

**EXTENDED RANGE FORECAST OF ATLANTIC SEASONAL HURRICANE  
ACTIVITY AND LANDFALL STRIKE PROBABILITY FOR 2010**

We continue to foresee above-average activity for the 2010 Atlantic hurricane season. We have increased our seasonal forecast from the mid-point of our initial early December prediction due to a combination of anomalous warming of Atlantic tropical sea surface temperatures and a more confident view that the current El Niño will weaken. We anticipate an above-average probability of United States and Caribbean major hurricane landfall.

(as of 7 April 2010)

By Philip J. Klotzbach<sup>1</sup> and William M. Gray<sup>2</sup>

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

Department of Atmospheric Science  
Colorado State University  
Fort Collins, CO 80523  
Email: [amie@atmos.colostate.edu](mailto:amie@atmos.colostate.edu)

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<sup>1</sup> Research Scientist

<sup>2</sup> Professor Emeritus of Atmospheric Science

## **Why issue extended-range 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 April. 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 season. Our early April statistical forecast methodology shows strong evidence over 58 past years that significant improvement over climatology can be attained. We would never issue a seasonal hurricane forecast unless we had a statistical model developed 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.

ATLANTIC BASIN SEASONAL HURRICANE FORECAST FOR 2010

Forecast Parameter and 1950-2000 Climatology (in parentheses)	Issue Date 9 December 2009	Issue Date 7 April 2010
Named Storms (NS) (9.6)	11-16	15
Named Storm Days (NSD) (49.1)	51-75	75
Hurricanes (H) (5.9)	6-8	8
Hurricane Days (HD) (24.5)	24-39	35
Major Hurricanes (MH) (2.3)	3-5	4
Major Hurricane Days (MHD) (5.0)	6-12	10
Accumulated Cyclone Energy (ACE) (96.1)	100-162	150
Net Tropical Cyclone Activity (NTC) (100%)	108-172	160

PROBABILITIES FOR AT LEAST ONE MAJOR (CATEGORY 3-4-5) HURRICANE  
LANDFALL ON EACH OF THE FOLLOWING COASTAL AREAS:

- 1) Entire U.S. coastline - 69% (average for last century is 52%)
- 2) U.S. East Coast Including Peninsula Florida - 45% (average for last century is 31%)
- 3) Gulf Coast from the Florida Panhandle westward to Brownsville - 44% (average for last century is 30%)

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

- 1) 58% (average for last century is 42%)

## ABSTRACT

Information obtained through March 2010 indicates that the 2010 Atlantic hurricane season will have significantly more activity than the average 1950-2000 season. We estimate that 2010 will have about 8 hurricanes (average is 5.9), 15 named storms (average is 9.6), 75 named storm days (average is 49.1), 35 hurricane days (average is 24.5), 4 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 is estimated to be about 130 percent of the long-period average. We expect Atlantic basin Net Tropical Cyclone (NTC) activity in 2010 to be approximately 160 percent of the long-term average. We have increased our seasonal forecast from the mid-point of our early December forecast.

This forecast is based on an extended-range early April statistical prediction scheme that utilizes 58 years of past data. Analog predictors are also utilized. The influence of El Niño conditions is implicit in these predictor fields, and therefore we do not utilize a specific ENSO forecast as a predictor.

We expect current moderate El Niño conditions to transition to neutral conditions by this year's hurricane season. The predicted weakening of El Niño conditions combined with a very strong anomalous warming of the tropical Atlantic are the primary reasons why we are increasing our forecast. We believe that these two features will lead to favorable dynamic and thermodynamic conditions for hurricane formation and intensification.

## **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 nine years and was second author on these forecasts from 2001-2005. I have greatly profited and enjoyed our close personal and working relationship.

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. He is currently making new seasonal and two-week forecast innovations that are improving our forecasts. The success of the last two years of seasonal forecasts is an example. Phil was awarded his Ph.D. degree in 2007. He is currently spending most of his time working towards better understanding and improving these Atlantic basin hurricane forecasts.

### Acknowledgment

We are grateful to the National Science Foundation (NSF) for providing partial support for the research necessary to make these forecasts. We also 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 project members 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 also 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<sup>2</sup>) for each 6-hour period of its existence. The 1950-2000 average value of this parameter is 96.

Atlantic Multi-Decadal Oscillation (AMO) – A mode of natural variability that occurs in the North Atlantic Ocean and evidencing itself in fluctuations in both sea surface temperature and sea level pressure fields. The AMO is likely related to fluctuations in the strength of the 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  $\text{ms}^{-1}$  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  $5 \text{ ms}^{-1}$ , circling the globe in approximately 40-50 days.

Main Development Region (MDR) – An area in the tropical Atlantic where a majority of major hurricanes form, defined 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  $50 \text{ ms}^{-1}$ ) 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.

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.

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 (18  $\text{ms}^{-1}$  or 34 knots) and 73 (32  $\text{ms}^{-1}$  or 63 knots) miles per hour.

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 27th year in which the CSU Tropical Meteorology Project has made forecasts of the upcoming season's Atlantic basin hurricane activity. Our research team has shown that a sizable portion of the year-to-year variability of Atlantic tropical cyclone (TC) activity can be hindcast with skill exceeding climatology. These forecasts are based on a statistical methodology derived from 58 years of past data. Qualitative adjustments are added to accommodate additional processes which may not be explicitly represented by our statistical analyses. These evolving forecast techniques are based on a variety of climate-related global and regional predictors previously shown to be related to the forthcoming seasonal Atlantic basin TC activity and landfall probability. We believe that seasonal forecasts must be based on methods that show significant hindcast skill in application to long periods of prior data. It is only through hindcast skill that one can demonstrate that seasonal forecast skill is possible. This is a valid methodology provided that the atmosphere continues to behave in the future as it has in the past.

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

A direct correlation of a forecast parameter may not be the best measure of the importance of this predictor to the skill of a 2-3 parameter forecast model. This is the nature of the seasonal or climate forecast problem where one is dealing with a very complicated atmospheric-oceanic system that is highly non-linear. There is a maze of changing physical linkages between the many variables. These linkages can undergo unknown changes from weekly to decadal time scales. It is impossible to understand how all these processes interact with each other. No one can completely understand the full complexity of the atmosphere-ocean system. But, it is still possible to develop a reliable statistical forecast scheme which incorporates a number of the climate system's non-linear interactions. Any seasonal or climate forecast scheme should show significant hindcast skill before it is used in real-time forecasts.

## **2 April Forecast Methodology**

We developed a new April forecast scheme which was used for the first time in 2008. This scheme has worked reasonably well over the past two years. Complete details on the earlier April forecast schemes used from 1995-2007 are available in our April 2008 forecast ([Klotzbach and Gray 2008](#)).

### **2.1 Current April Statistical Forecast Scheme**

We have found that using two late-winter predictors and our early December hindcast, we can obtain early April hindcasts that show considerable skill over the period from 1950-2007. This new model has worked reasonably well in real-time forecasts for the 2008 and 2009 hurricane seasons.

This new scheme was created by evaluating the two late-winter predictors using least-squared regression. These two predictors were then weighed as 70 percent of the final forecast and combined with a 30 percent weighting from the December statistical forecast.

Final April NTC Forecast = 0.7 \* (Early April Statistical Regression Scheme) + 0.3 \* (Final December Regression Scheme).

The new forecast scheme detailed below correlates with observations at 0.80 for the years from 1995-2007 and 0.85 for the years from 2002-2007. The model successfully predicted a very active 2008 season (predicting an NTC of 184), while failing to predict the quieter hurricane season that occurred in 2009 (predicting an NTC of 117). We believe that we have solid physical links between these predictors and the upcoming Atlantic basin hurricane season.

Table 1 displays hindcasts for 1950-2007 using the current scheme, while Figure 1 displays observations versus NTC hindcasts. We have correctly predicted above- or below-average seasons in 45 out of 58 hindcast years (78%). Our predictions have had a smaller error than climatology in 37 out of 58 years (64%). Our average hindcast error is 31 NTC units, compared with 46 NTC units for climatology. This scheme also shows considerable stability when broken in half, explaining 54 percent of the variance from 1950-1978 and 65 percent of the variance from 1979-2007. This new scheme is also well-tuned to the multi-decadal active hurricane periods from 1950-1969 and 1995-2007 versus the inactive hurricane period from 1970-1994 (Table 2). Figure 2 displays the locations of the two late-winter predictors used in this scheme in map form. Please refer to Figure 1 of our early December forecast for locations of predictors used in our early December prediction scheme. Table 3 lists the three (two new late-winter predictors and our early December prediction) that are utilized for this year's April forecast. A more extensive discussion of current conditions in the Atlantic and Pacific Oceans is provided in Sections 5 and 6.

From 1966-2007, the hindcast model only had three errors greater than 20 NTC units larger than climatology. These years were 1979 (39 NTC units), 1985 (21 NTC units) and 2006 (28 NTC units).



Table 1: Observed versus hindcast NTC for 1950-2007 using the current forecast 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 43 out of 58 years (74%), while hindcast improvement over climatology occurred in 37 out of 58 years (64%).

Year	Observed NTC	Hindcast NTC	Observed minus Hindcast	Observed minus Climatology	Hindcast improvement over Climatology
1950	247	161	86	147	61
1951	148	135	13	48	35
1952	103	<b>148</b>	-44	3	<b>-41</b>
1953	127	140	-14	27	13
1954	127	<b>96</b>	31	27	<b>-4</b>
1955	207	149	58	107	49
1956	68	<b>128</b>	-60	-32	<b>-28</b>
1957	86	<b>123</b>	-38	-14	<b>-23</b>
1958	144	147	-2	44	42
1959	96	86	10	-4	<b>-6</b>
1960	93	<b>132</b>	-39	-7	<b>-32</b>
1961	230	176	55	130	76
1962	41	<b>120</b>	-80	-59	<b>-20</b>
1963	116	<b>91</b>	26	16	<b>-9</b>
1964	184	150	34	84	50
1965	86	<b>137</b>	-51	-14	<b>-37</b>
1966	140	132	8	40	32
1967	102	<b>104</b>	-2	2	<b>-1</b>
1968	47	90	-42	-53	10
1969	182	158	24	82	58
1970	64	90	-26	-36	10
1971	91	96	-5	-9	4
1972	35	56	-21	-65	44
1973	53	88	-35	-47	12
1974	83	58	25	-17	<b>-8</b>
1975	92	84	7	-8	1
1976	86	81	5	-14	9
1977	47	68	-20	-53	32
1978	82	51	31	-18	<b>-13</b>
1979	97	54	42	-3	<b>-39</b>
1980	130	<b>89</b>	41	30	<b>-11</b>
1981	113	102	11	13	2
1982	38	78	-41	-62	22
1983	31	62	-31	-69	38
1984	80	<b>111</b>	-30	-20	<b>-11</b>
1985	106	132	-27	6	<b>-21</b>
1986	37	37	-1	-63	63
1987	46	95	-49	-54	5
1988	117	<b>89</b>	28	17	<b>-11</b>
1989	130	124	5	30	24
1990	100	96	4	0	<b>-4</b>
1991	58	49	9	-42	33
1992	67	57	10	-33	23
1993	52	97	-45	-48	3
1994	35	70	-35	-65	30
1995	222	177	45	122	77
1996	192	137	55	92	37
1997	54	73	-19	-46	27
1998	169	190	-22	69	47
1999	182	151	30	82	51
2000	134	140	-7	34	27
2001	135	112	23	35	12
2002	83	<b>101</b>	-18	-17	<b>-1</b>
2003	175	144	31	75	44
2004	232	162	69	132	62
2005	279	150	129	179	50
2006	85	<b>128</b>	-43	-15	<b>-28</b>
2007	99	<b>102</b>	-3	-1	<b>-2</b>
<b>Average</b>	<b>112</b>	<b>110</b>	<b>31</b>	<b>46</b>	<b>+15</b>

