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

We continue to foresee well above-average activity for the 2011 Atlantic hurricane season. Our seasonal forecast has been reduced slightly from early December, since there is a little uncertainty about ENSO and the maintenance of anomalously warm tropical Atlantic SST conditions. We continue to anticipate an above-average probability of United States and Caribbean major hurricane landfall.

(as of 6 April 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
Named Storms (NS) (9.6)	17	16
Named Storm Days (NSD) (49.1)	85	80
Hurricanes (H) (5.9)	9	9
Hurricane Days (HD) (24.5)	40	35
Major Hurricanes (MH) (2.3)	5	5
Major Hurricane Days (MHD) (5.0)	10	10
Accumulated Cyclone Energy (ACE) (96.1)	165	160
Net Tropical Cyclone Activity (NTC) (100%)	180	175

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

1) Entire U.S. coastline - 72% (average for last century is 52%)

2) U.S. East Coast Including Peninsula Florida - 48% (average for last century is 31%)

3) Gulf Coast from the Florida Panhandle westward to Brownsville - 47% (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) 61% (average for last century is 42%)

ABSTRACT

Information obtained through March 2011 indicates that the 2011 Atlantic hurricane season will have significantly more activity 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 is estimated to be about 140 percent of the long-period average. We expect Atlantic basin Net Tropical Cyclone (NTC) activity in 2011 to be approximately 175 percent of the long-term average. We have decreased our seasonal forecast slightly from early December, due to anomalous warming in the eastern and central tropical Pacific and cooling in the tropical Atlantic.

This forecast is based on a new extended-range early April statistical prediction scheme that utilizes 29 years of past data. Analog predictors are also utilized. We expect current La Niña conditions to transition to near-neutral conditions during the heart of the hurricane season. Overall, conditions remain conducive for a very active hurricane season.

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 year. Our new early April statistical forecast methodology shows strong evidence over 29 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.

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 both 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 April forecast is based on a statistical methodology derived from 29 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.

2 April Forecast Methodology

2.1 New April Statistical Forecast Scheme

We have developed a new April statistical forecast model which we are using for the first time this year. This model has been built over the period from 1982-2010 to incorporate the most recent and reliable data that is available. It utilizes a total of four predictors. The new Climate Forecast System Reanalysis (CFSR) (Saha et al. 2010) has been completed from 1979-2009, while the NOAA Optimum Interpolation (OI) SST

(Reynolds et al. 2002) is available from 1982-present. The CFSR will begin to be updated in real-time later this year, but for the time being, we utilize the NCEP/NCAR Reanalysis for 2010 and 20ll values. This new model shows significant skill in predicting levels of Net Tropical Cyclone (NTC) activity over the 1982-2010 developmental period. The model correlates with NTC at 0.79 when all years are included in the model, while a drop-one cross-validation (jackknife) analysis yields a correlation with NTC of 0.68.

Table 1 displays cross-validated NTC hindcasts for 1982-2010 using the new statistical scheme, while Figure 1 displays observations versus cross-validated NTC hindcasts. We have correctly predicted above- or below-average seasons in 21 out of 29 hindcast years (72%). Our predictions have had a smaller error than climatology in 19 out of 29 years (66%). Our average hindcast error is 39 NTC units, compared with 55 NTC units for climatology. Figure 2 displays the locations of each of our predictors, while Table 2 displays the individual linear correlations between each predictor and NTC over the 1982-2010 hindcast period. All predictors correlate significantly at the 90% level using a two-tailed Student's t-test and assuming that each year represents an individual degree of freedom. The reader will note that we are incorporating a dynamical SST forecast from the European Centre for Medium-Range Weather Forecasts (ECMWF). Hindcast data provided by Frederic Vitart indicates that the ECMWF model has significant forecast skill for SSTs across the various Nino regions for September from a 1 March forecast date. We utilize the ECMWF ensemble mean prediction for September Nino 3 SSTs. Hindcast data from 1982-2010 show that the ECMWF forecast from 1 March correlates with observed September Nino 3 SSTs at 0.63. Table 3 displays the 2011 observed values for each of the four predictors in the new statistical forecast scheme.

Table 1: Observed versus early April cross-validated hindcast NTC for 1982-2010 using our new forecast scheme. Average errors for cross-validated 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 21 out of 29 years (72%), while hindcast improvement over climatology occurred in 19 out of 29 years (66%). The hindcast has improved upon climatology in all but four years since 1993.

Year	Observed NTC	Hindcast NTC	Observed minus Hindcast	Observed minus Climatology	Hindcast improvement over Climatology
1982	38	**101**	-63	-62	**-1**
1983	31	20	11	-69	58
1984	80	**163**	-82	-20	**-63**
1985	106	**60**	45	6	**-40**
1986	37	32	5	-63	58
1987	46	71	-25	-54	29
1988	117	134	-17	17	0
1989	130	**96**	34	30	**-4**
1990	100	91	9	0	**-9**
1991	58	97	-39	-42	3
1992	67	20	47	-33	**-14**
1993	52	60	-8	-48	40
1994	35	71	-35	-65	29
1995	222	158	64	122	58
1996	192	189	3	92	89
1997	54	91	-38	-46	9
1998	169	166	3	69	66
1999	182	121	60	82	21
2000	134	154	-21	34	13
2001	135	113	22	35	13
2002	83	**136**	-53	-17	**-36**
2003	175	139	36	75	39
2004	232	**89**	142	132	**-11**
2005	279	185	94	179	85
2006	85	**139**	-54	-15	**-39**
2007	99	**135**	-36	-1	**-35**
2008	162	201	-39	62	24
2009	69	78	-9	-31	22
2010	195	235	-40	95	55
Average	**116**	**116**	**39**	**55**	**+16**

