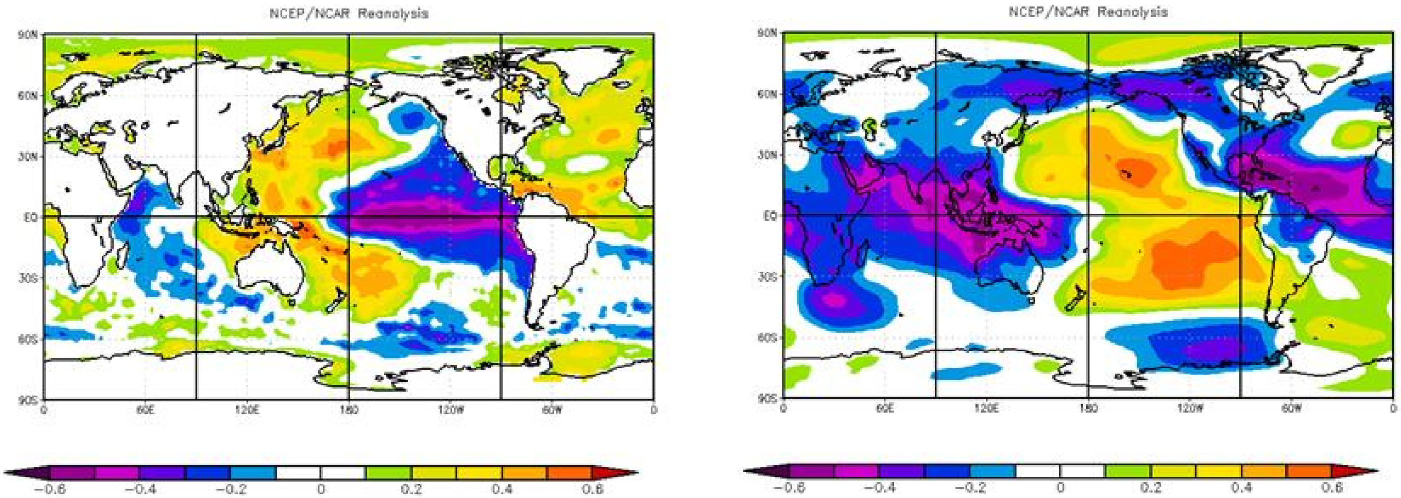
(10-25°S, 70-90°W)

Upper-level northerly winds off of the west coast of South America are associated with an anomalous ridge over South America and an anomalous trough in the tropical eastern and central Pacific. This anomalous upper-level trough is typically associated with cold waters (La Niña) in the eastern and central Pacific. Blake (2004) has shown that an upper-level ridge over South America is favorable for an active August due to an associated reduction in upper-level westerly winds over the tropical Atlantic. Negative values of this predictor tend to be associated with lower-than-normal sea level pressures and reduced vertical shear over both the Caribbean and the MDR (Figure 17).

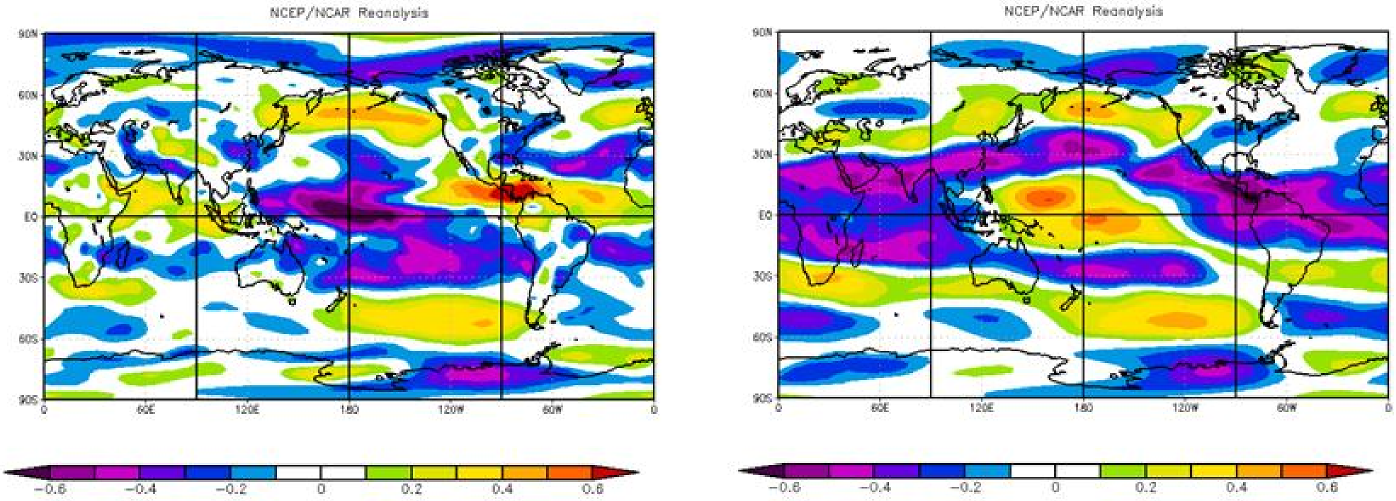
### Predictor 3. July 200 MB U over North Africa (-)

(15-25°N, 20°W-50°E)

Anomalous upper-level easterly winds over North Africa in July are typically associated with an active African monsoon and La Niña conditions (Figure 18). These upper-level easterly winds in July tend to persist through the August-October time period and are very strongly correlated with anomalous upper-level easterly winds throughout the MDR and the Caribbean during the August-October period. Lower-sea-level pressures in the tropical Atlantic are also associated with easterly anomalies over North Africa. Reduced vertical shear provides a more favorable dynamic environment for storm formation and intensification, while lower-than-normal sea level pressures imply a more favorable thermodynamic environment.