### Hindcast vs. Observed NTC - 1 April

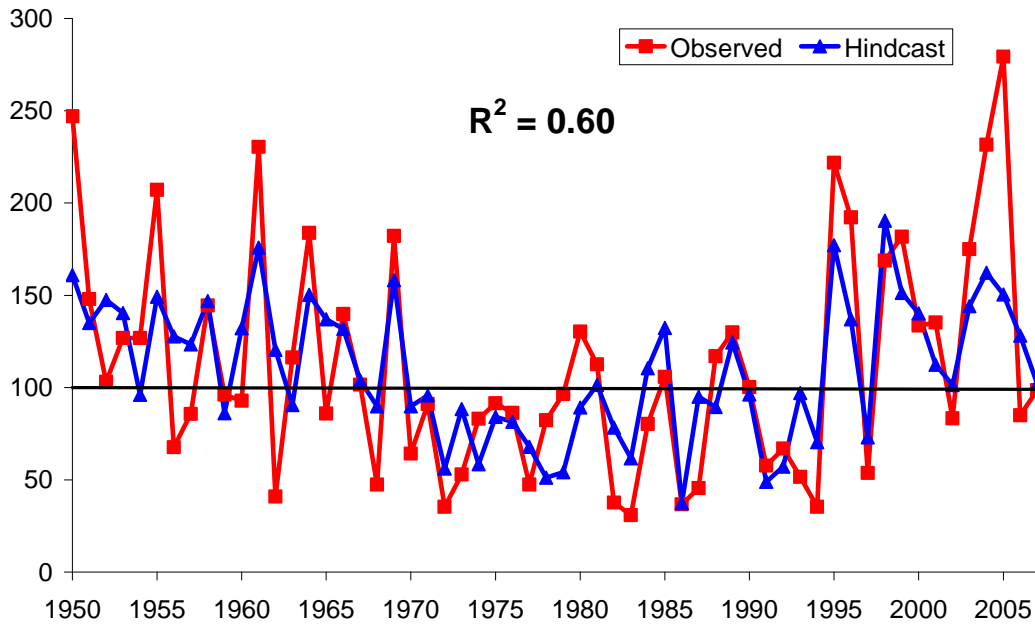


Figure 1: Observed versus hindcast values of NTC for 1950-2007.

Table 2: Hindcast versus observed average NTC for active vs. inactive multi-decadal periods in our developmental data set.

<i>Years</i>	<i>Average Hindcast NTC</i>	<i>Average Observed NTC</i>
1950-1969 (Active)	130	129
1970-1994 (Inactive)	81	75
1995-2007 (Active)	136	157

## New April Forecast Predictors

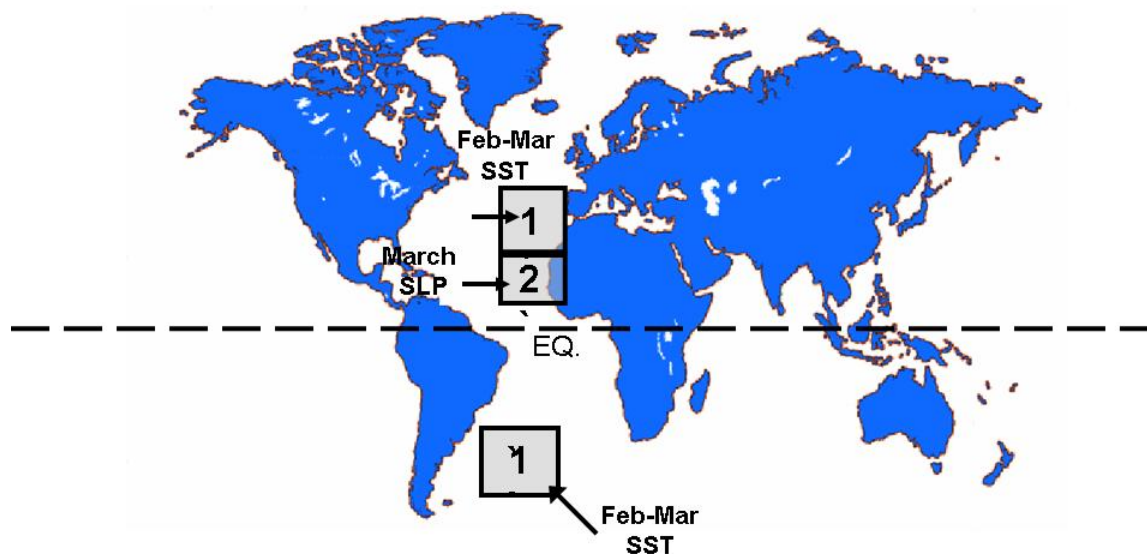


Figure 2: Location of late-winter predictors for our April extended-range statistical prediction for the 2010 hurricane season.

Table 3: Listing of 1 April 2010 predictors for the 2010 hurricane season. A plus (+) means that positive values of the parameter indicate increased hurricane activity during the following year.

Predictor	2010 Forecast Values
1) February-March SST Gradient (30-45°N, 10-30°W) – (30-45°S, 20-45°W) (+)	-0.5 SD
2) March SLP (10-30°N, 10-30°W) (-)	-0.3 SD
3) Early December Hindcast (+)	103 NTC

There is also extended-range forecast skill from 1 April for United States hurricane landfall probabilities over the hindcast period from 1950-2007. In the 15 out of 58 years where our current hindcast scheme forecast NTC values above 139, we had nearly twice as many hurricane (38 versus 20) and more than twice as many major hurricane (16 versus 7) landfalls along the U.S. coastline when compared with the 15 out of 58 years where our hindcast scheme gave NTC values below 84. For the Florida Peninsula and the U.S. East Coast, the ratio between NTC hindcast values greater than 139 and below 84 are 23 to 9 for hurricanes and 7 to 2 for major hurricanes, respectively.

### 2.2 Physical Associations among Predictors Listed in Table 3

The locations and brief descriptions of our two late-winter predictors for our early April statistical forecast are now discussed. It should be noted that both forecast parameters correlate significantly with physical features during August through October that are known to be favorable for elevated levels of hurricane activity. These factors are primarily related to August-October vertical wind shear in the Atlantic Main Development Region (MDR) from 10-20°N, 20-70°W as shown in Figure 3.

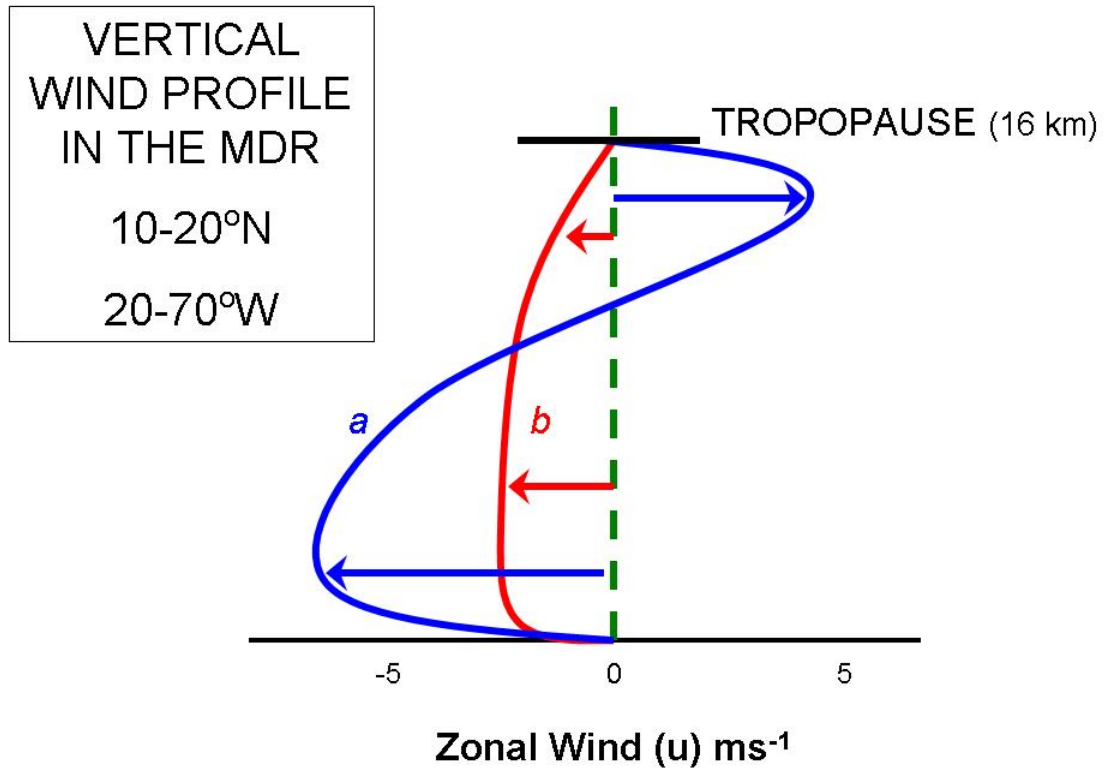


Figure 3: Vertical wind profile typically associated with (a) inactive Atlantic basin hurricane seasons and (b) active Atlantic basin hurricane seasons. Note that (b) has reduced levels of vertical wind shear.

For each of these predictors, we display a four-panel figure showing linear correlations between values of each predictor and August-October values of sea surface temperature (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 Atlantic basin hurricane seasons.

For more information about the predictors utilized in our early December statistical forecast (used as 30% of our early April forecast), please refer to our early December 2009 forecast:

<http://tropical.atmos.colostate.edu/Forecasts/2009/dec2009/dec2009.pdf>

Predictor 1. February-March SST Gradient between the Subtropical Eastern Atlantic and the South Atlantic (+)

(30-45°N, 10-30°W) - (30-45°S, 20-45°W)

A combination of above-normal SSTs in the eastern subtropical Atlantic and cooler-than-normal SSTs in the South Atlantic are associated with a weaker-than-normal Azores high and reduced trade wind strength during the boreal spring (Knaff 1997). This heightened SST gradient in February-March is strongly correlated with weaker trade winds and upper tropospheric westerly winds, lower-than-normal sea level pressures and above-normal SSTs in the tropical Atlantic during the following August-October period (Figure 4). All three of these August-October features are commonly associated with active Atlantic basin hurricane seasons, through reductions in vertical wind shear, increased vertical instability and increased mid-tropospheric moisture, respectively. A stronger-than-normal temperature gradient between the North Atlantic and South Atlantic correlates quite strongly (~0.6) with active Atlantic basin tropical cyclone seasons. Based on data from the NCEP reanalysis, SSTs in the South Atlantic have been warming faster than SSTs in the North Atlantic over the period from 1950-2007, and therefore, the SST gradient calculation for Predictor 1 has been de-trended. February-March values of this de-trended SST gradient correlate at 0.54 with August-October values of the Atlantic Meridional Mode (AMM) (Kossin and Vimont 2007) over the period from 1950-2007. The AMM has been shown to impact Atlantic hurricane activity through alterations in the position and intensity of the Atlantic Inter-Tropical Convergence Zone (ITCZ). Changes in the Atlantic ITCZ bring about changes in tropical Atlantic vertical and horizontal wind shear patterns and in tropical Atlantic SST patterns.

Predictor 2. March SLP in the Subtropical Atlantic (-)

(10-30°N, 10-30°W)

Our April statistical scheme in the late 1990s used a similar predictor when evaluating the strength of the March Atlantic sub-tropical ridge (Azores High). If the pressure in this area is higher than normal, it correlates strongly with enhanced Atlantic trade winds. These stronger trades enhance mixing and upwelling, driving cooler tropical Atlantic SSTs. These cooler SSTs are associated with higher-than-normal sea level pressures which can create a self-enhancing feedback that relates to higher pressure, stronger trades and cooler SSTs during the hurricane season (Figure 5) (Knaff 1998). All three of these factors are associated with inactive hurricane seasons. Sea level pressure values in this region have been trending slightly upward since the 1950s. We have removed half of the trend in the SLP values for our predictor calculations to avoid a potentially non-physical lowering of forecast values.

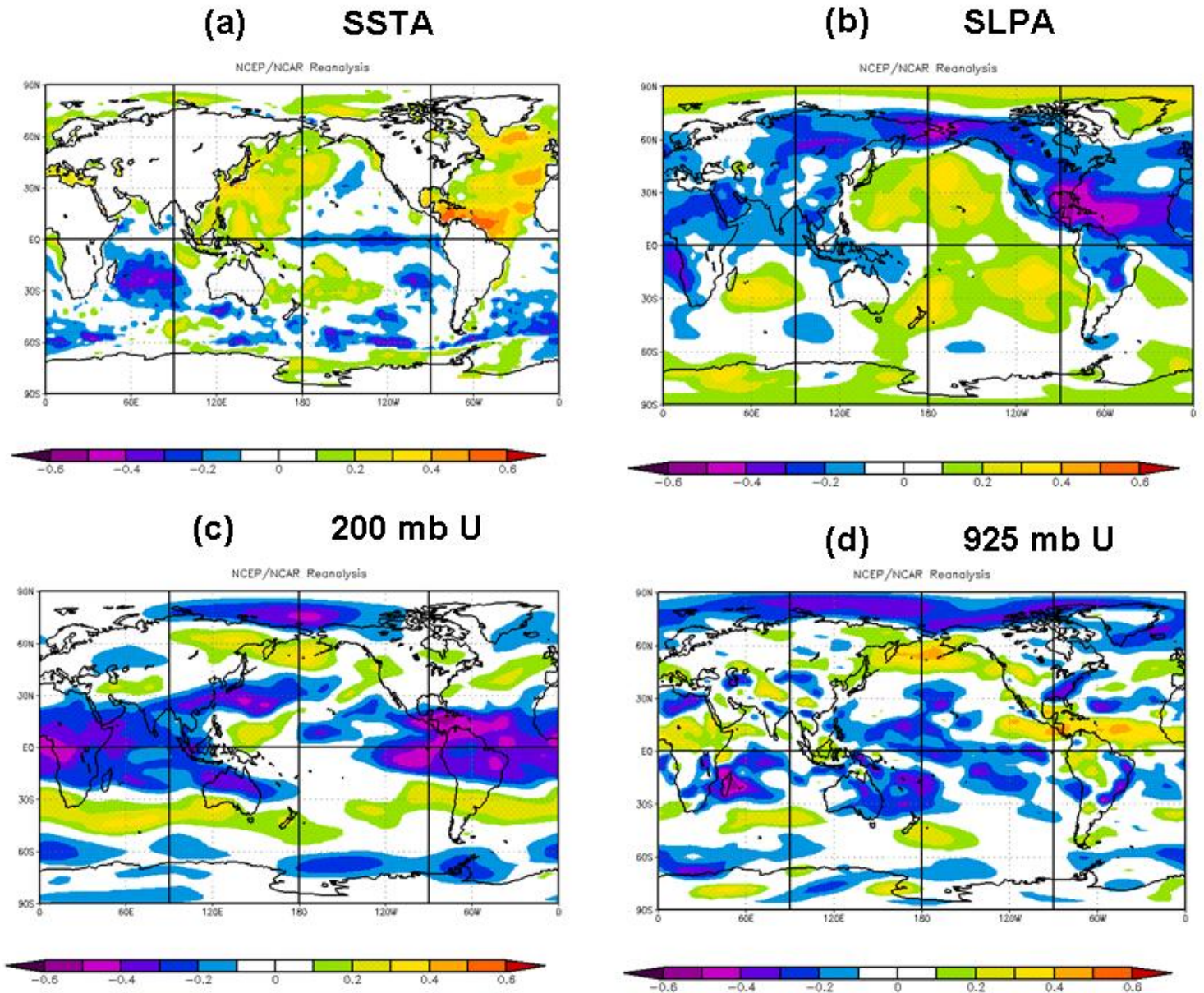


Figure 4: Linear correlations between the February-March SST gradient between the subtropical eastern Atlantic and the South Atlantic (Predictor 1) and August-October sea surface temperature (panel a), August-October sea level pressure (panel b), August-October 200 mb zonal wind (panel c) and August-October 925 mb zonal wind (panel d). All four of these parameter deviations in the tropical Atlantic are known to be favorable for enhanced hurricane activity.

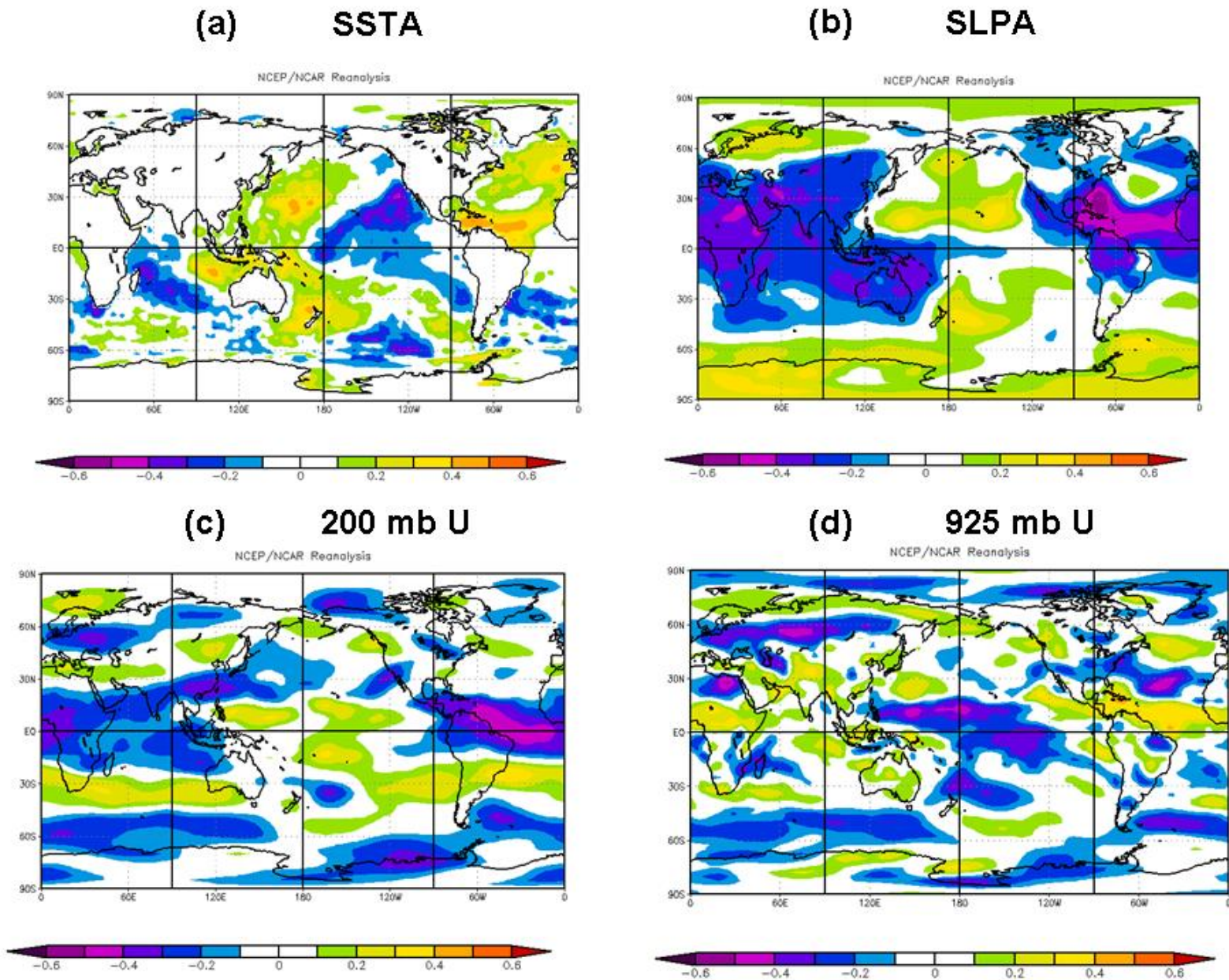


Figure 5: Linear correlations between March SLP in the subtropical Atlantic (Predictor 2) and August-October sea surface temperature (panel a), August-October sea level pressure (panel b), August-October 200 mb zonal wind (panel c) and August-October 925 mb zonal wind (panel d). All four of these parameter deviations in the tropical Atlantic are known to be favorable for enhanced hurricane activity. All values have been multiplied by -1 to allow for easy comparison with Figure 4.

### 3 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 certainly, there is with all forecasts an uncertainty as to how well they will verify.

Table 4 provides our early April forecasts, with error bars (based on one standard deviation of absolute errors) as calculated from hindcasts over the 1990-2007 period, using equations developed over the 1950-1989 period. We typically expect to see 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 4: Model hindcast error and our 2010 hurricane forecast. Uncertainty ranges are given in one standard deviation (SD) increments.

Parameter	Hindcast Error (SD)	2010 Forecast	Uncertainty Range – 1 SD (67% of Forecasts Likely in this Range)
Named Storms (NS)	4.0	15	11.0 – 19.0
Named Storm Days (NSD)	19.4	75	55.6 – 94.4
Hurricanes (H)	2.2	8	5.8 – 10.2
Hurricane Days (HD)	9.5	35	25.5 – 44.5
Major Hurricanes (MH)	1.4	4	2.6 – 5.4
Major Hurricane Days (MHD)	4.4	10	5.6 – 14.4
Accumulated Cyclone Energy (ACE)	39	150	111 – 189
Net Tropical Cyclone (NTC) Activity	41	160	119 – 201

#### 4 Analog-Based Predictors for 2010 Hurricane Activity

Certain years in the historical record have global oceanic and atmospheric trends which are similar to 2010. These years also provide useful clues as to likely trends in activity that the forthcoming 2010 hurricane season may bring. For this early April extended range forecast, we determine which of the prior years in our database have distinct trends in key environmental conditions which are similar to current February-March 2010 conditions. Table 5 lists our analog selections.