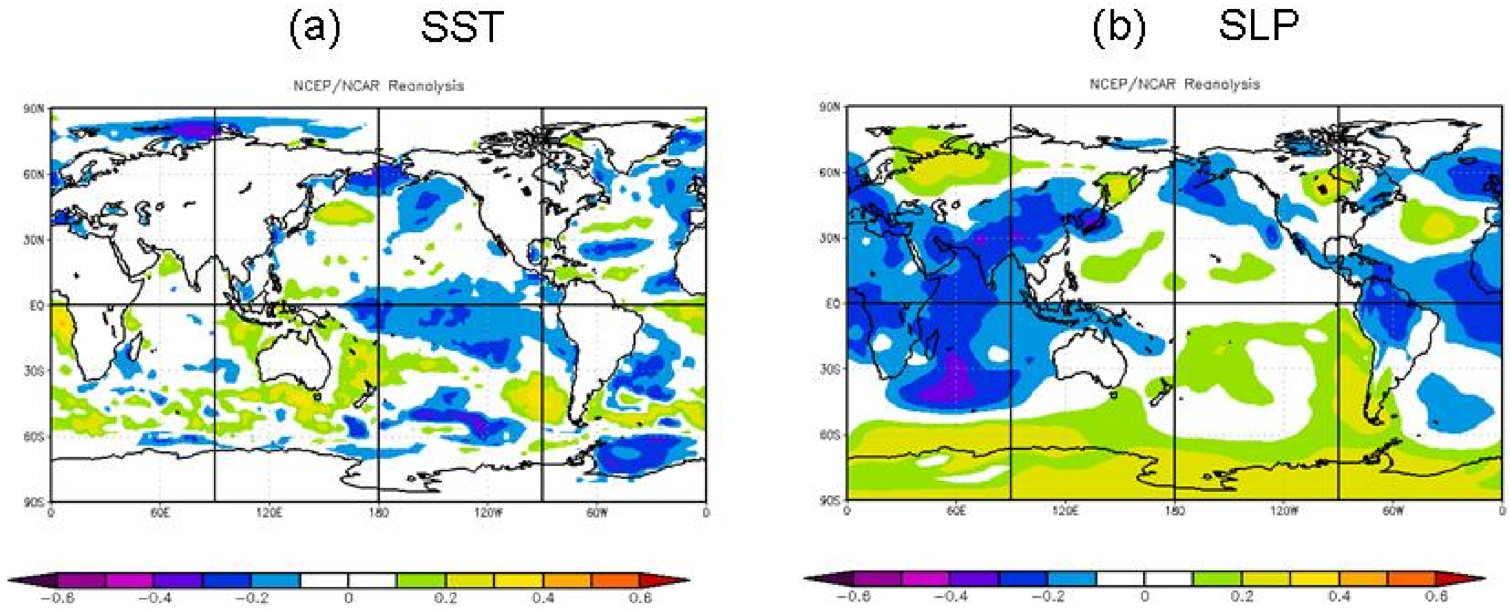

(a) SST

(b) SLP


(c) 925 mb U

(d) 200 mb U

Figure 16: Linear correlations between July 925 mb zonal wind in the tropical Atlantic/eastern Pacific (Predictor 1) and August-October sea surface temperature (panel a), August-October sea level pressure (panel b), August-October 925 mb zonal wind (panel c) and August-October 200 mb zonal wind (panel d). All four of these parameter deviations are known to be favorable for enhanced hurricane activity.



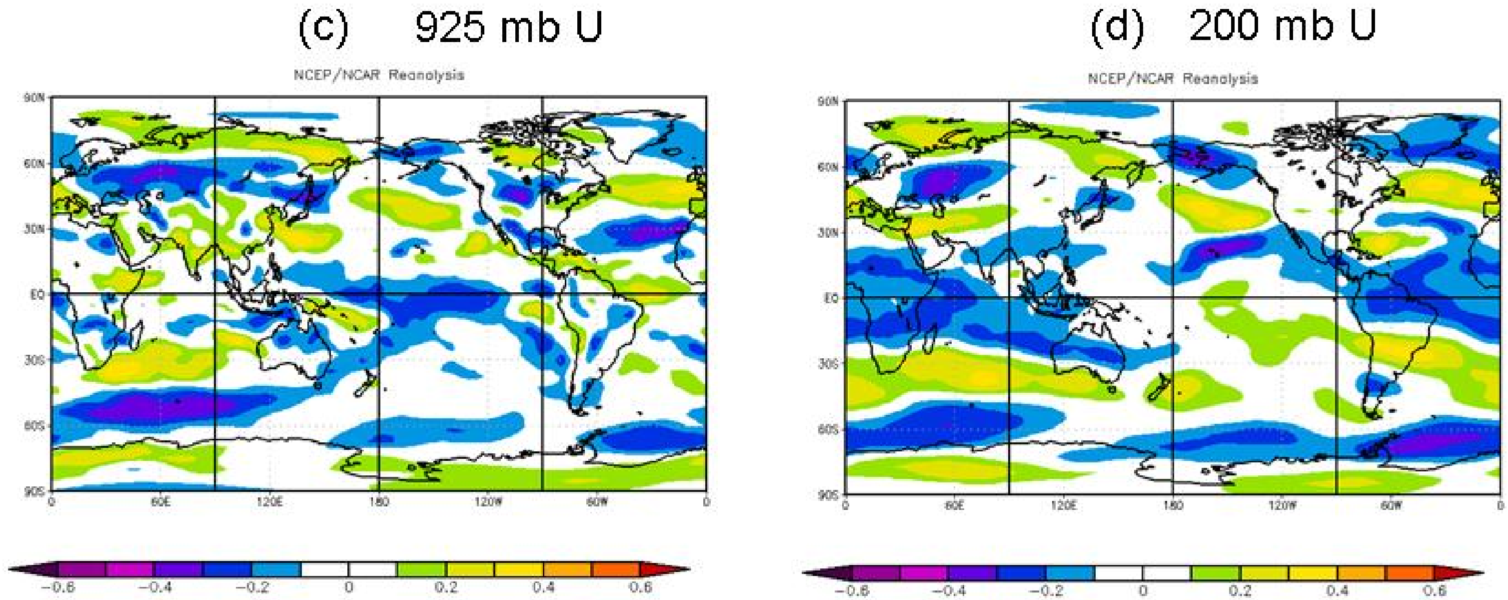
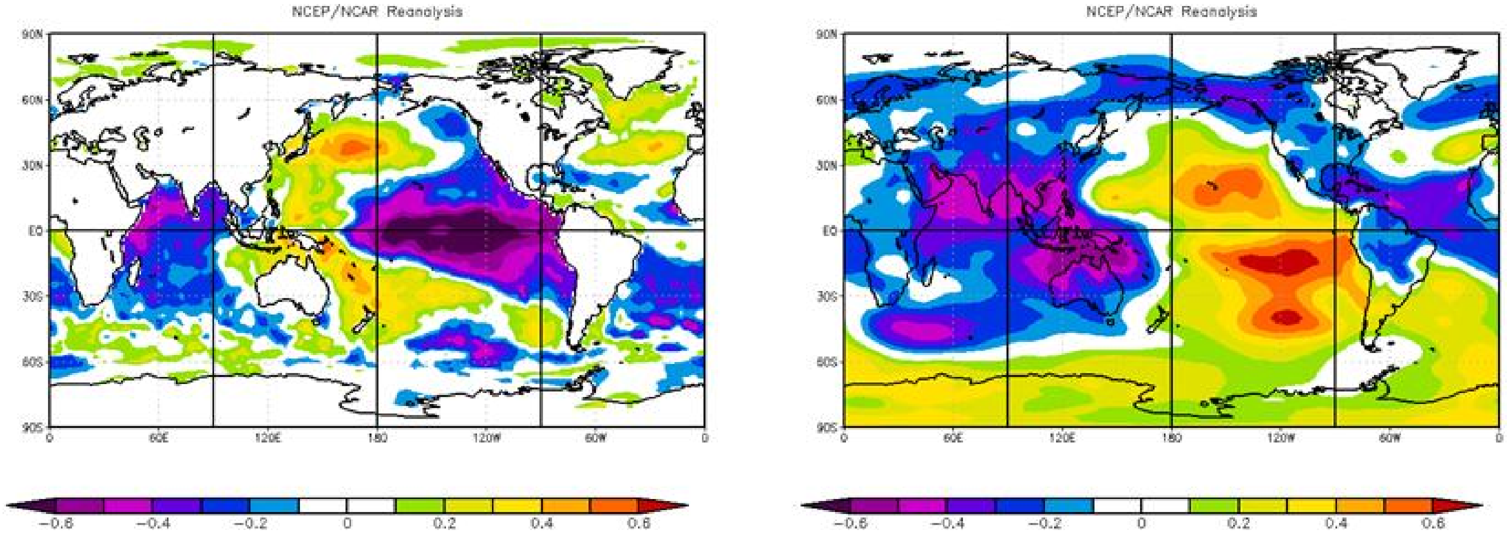


Figure 17: Linear correlations between July 200 mb meridional wind near the west coast of South America (Predictor 2) and August-October sea surface temperature (panel a), August-October sea level pressure (panel b), August-October 925 mb zonal wind (panel c) and August-October 200 mb zonal wind (panel d). All four of these parameter deviations are known to be favorable for enhanced hurricane activity. Zonal wind values have been multiplied by -1 to allow for easy comparison with Figure 16.