We select prior hurricane seasons since 1949 which have similar atmospheric-oceanic conditions to those currently being experienced. We searched for years that were generally characterized by El Niño conditions, well above-average tropical Atlantic SSTs and above-average far North Atlantic SSTs during February-March.

There were five hurricane seasons since 1949 with characteristics most similar to what we observed in February-March 2010. The best analog years that we could find for the 2010 hurricane season were 1958, 1966, 1969, 1998 and 2005. We anticipate that



2010 seasonal hurricane activity will have activity slightly less than what was experienced in the average of these five years. This is primarily due to the fact that 2005 was selected as one of our analog years, and we do not expect to see as many storms as were experienced that year. We believe that 2010 will have well above-average activity in the Atlantic basin.

Table 5: Best analog years for 2010 with the associated hurricane activity listed for each year.

Year	NS	NSD	H	HD	MH	MHD	ACE	NTC
1958	10	55.50	7	30.25	5	9.50	121	144
1966	11	64.00	7	41.75	3	8.75	145	140
1969	18	91.50	12	40.00	5	6.75	166	182
1998	14	88.00	10	48.50	3	9.50	182	169
2005	28	131.50	15	49.75	7	17.75	250	279
Mean	16.2	86.10	10.2	42.10	4.6	10.50	173	183
2010 Forecast	15	75	8	35	4	10	150	160

## 5 ENSO

Moderate-to-strong El Niño conditions have been in place during the winter of 2009-2010. This event has shown some signs of weakening over the past few weeks, although an eastward-propagating Kelvin wave is likely to prolong the current warm ENSO event, at least in the short term. SSTs are generally 0.5°C – 1.5°C above average across the eastern and central tropical Pacific. Table 6 displays January and March SST anomalies for several Nino regions. Note that all four regions have experienced slight cooling since January.

Table 6: January and March SST anomalies for Nino 1+2, Nino 3, Nino 3.4, and Nino 4, respectively. March-January SST anomaly differences are also provided.

Region	January SST Anomaly (°C)	March SST Anomaly (°C)	March – January SST Anomaly (°C)
Nino 1+2	0.3	0.0	-0.3
Nino 3	1.0	0.6	-0.4
Nino 3.4	1.6	1.2	-0.4
Nino 4	1.4	1.0	-0.4

There is a considerable degree of uncertainty as to what is going to happen with the current moderate El Niño event. The spring months are known as the ENSO predictability barrier time period, as this is when both statistical and dynamical models show their least amount of skill. This is likely due to the fact that from a climatological perspective, trade winds across the Pacific are weakest during the late spring and early summer, and therefore, changes in phase of ENSO are often observed to occur during the

April-June period. Most statistical and dynamical models are calling for a transition to neutral conditions (SSTs between  $-0.5^{\circ}\text{C}$  and  $0.5^{\circ}\text{C}$ ) by the August-October period (Figure 6). We find that, in general, the European Centre for Medium-Range Weather Forecasts (ECMWF) shows the best prediction skill of the various ENSO models. The ECMWF model is calling for a June-August-averaged Nino 3.4 SST anomaly of  $-0.3^{\circ}\text{C}$ , giving us increased confidence in our neutral prediction of ENSO for the upcoming hurricane season. Note that none of the ECMWF ensemble members keep El Niño conditions persisting beyond July, and only one ensemble member (out of 41 total members) keeps above-average tropical Pacific SSTs beyond August (Figure 7).

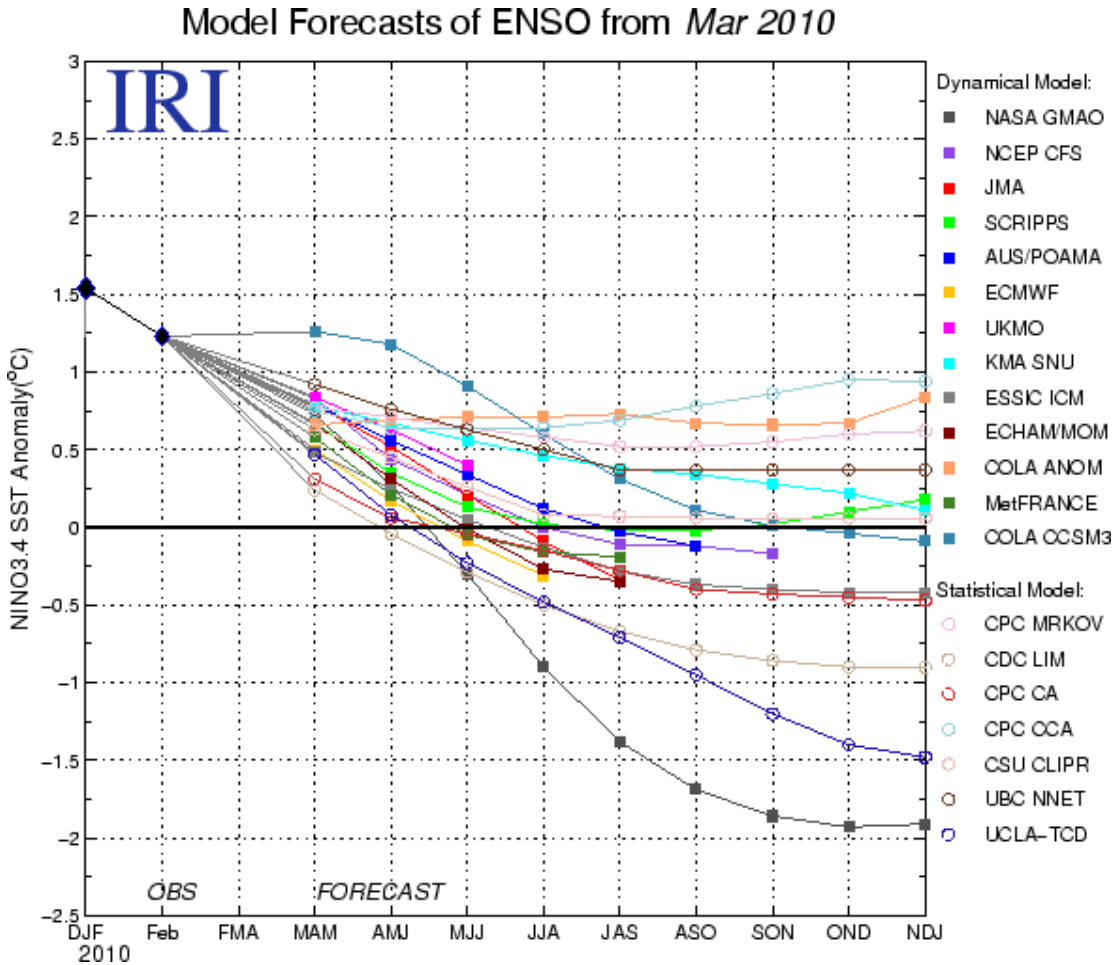
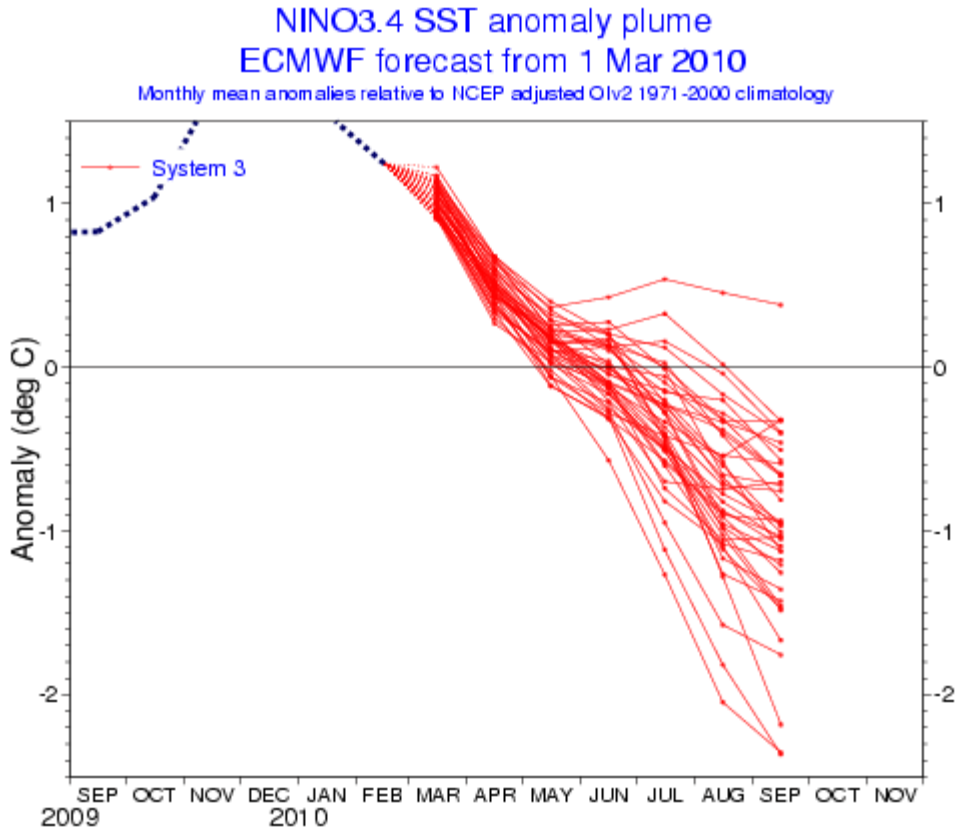


Figure 6: ENSO forecasts from various statistical and dynamical models. Figure courtesy of the International Research Institute (IRI). Most forecast models are calling for a transition to neutral conditions by August-October.



Forecast issue date: 15 Mar 2010

ECMWF

Figure 7: ECMWF ensemble model forecast for the Nino 3.4 region. Only one ensemble member has warmer-than-normal conditions by September.

Another reason why we believe that the current moderate El Niño will begin transitioning to neutral conditions soon is due to the current sub-surface ocean temperature anomaly pattern. Note that below-normal equatorial heat anomalies have reached the central Pacific. This reduction in upper-ocean heat content in the central Pacific is typically seen with a weakening El Niño (Figure 8).

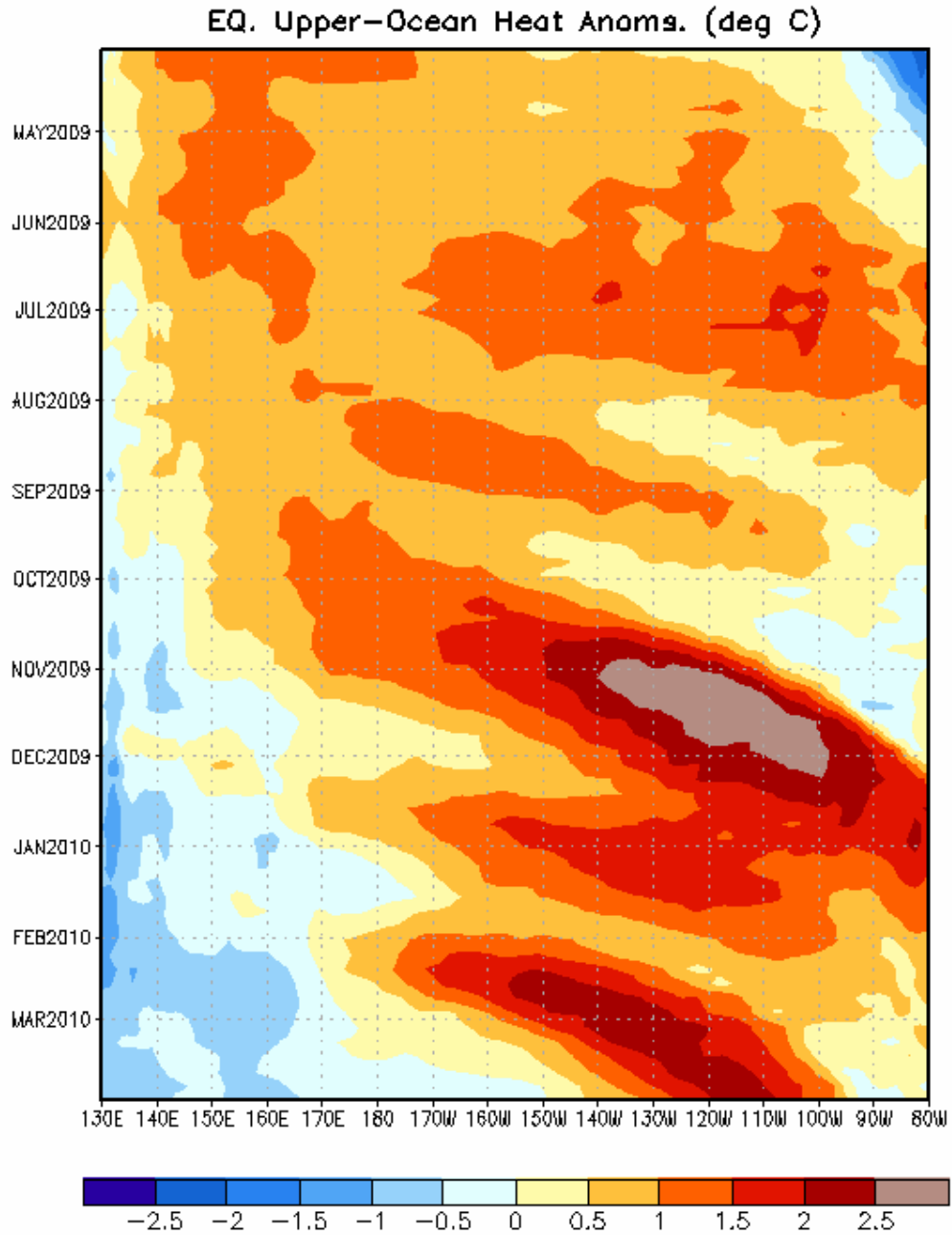


Figure 8: Current equatorial sub-surface upper-ocean heat anomaly pattern in the tropical Pacific.

Based on this information, we believe that the current moderate El Niño will likely transition to neutral conditions by this summer and early fall. El Niños typically increase levels of vertical wind shear in the tropical Atlantic, causing detrimental conditions for Atlantic tropical cyclone formation and intensification. Since we expect El Niño to dissipate over the next few months, we do not expect to see the high levels of

vertical shear across the Main Development Region that we experienced last year. We should know more about likely ENSO conditions for the upcoming hurricane season by the time of our next forecast on June 2.

## **6 Current Atlantic Basin Conditions**

Conditions in the Atlantic are quite favorable for an active season. SST anomalies across the Main Development Region for March are near their highest levels on record. Figure 9 displays the currently-observed SST anomaly pattern across the Atlantic. Note the very strong positive anomalies throughout the tropical Atlantic and the cool anomalies in the Gulf of Mexico and off the East Coast of the United States. This SST anomaly pattern is characteristic of the very strong negative North Atlantic Oscillation (NAO) index values that were present during January and February. A negative NAO is characterized by anomalous high pressure in the northern Atlantic and anomalous low pressure near the Azores High (Figure 10). This pressure gradient pattern causes a reduction in the trade winds (Figure 11). Reduced trade winds drive less upwelling and evaporation from the sea surface, typically resulting in a warming of SSTs. Warmer Atlantic SSTs in the MDR are associated with an active THC/positive AMO, weaker tropospheric vertical wind shear, weaker trade winds, increased instability and lower-than-normal sea level pressures. All of these conditions are generally associated with much more active Atlantic basin hurricane seasons.

The big question is whether or not this anomalous warming will persist through the upcoming hurricane season. We will be monitoring these conditions over the next couple of months.

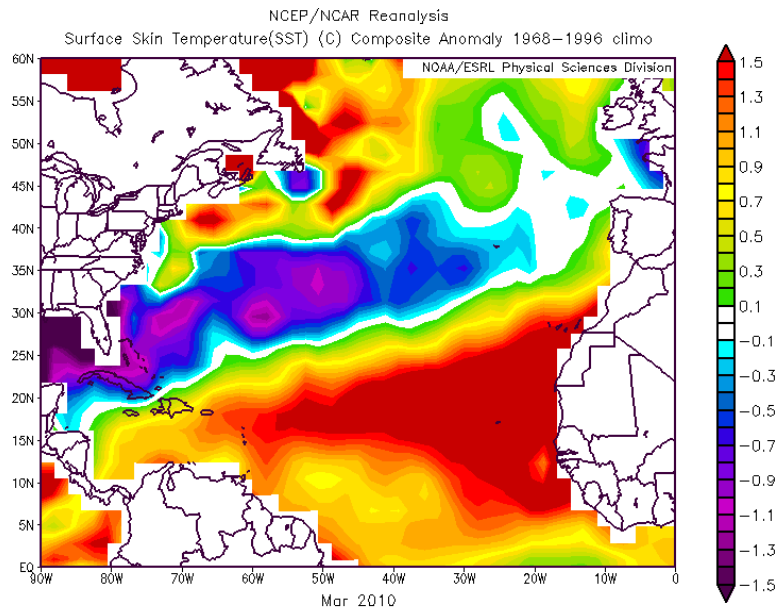


Figure 9: March 2010 SST anomaly pattern across the Atlantic Ocean.

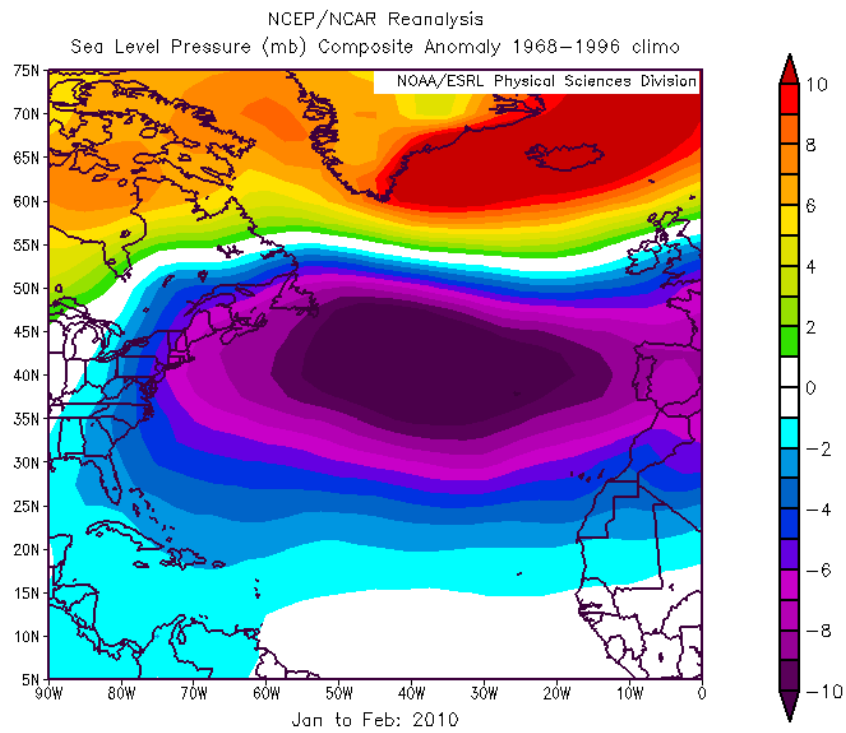


Figure 10: Sea level pressure anomaly pattern observed during January-February 2010. This sea level pressure anomaly pattern is typically observed in negative NAO winters.

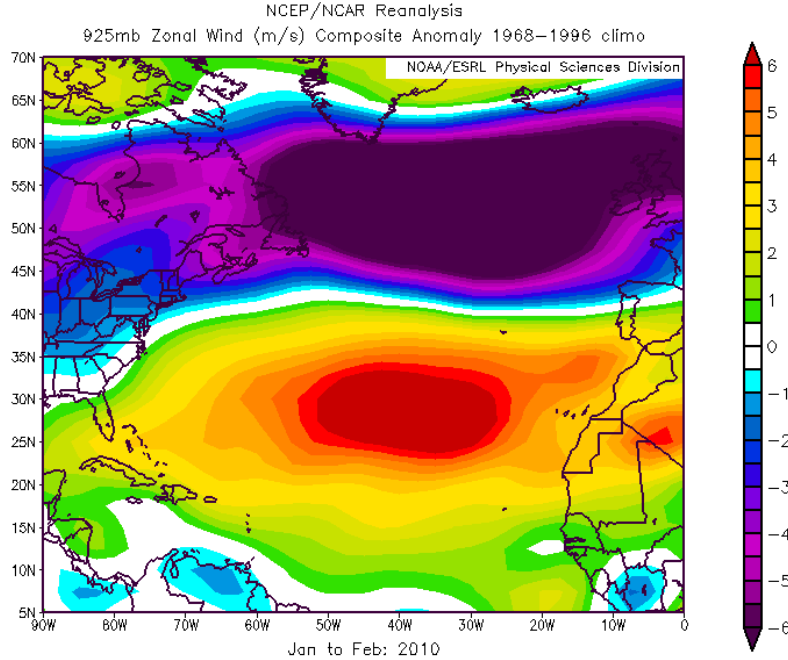


Figure 11: Anomalous low-level wind observed during January-February 2010. Very strong westerly anomalies were observed over the tropical Atlantic, indicating a reduction in the easterly trade winds. Weaker trades typically warm the tropical Atlantic.

## 7 Adjusted 2010 Forecast

Table 7 shows our final adjusted early April forecast for the 2010 season which is a combination of our statistical scheme, our analog forecast and qualitative adjustments for other factors not explicitly contained in any of these schemes. Our statistical forecast calls for an approximately average season, while our analog forecast is calling for a very active season. We foresee an active Atlantic basin hurricane season.

We have increased our early April forecast from our forecast of early December due to the considerable warming in tropical Atlantic SSTs along with an anticipated weakening of the current moderate El Niño.

Table 7: Summary of our early April statistical forecast, our analog forecast and our adjusted final forecast for the 2010 hurricane season.