(a) SST (b) SLP



(c) 925 mb U (d) 200 mb U

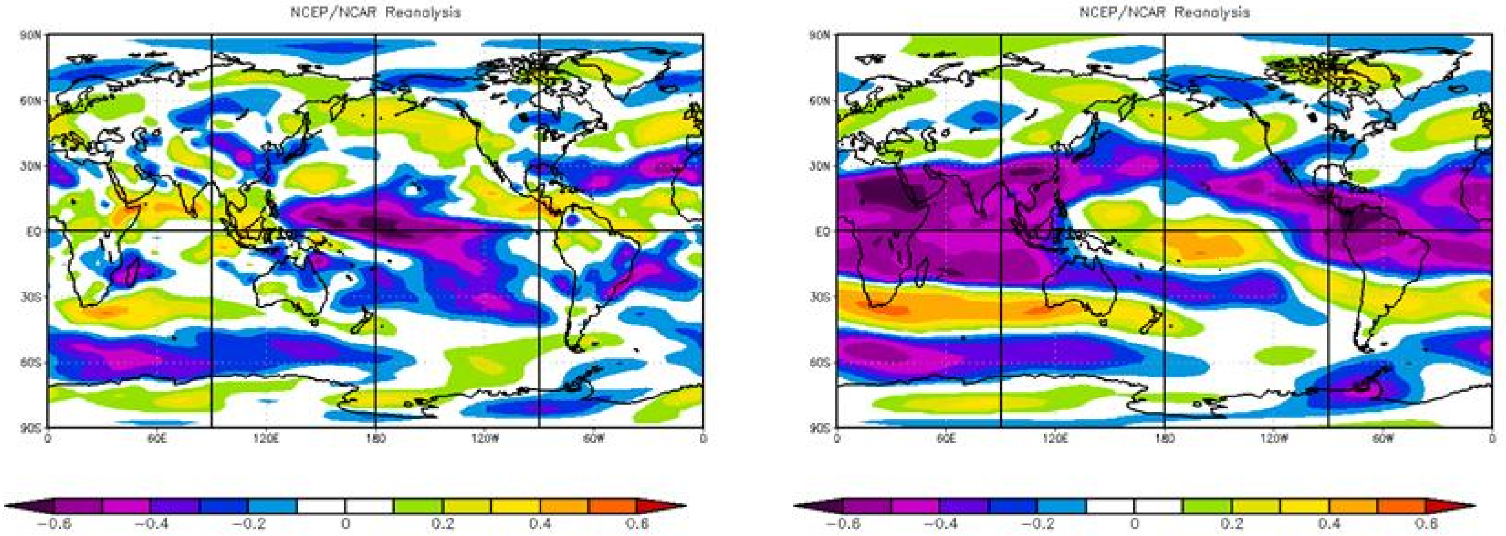


Figure 18: Linear correlations between July 200 mb zonal wind over North Africa (Predictor 3) and August-October sea surface temperature (panel a), August-October sea level pressure (panel b), August-October 925 mb zonal wind (panel c) and August-October 200 mb zonal wind (panel d). All four of these parameter deviations are known to be favorable for enhanced hurricane activity. Zonal wind values have been multiplied by -1 to allow for easy comparison with Figure 16.

## 6 Analog-Based Predictors for 2011 Hurricane Activity

Certain years in the historical record have global oceanic and atmospheric trends which are substantially similar to 2011. These years also provide useful clues as to likely trends in activity that the 2011 hurricane season may bring. For this early August forecast we determine which of the prior years in our database have distinct trends in key environmental conditions which are similar to current June-July 2011 conditions. Table 16 lists the best analog selections from our historical database.

We select prior hurricane seasons since 1950 which have similar atmospheric-oceanic conditions to those currently being experienced. We searched for years that had the closest optimal combination of neutral ENSO conditions, above-average tropical Atlantic SSTs and below-average tropical Atlantic sea level pressures.

There were four hurricane seasons with characteristics most similar to what we observed in June-July 2011. The best analog years that we could find for the 2011 hurricane season were 1952, 1966, 2005 and 2008. We anticipate that 2011 seasonal hurricane activity will have activity that is in line with the average of these four analog years. We believe that 2011 will have well above-average activity in the Atlantic basin.

Table 16: Best analog years for 2011 with the associated hurricane activity listed for each year.

| Year | NS | NSD | H | HD | MH | MHD | ACE | NTC |
|---|---|---|---|---|---|---|---|---|
| 1952 | 7 | 39.75 | 6 | 22.75 | 3 | 7 | 87 | 103 |
| 1966 | 11 | 64.00 | 7 | 41.75 | 3 | 8.75 | 145 | 140 |
| 2005 | 28 | 131.50 | 15 | 49.75 | 7 | 17.75 | 250 | 279 |
| 2008 | 16 | 88.25 | 8 | 30.50 | 5 | 7.50 | 146 | 162 |
| | | | | | | | | |
| **Mean** | **15.5** | **80.9** | **9.0** | **36.2** | **4.5** | **10.3** | **157.1** | **171.2** |
| 2011 Forecast | 16 | 80 | 9 | 35 | 5 | 10 | 160 | 175 |
| 1950-2000 Climo | 9.6 | 49.1 | 5.9 | 24.5 | 2.3 | 5.0 | 96 | 100 |

## 7 ENSO

Neutral ENSO conditions persist across the tropical Pacific. SST anomalies are currently near average across the central and eastern tropical Pacific. Table 17 displays July and May SST anomalies for several Nino regions. Slight cooling has occurred in the eastern tropical Pacific, while slight warming has occurred in the central tropical Pacific over the past two months.

Table 17: May and July 2011 SST anomalies for Nino 1+2, Nino 3, Nino 3.4, and Nino 4, respectively. July-May SST anomaly differences are also provided.

| Region | May SST Anomaly (°C) | July SST Anomaly (°C) | July minus May SST Change (°C) |
|---|---|---|---|
| Nino 1+2 | 0.6 | 0.2 | -0.4 |
| Nino 3 | 0.1 | 0.1 | 0.0 |
| Nino 3.4 | -0.2 | -0.1 | +0.1 |
| Nino 4 | -0.4 | -0.1 | +0.3 |

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 (Figure 19).

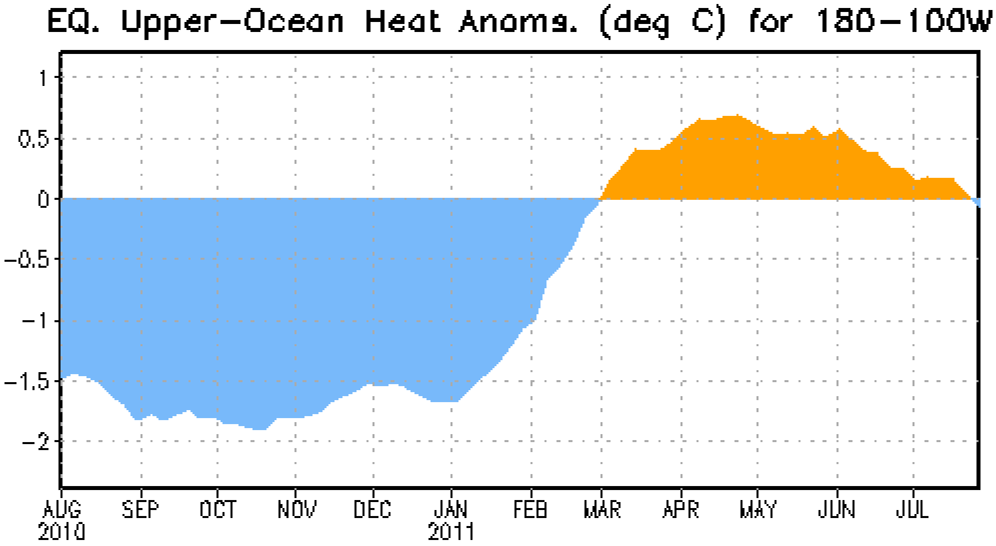


Figure 19: Central and eastern tropical Pacific upper ocean (0-300 meters) heat content anomalies over the past year. Note the significant warming of these anomalies from December 2010 through March 2011 and the downward trend since then.

There is generally improved consensus amongst the various dynamical and statistical ENSO forecast models for a forecast issued in July compared with a forecast issued during May for the August-October period. The springtime ENSO predictability barrier has passed, and consequently, the skill of the various models also tends to improve. Figure 20 displays the current forecasts issued by various ENSO models. All models except for the ESSIC Intermediate Coupled Model are calling for neutral conditions during August-October.

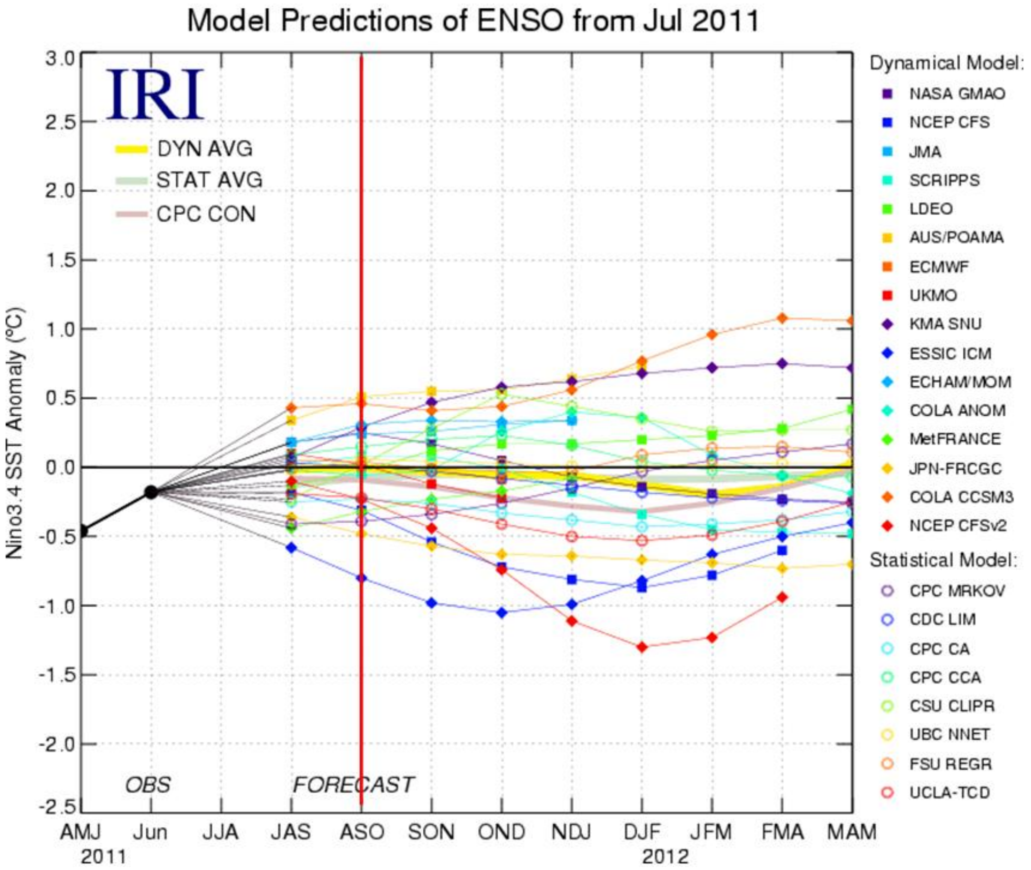


Figure 20: ENSO forecasts from various statistical and dynamical models. Figure courtesy of the International Research Institute (IRI).

As was found with the early June prediction, the European Centre for Medium-Range Weather Forecasts (ECMWF) typically shows the best prediction skill of the various ENSO models. The correlation skill between a 1 July forecast from the ECMWF model and the observed September Nino 3.4 anomaly is 0.89, based on hindcasts/forecasts from 1982-2010, explaining approximately 79% of the variance in Nino 3.4 SST. For reference, the correlation skill of a 1 May forecast from the ECMWF model was 0.82, indicating that approximately 15% additional variance can be explained by shortening the lead time of the forecast from 1 May to 1 July. The average of the various ECMWF ensemble members is calling for a September Nino 3.4 SST anomaly of approximately -0.1°C, and no members call for El Niño conditions (Figure 21).

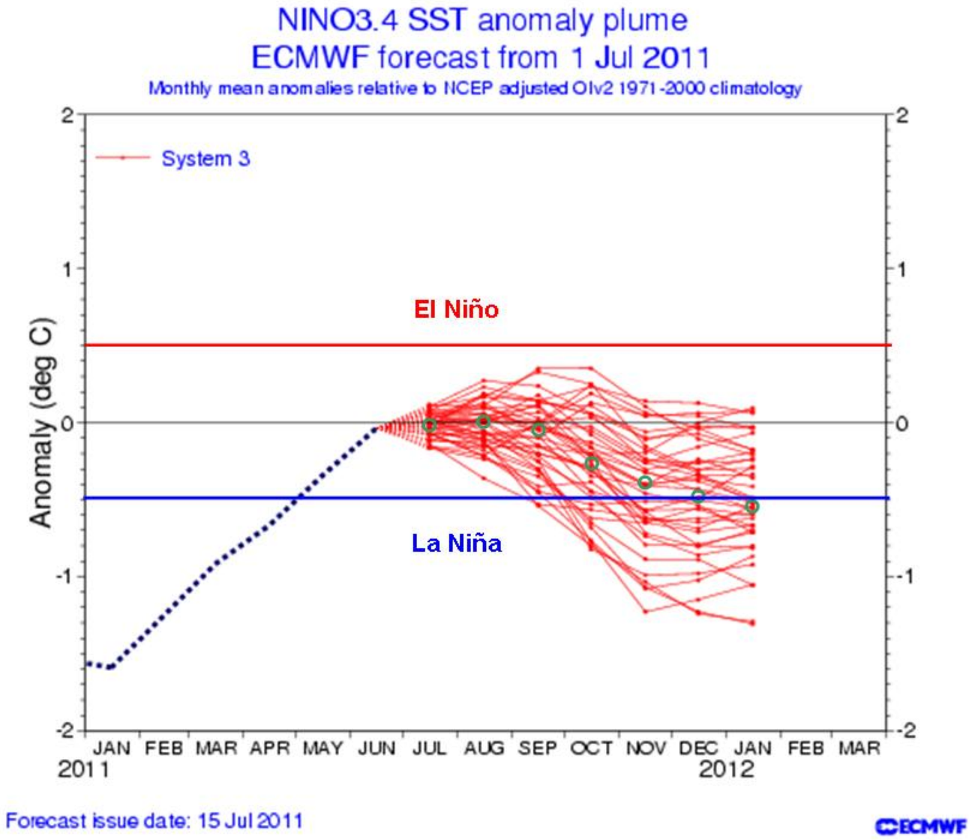


Figure 21: ECMWF ensemble model forecast for the Nino 3.4 region. Green circles represent the approximate centroid of the ensembles for each individual month.

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 the next section), we believe that ENSO will not be a significant detrimental factor for this year's hurricane season.

## 8 Current Atlantic Basin Conditions

Conditions in the Atlantic remain very favorable for an active Atlantic hurricane season. While SST anomalies across the MDR and the Caribbean are not as warm as they were in 2010, they are still running at well above-average levels (Figure 22). Sea level pressure anomalies over the past two months have been at near-record low levels, implying that the trade winds are weak, low- and mid-level instability is increased, and the Tropical Upper Tropospheric Trough (TUTT) is reduced in strength, which typically relates to reduced vertical wind shear across the tropical Atlantic and Caribbean (Figure 23) (Knaff 1997).