Forecast Parameter and 1950-2000 Climatology (in parentheses)	Statistical Scheme	Analog Scheme	Adjusted Final Forecast
Named Storms (9.6)	10.0	16.2	15
Named Storm Days (49.1)	48.7	86.1	75
Hurricanes (5.9)	5.9	10.2	8
Hurricane Days (24.5)	23.0	42.1	35
Major Hurricanes (2.3)	2.4	4.6	4
Major Hurricane Days (5.0)	5.6	10.5	10
Accumulated Cyclone Energy Index (96.1)	93	173	150
Net Tropical Cyclone Activity (100%)	102	183	160

## 8 Landfall Probabilities for 2010

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 accurately forecast months in advance, the total seasonal probability of landfall can be forecast with statistical skill. With the observation that, statistically, 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 20<sup>th</sup> 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 8). 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 8: 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 9 lists strike probabilities for the 2010 hurricane season for different TC categories for the entire U.S. coastline, the Gulf Coast and the East Coast including the Florida peninsula. In our early June forecast of 2009, we debuted probabilities for various islands and landmasses in the Caribbean and in Central America. Note that Atlantic basin NTC activity in 2010 is expected to be above its long-term average of 100, and therefore, landfall probabilities are above their long-term average.

Please 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. The probability of each U.S. coastal state being impacted by hurricanes and major hurricanes is also included. In addition, we now include probabilities of named storms, hurricanes and major hurricanes tracking within 50 and 100 miles of various islands and landmasses in the Caribbean and Central America.

Table 9: 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 2010. 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%)	84% (68%)	69% (52%)	95% (84%)	99% (97%)
Gulf Coast (Regions 1-4)	76% (59%)	59% (42%)	44% (30%)	77% (60%)	94% (83%)
Florida plus East Coast (Regions 5-11)	67% (50%)	60% (44%)	45% (31%)	78% (61%)	93% (81%)
Caribbean (10-20°N, 60-88°W)	94% (82%)	74% (57%)	58% (42%)	89% (75%)	99% (96%)

## 9 Have Atmospheric CO<sub>2</sub> 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<sub>2</sub> levels with SST increases during the late 20<sup>th</sup> century and say that this has brought on higher levels of hurricane intensity.

These speculations that hurricane intensity has increased 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 15-year period of 1980-1994 (Figure 12) and the prior quarter-century period of 1970-1994. It has been tempting for many who do not have a strong background in hurricane knowledge to jump on this recent 15-year increase in major hurricane activity as strong evidence of a human influence on hurricanes. It should be noted, however, that the last 15-year active major hurricane period of 1995-2009 has, however, not been more active than the earlier 15-year period of 1950-1964 when the Atlantic Ocean circulation conditions were similar to what has been observed in the last 15 years. These conditions occurred even though atmospheric CO<sub>2</sub> amounts were lower in the earlier period.

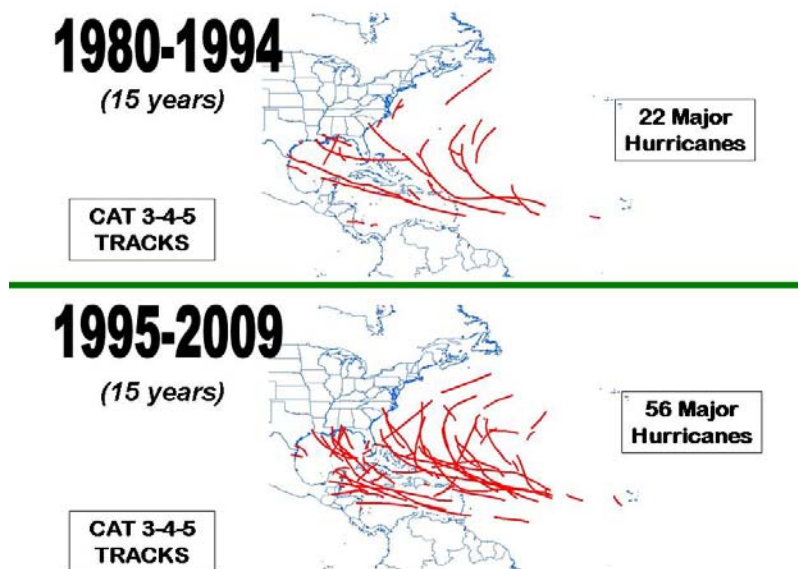


Figure 12: The tracks of major (Category 3-4-5) hurricanes during the 15-year period of 1995-2009 when the Atlantic thermohaline circulation (THC) was strong versus the prior 15-year period of 1980-1994 when the THC was weak. Note that there were more than 2.5 times as many major hurricanes when the THC was strong as when it was weak.

Table 10 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 (3.8) during strong vs. weak THC periods. Normalized U.S. hurricane damage studies by Pielke and Landsea (1998) show that landfalling major hurricanes account on average for about 80-85 percent of all hurricane destruction even though these major hurricanes make up only 20-25 percent of named storms.

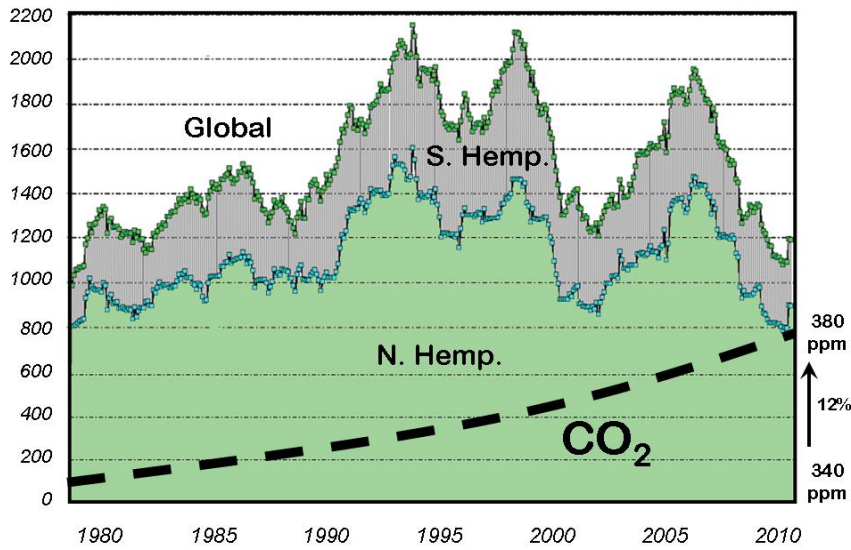
Although global surface temperatures increased during the late 20<sup>th</sup> century, there is no reliable data to indicate increased hurricane frequency or intensity in any of the globe's other tropical cyclone basins since 1979. Global Accumulated Cyclone Energy (ACE)

shows significant year-to-year and decadal variability over the past thirty years but no increasing trend (Figure 13). Similarly, Klotzbach (2006) found no significant change in global TC activity during the period from 1986-2005.

Table 10. Comparison of Atlantic basin hurricane activity in two 15-year periods when the Atlantic Ocean THC (or AMO) was strong versus an intermediate period (1970-1994) when it was weak.

	THC	SST (10-15°N; 70-40°W)	Avg. CO <sub>2</sub> ppm	NS	NSD	H	HD	MH	MHD	ACE	NTC
1950-1964 (15 years)	Strong	27.93	320	9.9	53.6	6.5	30.5	3.8	9.8	122	134
1970-1994 (25 years)	Weak	27.60	345	9.3	41.9	5.0	16.0	1.5	2.5	68	75
1995-2009 (15 years)	Strong	27.97	372	14.5	73.9	7.7	31.9	3.7	9.2	140	151
Year Ratio Strong/Weak THC		Δ 0.35°C	~ 0	1.3	1.5	1.4	1.6	2.5	3.8	1.9	1.9

TC ACCUMULATED CYCLONE ENERGY (24-month Running Sums)



Adapted from Ryan N. Maue

Figure 13: Northern Hemisphere, Southern Hemisphere, and global ACE over the period from 1979-2009. Figure has been adapted from Ryan Maue, Center for Ocean-Atmospheric Prediction Studies, Florida State University.

**Causes of 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 Atlantic Ocean thermohaline circulation (THC) (Figure 14). 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 sea surface temperature anomaly (SSTA) in the North Atlantic (Figure 15) 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 at water temperatures near freezing. There is a strong association between North Atlantic SSTA and North Atlantic salinity (Figure 16). 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 Grossman and Klotzbach (2009) for more discussion.

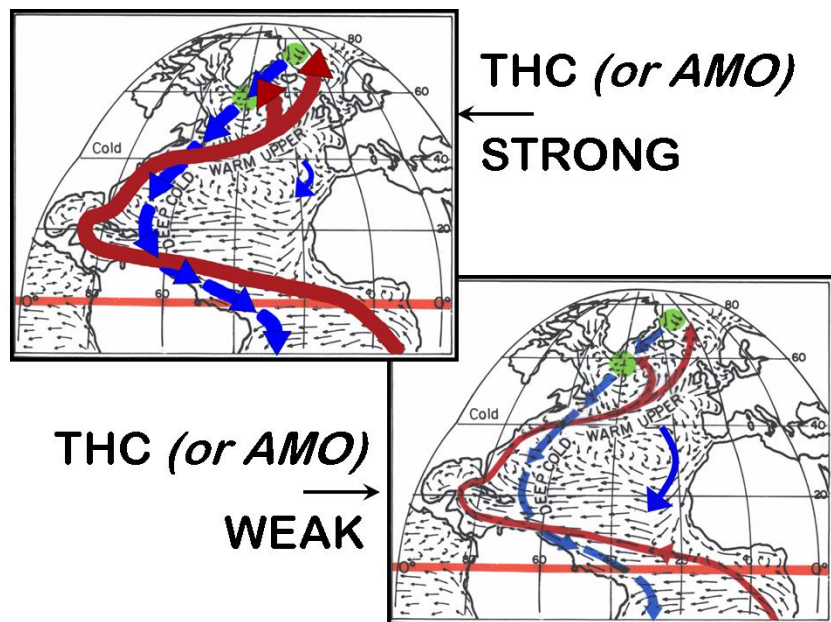


Figure 14: Illustration of strong (top) and weak (bottom) phases of the THC or AMO.

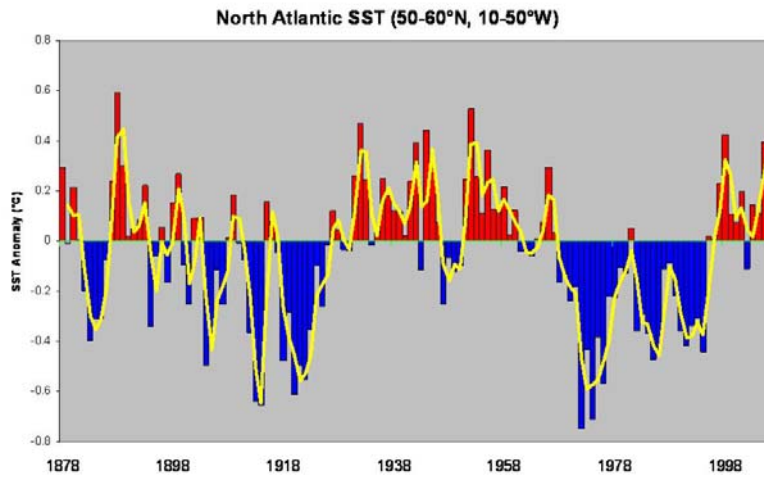


Figure 15: Long-period portrayal (1878-2006) of North Atlantic sea surface temperature anomalies (SSTA). The red (warm) periods are when the THC (or AMO) is stronger than average and the blue periods are when the THC (or AMO) is weaker than average.