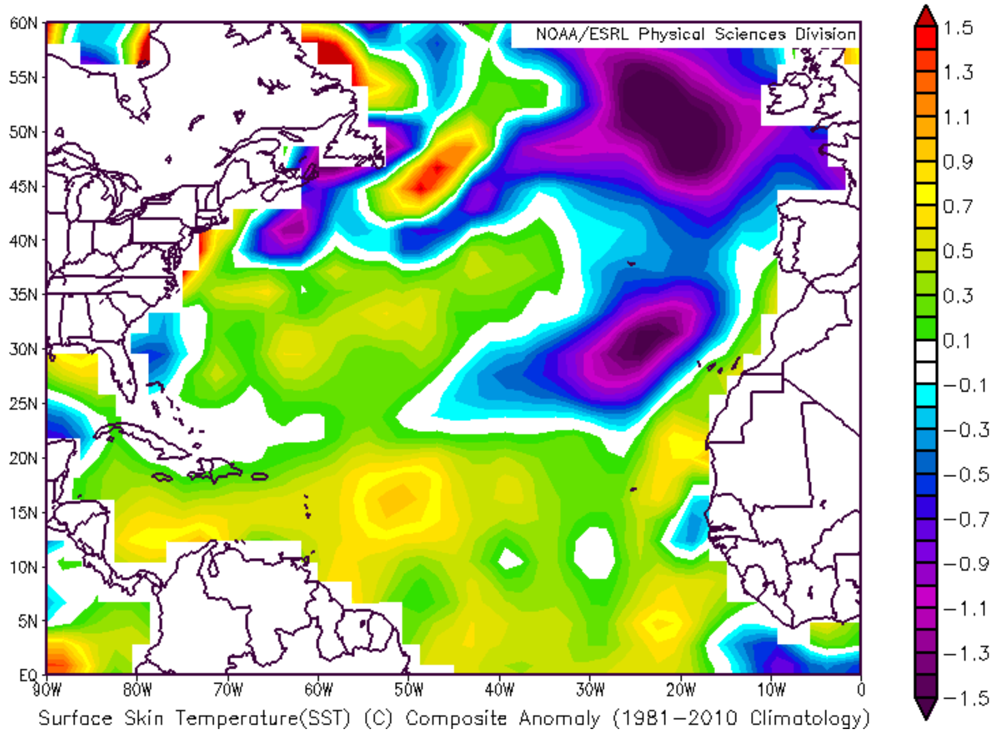


Figure 22: July 2011 SST anomaly. Note the positive anomalies throughout the tropical Atlantic and Caribbean.

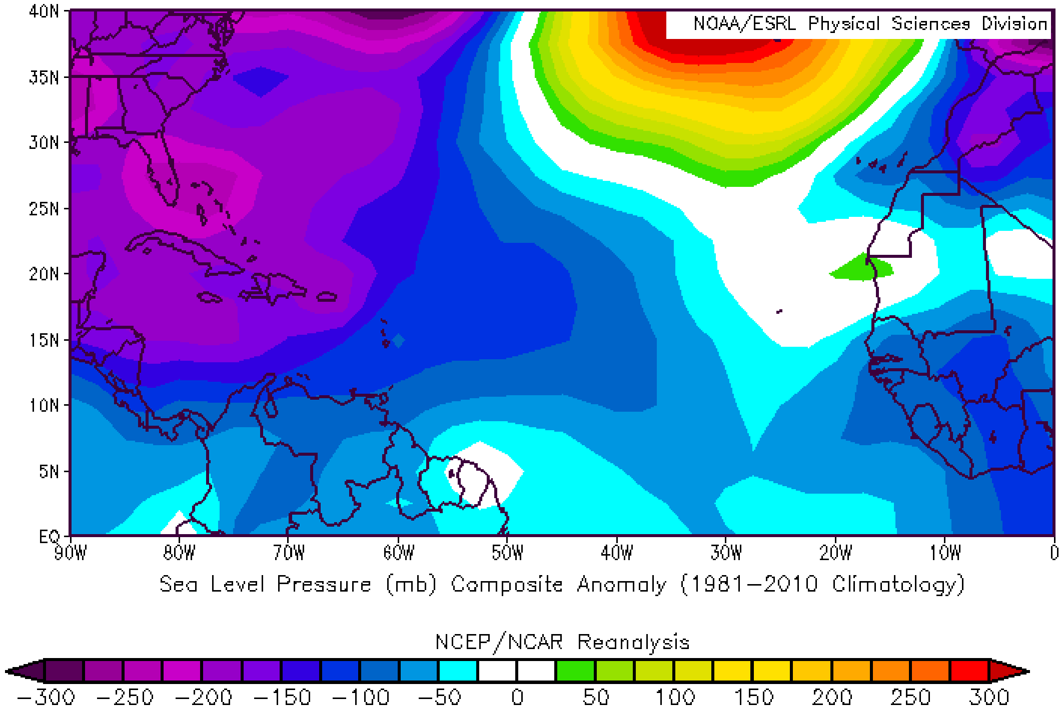


Figure 23: July 2011 Atlantic SLP anomaly. Note the large negative anomalies throughout the tropical Atlantic and Caribbean.

# 9 West Africa Conditions

Conditions over West Africa also appear conducive for an active hurricane season. According to Amato Evan (personal communication), monthly mean MDR dust for April-June was somewhat below the 1982-2010 average based on MODIS/Aqua aerosol optical thickness retrievals. Enhanced levels of dust are generally considered detrimental for an active hurricane season, due to a negative radiative impact on tropical Atlantic SSTs. Also, enhanced levels of dust are associated with more stable lapse rates, drier mid-levels of the atmosphere and overall subsidence, all of which inhibit TC formation (Evan et al. 2006).

Enhanced rainfall in the Sahel region of West Africa during the June-July time period has been associated with active hurricane seasons (Landsea and Gray 1992). Figure 24 displays a combined satellite/rain gauge estimate, referred to as the African Rainfall Estimation Algorithm Version 2 (RFE 2.0) of percent of normal rainfall over the June-July 2011 time period. In general, it appears that rainfall in the Western Sahel has been slightly above normal during June and July.

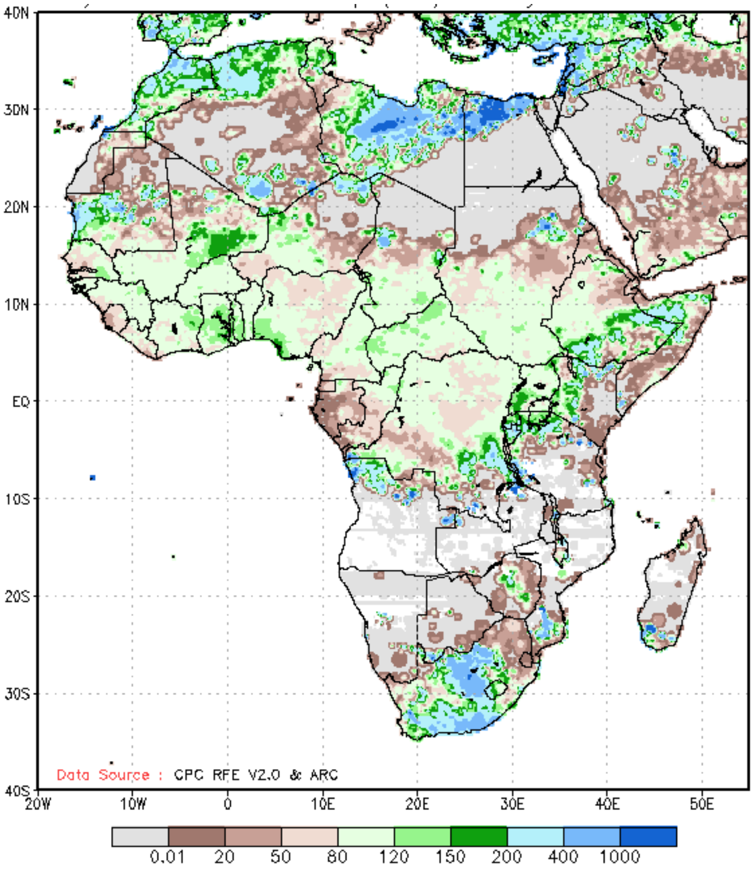


Figure 24: RFE version 2.0 estimate of percent of normal rainfall for June-July 2011.