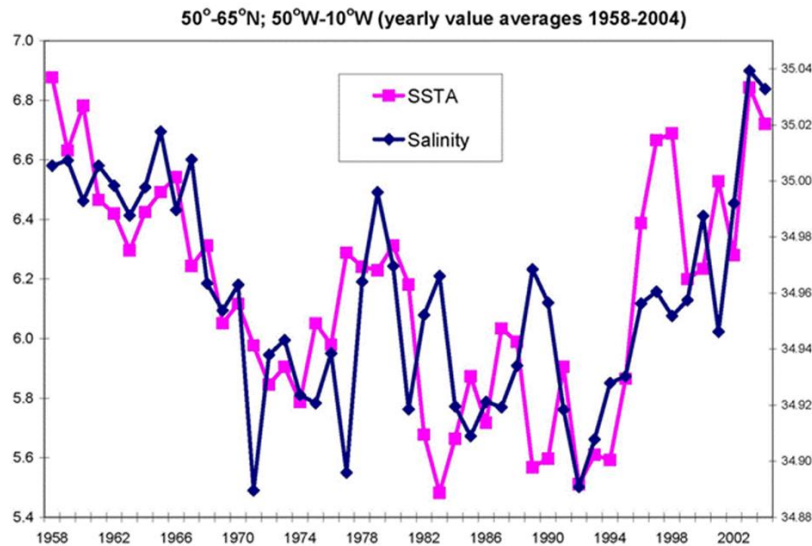


Figure 16: Illustration of the strong association of yearly average North Atlantic SSTA and North Atlantic salinity content between 1958 and 2004.

## B. WHY CO<sub>2</sub> 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 intensity potential. 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. When temperature and moisture conditions rise at both lower and upper levels, lapse rates are little effected (Figure 17).

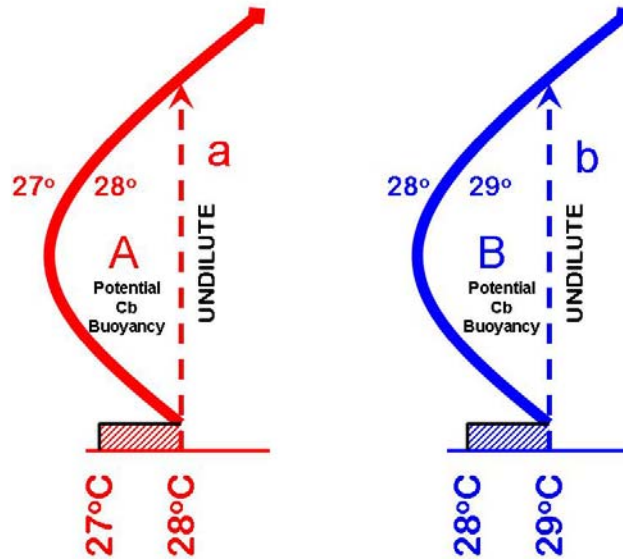


Figure 17: Illustration of how SST increases of 1°C will bring about higher planetary boundary layer (PBL) temperature and moisture increases that will also occur in small amounts throughout the troposphere. The combination of these changes is such that potential buoyancy for cumulonimbus (Cb) development is not much altered by increases in SST alone.

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 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 necessarily have more intense hurricanes due to lapse-rate alterations. We should not expect that the frequency and/or intensity of Category 4-5 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 19<sup>th</sup> century and the early part of the 20<sup>th</sup> century when SSTs were slightly lower.

**CO<sub>2</sub> Influence on Hurricane Activity.** We have been performing research with the International Satellite Cloud Climatology Project (ISCCP) and the NOAA National Centers for Environmental Prediction (NCEP) Reanalysis data sets. We have used this data to make an annual average of the global tropical (30°N-30°S; 0-360°) energy budget (Figure 18) for the years from 1984-2004. Note that the various surface and top of the atmosphere energy fluxes are very large. For the tropical surface, for instance, there are 637 Wm<sup>-2</sup> units of downward incoming solar and infrared (IR) energy. This downward energy flux is largely balanced by an upward surface energy flux of 615 Wm<sup>-2</sup> which is

due to upward fluxes from IR radiation, evaporated liquid water, and sensible heat. Similar large energy fluxes are present at the top of the atmosphere and within the troposphere.

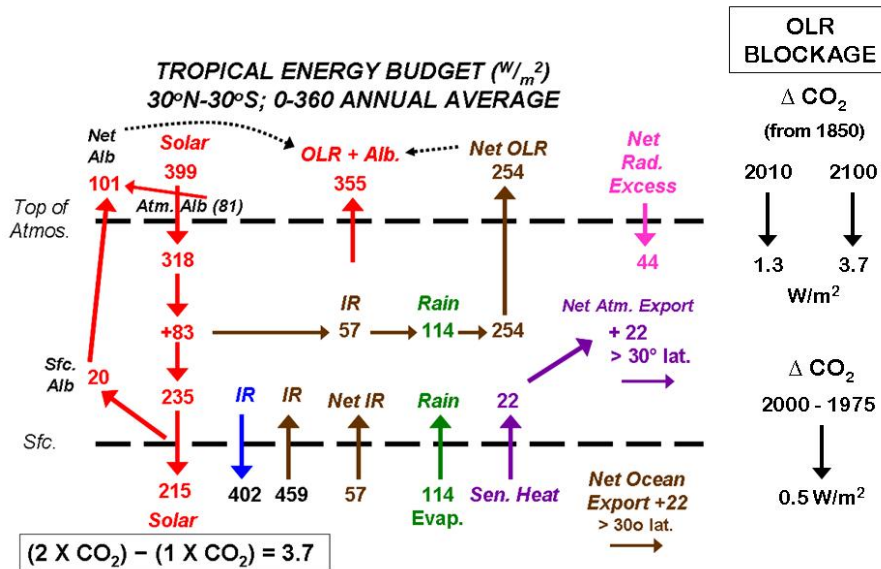


Figure 18: Vertical cross-section of the annual tropical energy budget as determined from a combination of ISCCP and NCEP Reanalysis data over the period of 1984-2004. Abbreviations are **IR** for longwave infrared radiation, **Alb** for albedo and **OLR** for outgoing longwave radiation. The tropics receives an excess of about  $44 \text{ Wm}^{-2}$  radiation energy which is convected and exported as sensible heat to latitudes poleward of  $30^\circ$ . Estimates are about half ( $22 \text{ Wm}^{-2}$ ) of this excess is transported by the atmosphere and the other half is transported by the oceans. Note, on the right, how small an OLR blockage has occurred up to now due to  $\text{CO}_2$  increases ( $\sim 1.3 \text{ Wm}^{-2}$ ) and the blockage of  $3.7 \text{ Wm}^{-2}$  that will occur from a doubling of  $\text{CO}_2$  by the end of this century.

It has been estimated that a doubling of  $\text{CO}_2$  (from the pre-industrial period) without any feedback influences would result in a blockage of OLR to space of about  $3.7 \text{ Wm}^{-2}$ . The currently-measured value of  $\text{CO}_2$  in the atmosphere is 380 parts per million by volume (ppmv). If we take the background pre-industrial value of  $\text{CO}_2$  to be 280 ppmv, then by theory we should currently be having (from  $\text{CO}_2$  increases alone) about  $(100/280) \times 3.7 = 1.3 \text{ Wm}^{-2}$  less OLR energy flux to space than was occurring in the mid-19<sup>th</sup> century.

This reduced OLR of  $1.3 \text{ Wm}^{-2}$  is very small in comparison with most of the other tropical energy budget exchanges. Slight changes in any of these other larger tropical energy budget components could easily negate or reverse this small  $\text{CO}_2$ -induced OLR blockage. For instance, an upper tropospheric warming of about  $1^\circ\text{C}$  with no change in moisture would enhance OLR sufficient that it would balance the reduced OLR influence from a doubling of  $\text{CO}_2$ . Similarly, if there were a reduction of upper level water vapor such that the long wave radiation emission level to space were lowered about 6 mb ( $\sim$



120 m) there would be an enhancement of OLR (with no change of temperature) sufficient to balance the suppression of OLR from a doubling of CO<sub>2</sub>. The 1.3 Wm<sup>-2</sup> reduction in OLR we have experienced since the mid-19<sup>th</sup> century (about one-third of the way to a doubling of CO<sub>2</sub>) is very small compared with the overall 399 Wm<sup>-2</sup> of solar energy impinging on the top of the tropical atmosphere and the mostly compensating 356 Wm<sup>-2</sup> of OLR and albedo energy going back to space. This 1.3 Wm<sup>-2</sup> energy gain (0.37% of the net energy returning to space) is much too small to ever allow a determination of its possible influence on TC activity. Any such potential CO<sub>2</sub> influence on TC activity is deeply buried as turbulence within the tropical atmospheres' many other energy components. It is possible that future higher atmospheric CO<sub>2</sub> levels may cause a small influence on global TC activity. But any such potential influence would likely never be able to be detected, given that our current measurement capabilities only allow us to assess TC intensity to within about 5 mph.

### C. CONTRAST OF THEORIES OF HURRICANE ACTIVITY CHANGES

**Theory of Human-Induced Increases due to Rising CO<sub>2</sub> Levels.** Those who think CO<sub>2</sub> increases have and will cause significant increases in hurricane activity believe that the physics of the CO<sub>2</sub>-hurricane association is directly related to radiation changes as indicated in Figure 19. They view CO<sub>2</sub> as blocking OLR to space. This acts to warm SSTs and add moisture to the boundary layer just above the ocean surface. These changes cause an increase in lapse rates (the lower levels warm while upper levels do not change much) which lead to more deep cumulonimbus convection (Cb). More Cb convection leads to a higher percentage of tropical disturbances forming into tropical cyclones and a greater spin-up of the inner-core of those systems which do form.

## DIRECT RADIATION HYPOTHESIS

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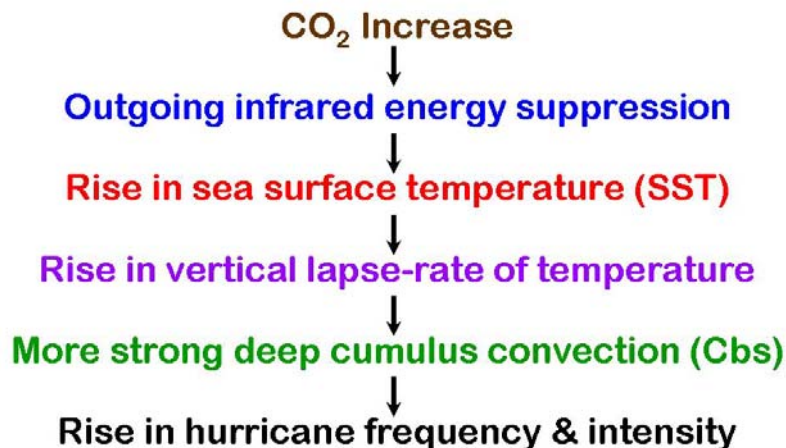


Figure 19: Physical linkage of those who believe that increases in CO<sub>2</sub> are making hurricanes more frequent and/or more intense.

This physical argument is too simplistic. It has no empirical verification in any other global TC basin except for the Atlantic. Table 11 shows the correlation of ACE with late summer-early fall SSTs in the Northeast Pacific, the Northwest Pacific and the Southern Hemisphere. Note the low (or even negative) correlations between ACE and SST in each of these three TC basins. It is obvious that other physical processes besides SST are primarily responsible for differences in hurricane activity in these basins.

Table 11. Correlation of ACE with late summer-early fall SSTs in three TC basins from 1980-2009.

	Yearly Mean ACE	ACE vs. SST Correlation (r)
Northeast Pacific	134	0.01
Northwest Pacific	310	-0.30
Southern Hemisphere	205	0.23
Globe (SST 20°N-20°S)	769	-0.08

**Theory of the THC (or AMO).** We do not view seasonal hurricane variability in the Atlantic as being directly related to changes in CO<sub>2</sub>-induced radiation forcing or to SST changes by themselves. For the Atlantic, we view long-period tropical cyclone variability primarily as a result of changes in the strength of the THC (or AMO). We hypothesize that these changes act as shown in Figure 20 and is discussed in the previous section. THC changes result in altering tropospheric vertical wind shear, trade wind strength, and SSTs in the Main Development Region (MDR) of 10-20°N; 20-70°W in the tropical Atlantic. A large component of the SST increase in this area is not a direct result of radiation differences but rather the combination of the effects of reduced southward advection of colder water in the east Atlantic and reduced trade wind strength. Weaker trade winds reduce upwelling and evaporation and typically act to increase SST.

The influence of the warmer Atlantic SST, as previously discussed, is not primarily to enhance lapse rates and Cb convection but rather as a net overall positive influence on lowering the MDR's surface pressure and elevating mean upward tropospheric vertical motion. This causes an increase in tropospheric moisture content.

## ATLANTIC OCEAN THC (or AMO) CHANGES

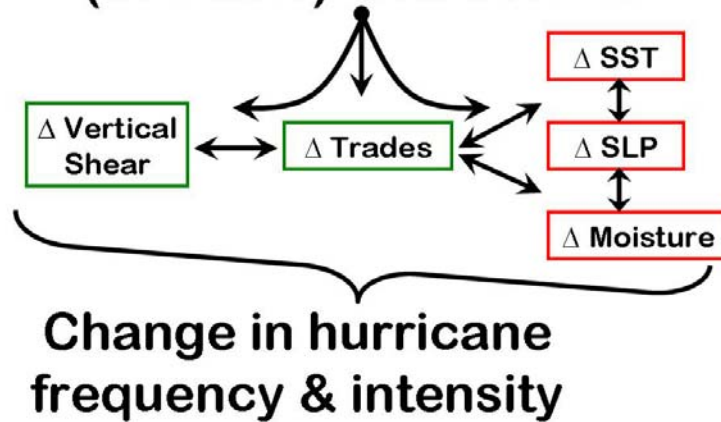


Figure 20: Idealized portrayal of how changes in the Atlantic THC bring about various parameter changes in the Atlantic's MDR. Vertical shear, trade-wind strength and SST are the key parameters which respond to THC changes. Favorable SLP and mid-level moisture changes occur in association with the shear, trade wind and SST changes.

### D. DISCUSSION

In a global warming or global cooling world, the atmosphere's upper air temperatures will warm or cool in unison with the SSTs. Vertical lapse rates will not be significantly altered. 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 21). Atlantic SSTs and hurricane activity do not follow global mean temperature trends.

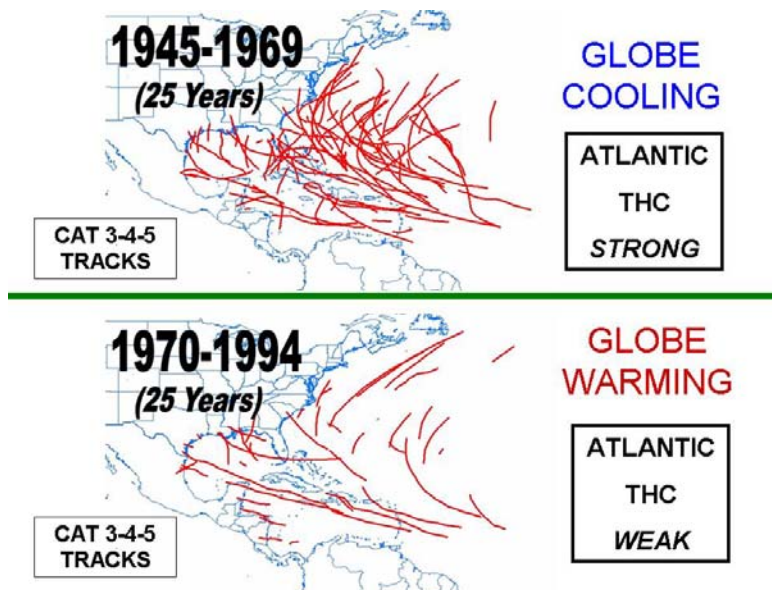


Figure 21: Tracks of major (Category 3-4-5) hurricanes during the 25-year period of 1945-1969 when the globe was undergoing a weak cooling versus the 25-year period of 1970-1994 when the globe was undergoing a modest warming. CO<sub>2</sub> amounts in the later period were approximately 18 percent higher than in the earlier period. Major Atlantic hurricane activity was only about one-third 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 12). Although global mean ocean and Atlantic SSTs have increased by about 0.4°C between these two 55-year periods (1900-1954 compared with 1955-2009), 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 44-year period of 1922-1965 (24 landfall events) and the 44-year period of 1966-2009 (7 landfall events) was especially large (Figure 22). For the entire United States coastline, 38 major hurricanes made landfall during the earlier 44-year period (1922-1965) compared with only 26 major hurricanes for the latter 44-year period (1966-2009). This occurred despite the fact that CO<sub>2</sub> averaged approximately 365 ppm during the latter period compared with 310 ppm during the earlier period.

Table 12: U.S. landfalling tropical cyclones by intensity during two 55-year periods.

<i>YEARS</i>	<i>Named Storms</i>	<i>Hurricanes</i>	<i>Major Hurricanes (Cat 3-4-5)</i>	<i>Global Temperature Increase</i>
1900-1954 (55 years)	208	113	44	+0.4°C
1955-2009 (55 years)	184	90	36	

We should not read too much into the three very active hurricane seasons of 2004, 2005, and 2008. 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.

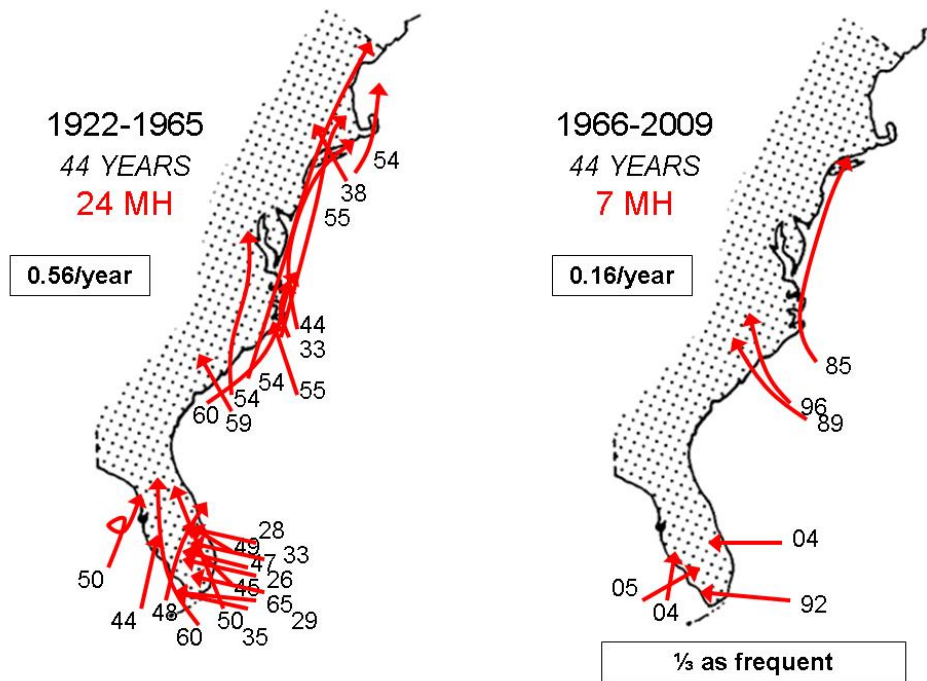


Figure 22: Contrast of tracks of East Coast and Florida Peninsula major landfalling hurricanes during the 44-year period of 1922-1965 versus the most recent 44-year period of 1966-2009.

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 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 to occur 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-19<sup>th</sup> century. Changes in the THC (or AMO) have been inferred from Greenland paleo ice-core temperature measurements going back thousand of years. These changes are natural and have nothing to do with human activity.

## **10 Forthcoming Updated Forecasts of 2010 Hurricane Activity**

We will be issuing seasonal updates of our 2010 Atlantic basin hurricane forecasts on **Wednesday 2 June and Wednesday 4 August**. We will also be issuing two-week forecasts for Atlantic TC activity during the climatological peak of the season from August-October. A verification and discussion of all 2010 forecasts will be issued in late November 2010. Our first seasonal hurricane forecast for the 2011 hurricane season will be issued in early December 2010. All of these forecasts will be available on the web at: <http://hurricane.atmos.colostate.edu/Forecasts>.

## **11 Acknowledgments**

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## 14 Verification of Previous Forecasts

Table 11: Summary verification of the authors' six previous years of seasonal forecasts for Atlantic TC activity between 2004-2009.

2004	5 Dec. 2003	Update 2 April	Update 28 May	Update 6 August	Obs.
Named Storms	13	14	14	13	15
Named Storm Days	55	60	60	55	93
Hurricanes	7	8	8	7	9
Hurricane Days	30	35	35	30	45.50
Major Hurricanes	3	3	3	3	6
Major Hurricane Days	6	8	8	6	22.25
Net Tropical Cyclone Activity	125	145	145	125	232
2005	3 Dec. 2004	Update 1 April	Update 31 May	Update 5 August	Obs.
Named Storms	11	13	15	20	28
Named Storm Days	55	65	75	95	131.50
Hurricanes	6	7	8	10	15
Hurricane Days	25	35	45	55	49.75
Major Hurricanes	3	3	4	6	7
Major Hurricane Days	6	7	11	18	17.75
Net Tropical Cyclone Activity	115	135	170	235	279
2006	6 Dec. 2005	Update 4 April	Update 31 May	Update 3 August	Obs.
Named Storms	17	17	17	15	10
Named Storm Days	85	85	85	75	52.75
Hurricanes	9	9	9	7	5
Hurricane Days	45	45	45	35	21.25
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.
Named Storms	14	17	17	15	15
Named Storm Days	70	85	85	75	37.75
Hurricanes	7	9	9	8	6
Hurricane Days	35	40	40	35	12.25
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.
Named Storms	13	15	15	17	16
Named Storm Days	60	80	80	90	88.25
Hurricanes	7	8	8	9	8
Hurricane Days	30	40	40	45	30.50
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.
Named Storms	14	12	11	10	9
Named Storm Days	70	55	50	45	30
Hurricanes	7	6	5	4	3
Hurricane Days	30	25	20	18	12
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