## 9 Adjusted 2011 Forecast

Table 18 shows our final adjusted early August forecast for the 2011 season which is a combination of our two statistical schemes (with June-July activity added in), our analog forecast and qualitative adjustments for other factors not explicitly contained in any of these schemes. Both our statistical forecasts and our analog forecast call for an active season. We foresee a very active Atlantic basin hurricane season due primarily to the expected continuation of favorable SST and SLP anomalies in the tropical Atlantic.

Table 18: Summary of both of our early August full season statistical forecasts (with June-July 2011 activity added in), our analog forecast and our adjusted final forecast for the 2011 hurricane season.

| Forecast Parameter and 1950-2000 Climatology (in parentheses) | Klotzbach (2007) Statistical Scheme | Klotzbach (2011) Statistical Scheme | Analog Scheme | Adjusted Final Forecast |
|---|---|---|---|---|
| Named Storms (9.6) | 14.7 | 16.4 | 15.5 | 16 |
| Named Storm Days (49.1) | 63.0 | 75.5 | 80.9 | 80 |
| Hurricanes (5.9) | 6.1 | 7.4 | 9.0 | 9 |
| Hurricane Days (24.5) | 23.8 | 31.2 | 36.2 | 35 |
| Major Hurricanes (2.3) | 2.6 | 3.5 | 4.5 | 5 |
| Major Hurricane Days (5.0) | 6.0 | 8.8 | 10.3 | 10 |
| Accumulated Cyclone Energy Index (96.1) | 107 | 138 | 157 | 160 |
| Net Tropical Cyclone Activity (100%) | 118 | 150 | 171 | 175 |

## 10 Landfall Probabilities for 2011

A significant focus of our recent research involves efforts to develop forecasts of the probability of hurricane landfall along the U.S. coastline and in the Caribbean. Whereas individual hurricane landfall events cannot be forecast months in advance, the total seasonal probability of landfall can be forecast with statistical skill. With the observation that landfall is a function of varying climate conditions, a probability specification has been developed through statistical analyses of all U.S. hurricane and named storm landfall events during the 20th century (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 shown linked to the overall Atlantic basin Net Tropical Cyclone activity (NTC; see Table 19). NTC is a combined measure of the year-to-year mean of six indices of hurricane activity, each expressed as a percentage difference from the long-term average. Long-term statistics show that, on average, the more active the overall Atlantic basin hurricane season is, the greater the probability of U.S. hurricane landfall.

Table 19: NTC activity in any year consists of the seasonal total of the following six parameters expressed in terms of their long-term averages. A season with 10 NS, 50 NSD, 6 H, 25 HD, 3 MH, and 5 MHD would then be the sum of the following ratios: 10/9.6 = 104, 50/49.1 = 102, 6/5.9 = 102, 25/24.5 = 102, 3/2.3 = 130, 5/5.0 = 100, divided by six, yielding an NTC of 107.

| | 1950-2000 Average | |
|---|---|---|
| 1) | Named Storms (NS) | 9.6 |
| 2) | Named Storm Days (NSD) | 49.1 |
| 3) | Hurricanes (H) | 5.9 |
| 4) | Hurricane Days (HD) | 24.5 |
| 5) | Major Hurricanes (MH) | 2.3 |
| 6) | Major Hurricane Days (MHD) | 5.0 |

Table 20 lists strike probabilities for the 2011 hurricane season for different TC categories for the entire U.S. coastline, the Gulf Coast and the East Coast including the Florida peninsula. We also issue probabilities for various islands and landmasses in the Caribbean and in Central America. Note that Atlantic basin NTC activity in 2011 is expected to be well above its long-term average of 100, and therefore, landfall probabilities are above their long-term average.

As an example we find that the probability of Florida being hit by a major (Cat 3-4-5) hurricane this year is 32% which is substantially higher than the yearly climatological average of 21%.

South Florida is much more prone to being impacted by a hurricane on an individual-year basis compared with northeast Florida. For instance, the probability of Miami-Dade County being impacted by hurricane-force wind gusts this year is 18%. For Duval County in northeast Florida, the probability of being impacted by hurricane-force wind gusts is only 4%. However, considering a 50-year period, the probability of Duval County experiencing hurricane-force wind gusts is 75%.

For the island of Puerto Rico, the probability of a named storm, hurricane and major hurricane tracking within 50 miles of the island this year is 48%, 24%, and 8%, respectively.

Table 20: Estimated probability (expressed in percent) of one or more landfalling tropical storms (TS), category 1-2 hurricanes (HUR), category 3-4-5 hurricanes, total hurricanes and named storms along the entire U.S. coastline, along the Gulf Coast (Regions 1-4), and along the Florida Peninsula and the East Coast (Regions 5-11) for 2011. Probabilities of a tropical storm, hurricane and major hurricane tracking into the Caribbean are also provided. The long-term mean annual probability of one or more landfalling systems during the last 100 years is given in parentheses.

| Region | TS | Category 1-2 HUR | Category 3-4-5 HUR | All HUR | Named Storms |
|---|---|---|---|---|---|
| Entire U.S. (Regions 1-11) | 92% (79%) | 85% (68%) | 70% (52%) | 95% (84%) | 99% (97%) |
| Gulf Coast (Regions 1-4) | 77% (59%) | 60% (42%) | 45% (30%) | 78% (60%) | 95% (83%) |
| Florida plus East Coast (Regions 5-11) | 68% (50%) | 62% (44%) | 46% (31%) | 79% (61%) | 93% (81%) |
| Caribbean (10-20°N, 60-88°W) | 94% (82%) | 75% (57%) | 59% (42%) | 90% (75%) | 99% (96%) |

## 11 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. In addition, three category 2 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.

There has, however, been a large increase in Atlantic basin major hurricane activity since 1995 in comparison with the prior 16-year period of 1979-1994 (Figure 25) 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 16-year active major hurricane period of 1995-2010 has not been more active than the earlier 16-year period of 1949-1964 when the Atlantic Ocean circulation conditions were similar to what has been observed during the last 16 years. These earlier active conditions occurred even though atmospheric $CO_2$ amounts were lower during the earlier period.

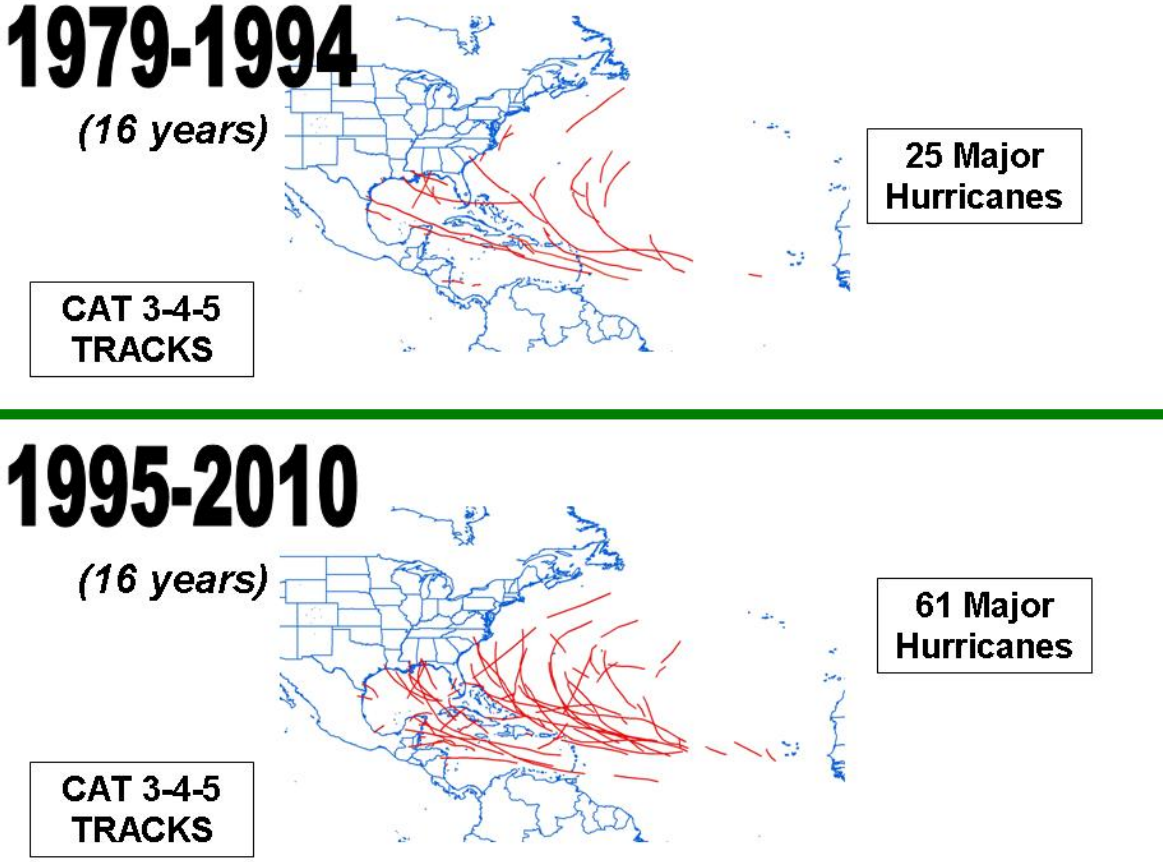


Figure 25: The tracks of major (Category 3-4-5) hurricanes during the 16-year period of 1995-2010 when the Atlantic thermohaline circulation (THC) was strong versus the prior 16-year period of 1979-1994 when the THC was weak. Note that there were approximately 2.5 times as many major hurricanes when the THC was strong as when it was weak.

Table 21 shows how large Atlantic basin hurricane variations are 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.

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 26). Similarly, Klotzbach (2006) found no significant change in global TC activity during the period from 1986-2005.

Table 21: Comparison of Atlantic annual basin hurricane activity in two 16-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 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1949-1964 (16 years) | Strong | 27.93 | 319 | 10.1 | 54.1 | 6.5 | 29.9 | 3.8 | 9.5 | 121 | 133 |
| 1970-1994 (25 years) | Weak | 27.60 | 345 | 9.3 | 41.9 | 5.0 | 16.0 | 1.5 | 2.5 | 68 | 75 |
| 1995-2010 (16 years) | Strong | 28.02 | 373 | 14.6 | 74.1 | 7.8 | 32.0 | 3.8 | 9.4 | 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 |

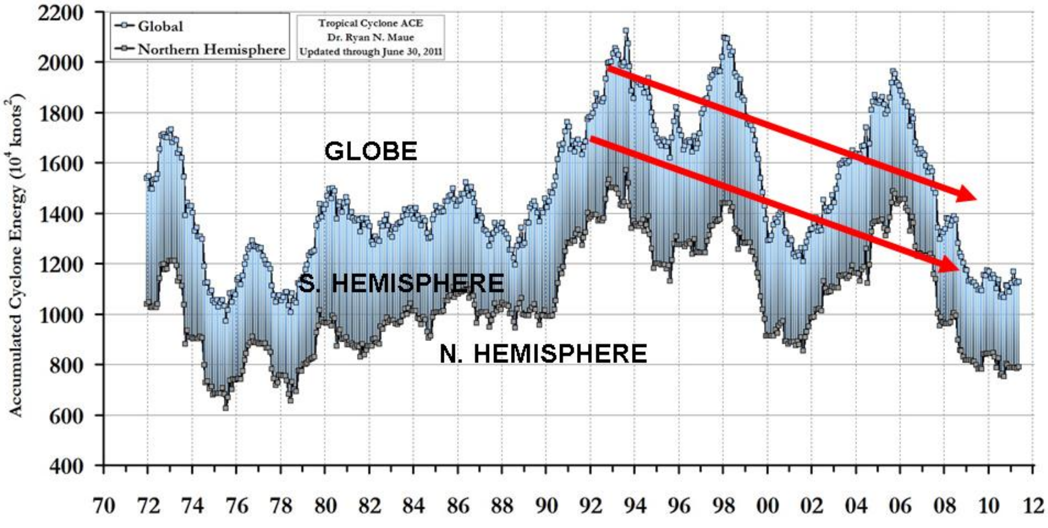


Figure 26: Northern Hemisphere and global Accumulated Cyclone Energy (ACE) over the period from December 1971-June 2011. Figure has been adapted from Ryan Maue.

**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 27). 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 28) 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 29). 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.

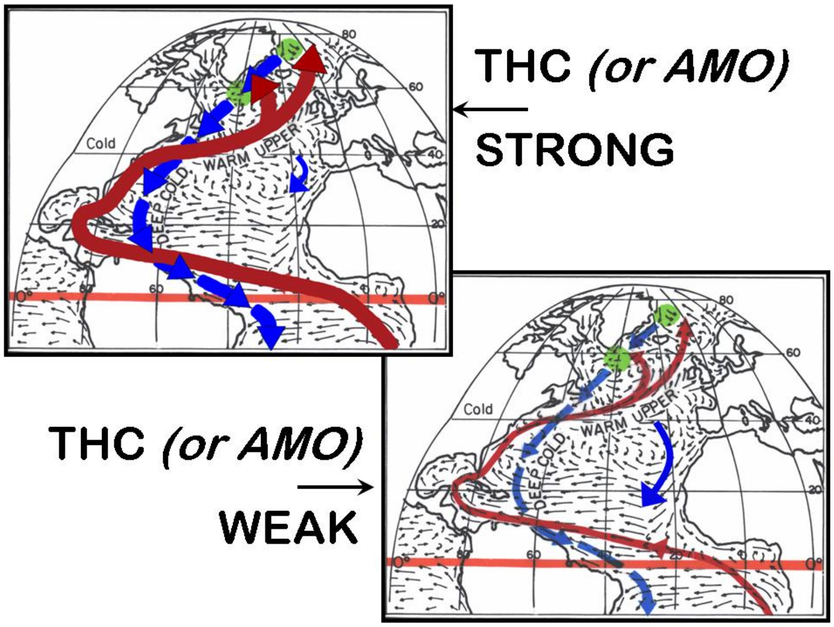


Figure 27: Illustration of strong (top) and weak (bottom) phases of the THC or AMO.

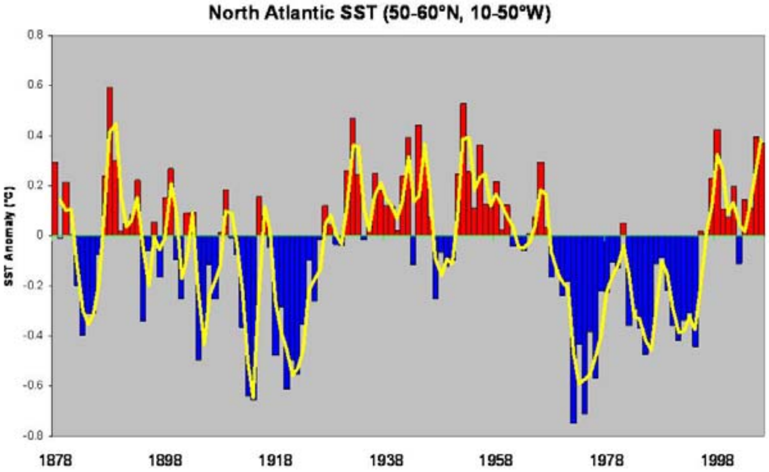


Figure 28: Long-period portrayal (1878-2006) of North Atlantic sea surface temperature anomalies (SSTA). The red (warm) periods are when the THC (or AMO) is stronger than average and the blue periods are when the THC (or AMO) is weaker than average.

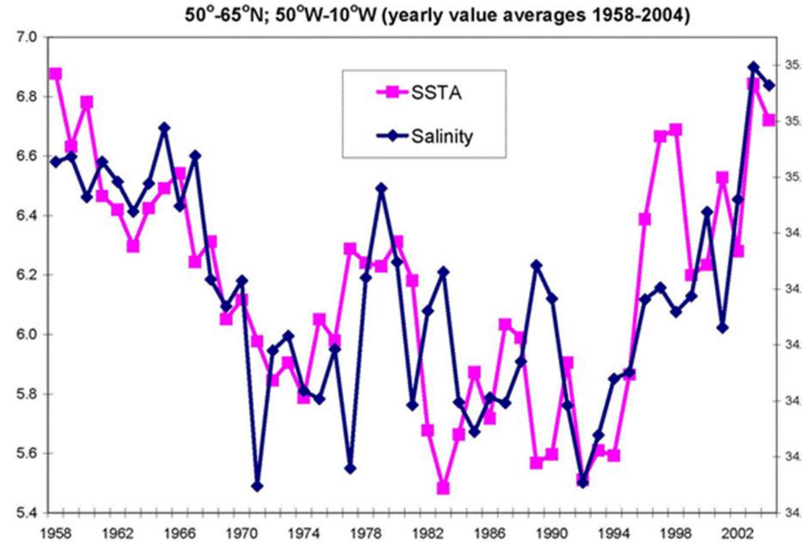


Figure 29: Illustration of the strong association of yearly average North Atlantic SSTA and North Atlantic salinity content between 1958 and 2004.

## 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 30). Atlantic SSTs and hurricane activity do not follow global mean temperature trends.

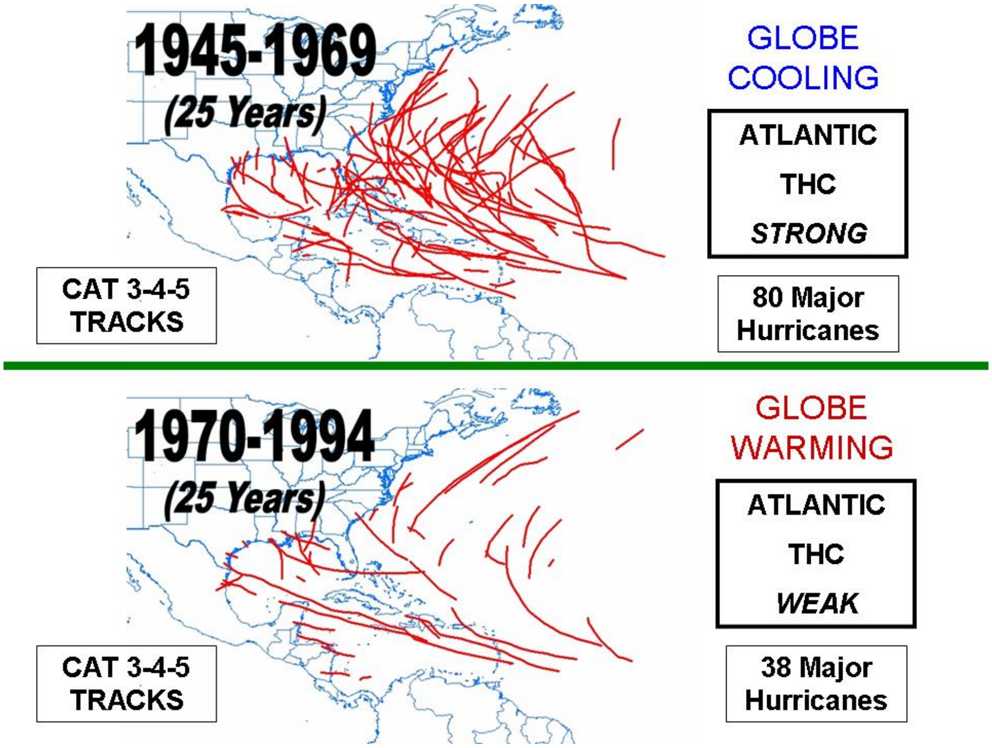


Figure 30: Tracks of major (Category 3-4-5) hurricanes during the 25-year period of 1945-1969 when the globe was undergoing a weak cooling versus the 25-year period of 1970-1994 when the globe was undergoing a modest warming. $CO_2$ amounts in the later period were approximately 18 percent higher than 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 22). Although global mean ocean and Atlantic SSTs have increased by about 0.4°C between two 55-year periods (1901-1955 compared with 1956-2010), 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 45-year period of 1921-1965 (24 landfall events) and the 45-year period of 1966-2010 (7 landfall events) was especially large (Figure 31). For the entire United States coastline, 39 major hurricanes made landfall during the earlier 45-year period (1921-1965) compared with only 26 major hurricanes for the latter 45-year period (1966-2010). 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 22: U.S. landfalling tropical cyclones by intensity during two 55-year periods.

| ***YEARS*** | ***Named Storms*** | ***Hurricanes*** | ***Major Hurricanes (Cat 3-4-5)*** | ***Global Temperature Increase*** |
|---|---|---|---|---|
| 1901-1955 (55 years) | 210 | 115 | 44 | +0.4°C |
| 1956-2010 (55 years) | 180 | 87 | 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.

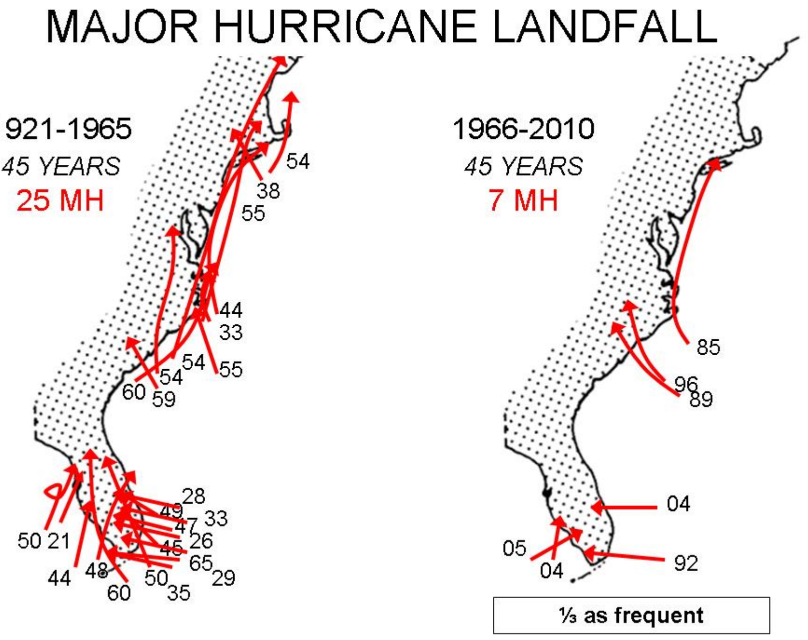


Figure 31: Contrast of tracks of East Coast and Florida Peninsula major landfalling hurricanes during the 45-year period of 1921-1965 versus the most recent 45-year period of 1966-2010.

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.

## 12 Forthcoming Updated Forecasts of 2011 Hurricane Activity

We will be issuing two-week forecasts for Atlantic TC activity during the climatological peak of the season from August-October. The first of these forecasts will be issued in a companion document today (August 3). Additional two-week forecasts will be issued every other Wednesday (e.g., August 17, August 31, etc.) The full schedule of two-week forecasts is available here: http://tropical.atmos.colostate.edu/Includes/Documents/Two_Week_Forecasts.html. An October-November outlook for the Caribbean will be issued on 30 September. A verification and discussion of all 2011 forecasts will be issued in late November 2011. All of these forecasts will be available on the web at: http://hurricane.atmos.colostate.edu/Forecasts.

## 13 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, all former directors of the National Hurricane Center (NHC) and the current director, Bill Read.

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# 15 Verification of Previous Forecasts

Table 23: Summary verification of the authors' five previous years of seasonal forecasts for Atlantic TC activity between 2006-2010.

| 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 |