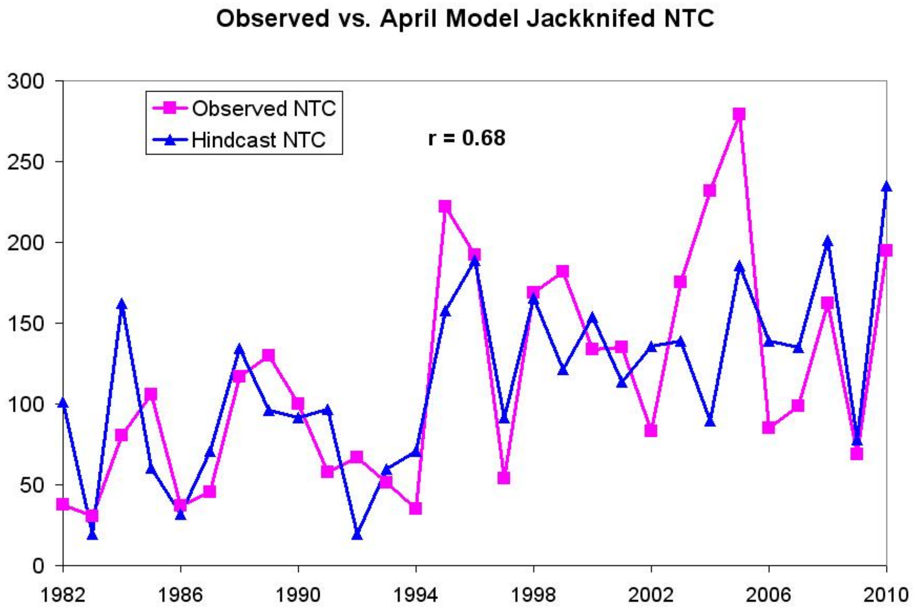


Figure 1: Observed versus early April jackknifed hindcast values of NTC for 1982-2010.

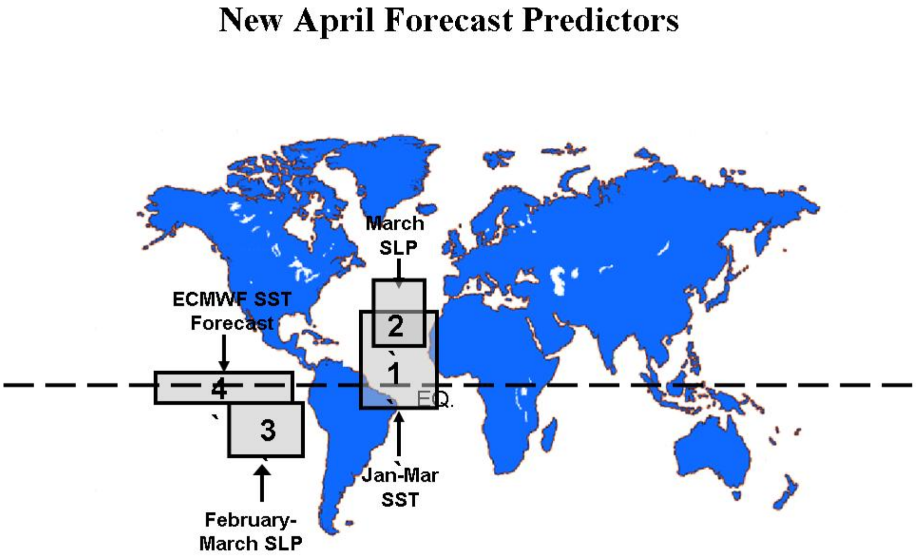


Figure 2: Location of predictors for our early April extended-range statistical prediction for the 2011 hurricane season.

Table 2: Linear correlation between each 1 April predictor and NTC over the 1982-2010 hindcast period.

Predictor	Correlation w/ NTC
1) January-March Atlantic SST (5°S-35°N, 10-40°W) (+)	0.60
2) March SLP (20-40°N, 20-35°W) (-)	-0.49
3) February-March SLP (5-20°S, 85-120°W) (+)	0.34
4) ECMWF 1 March SST Forecast for September Nino 3 (5°S-5°N, 90-150°W) (-)	-0.40

Table 3: Listing of 1 April 2011 predictors for the 2011 hurricane season. A plus (+) means that positive values of the parameter indicate increased hurricane activity.

Predictor	2011 Forecast Value
1) January-March Atlantic SST (5°S-35°N, 10-40°W) (+)	+1.2 SD
2) March SLP (20-40°N, 20-35°W) (-)	-0.1 SD
3) February-March SLP (5-20°S, 85-120°W) (+)	+1.4 SD
4) ECMWF 1 March SST Forecast for September Nino 3 (5°S-5°N, 90-150°W) (-)	-0.4 SD

2.2 Physical Associations among Predictors Listed in Table 2

The locations and brief descriptions of the predictors for our early April statistical forecast are now discussed. It should be noted that all predictors correlate with physical features during August through October that are known to be favorable for elevated levels of hurricane activity. These factors are generally 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.

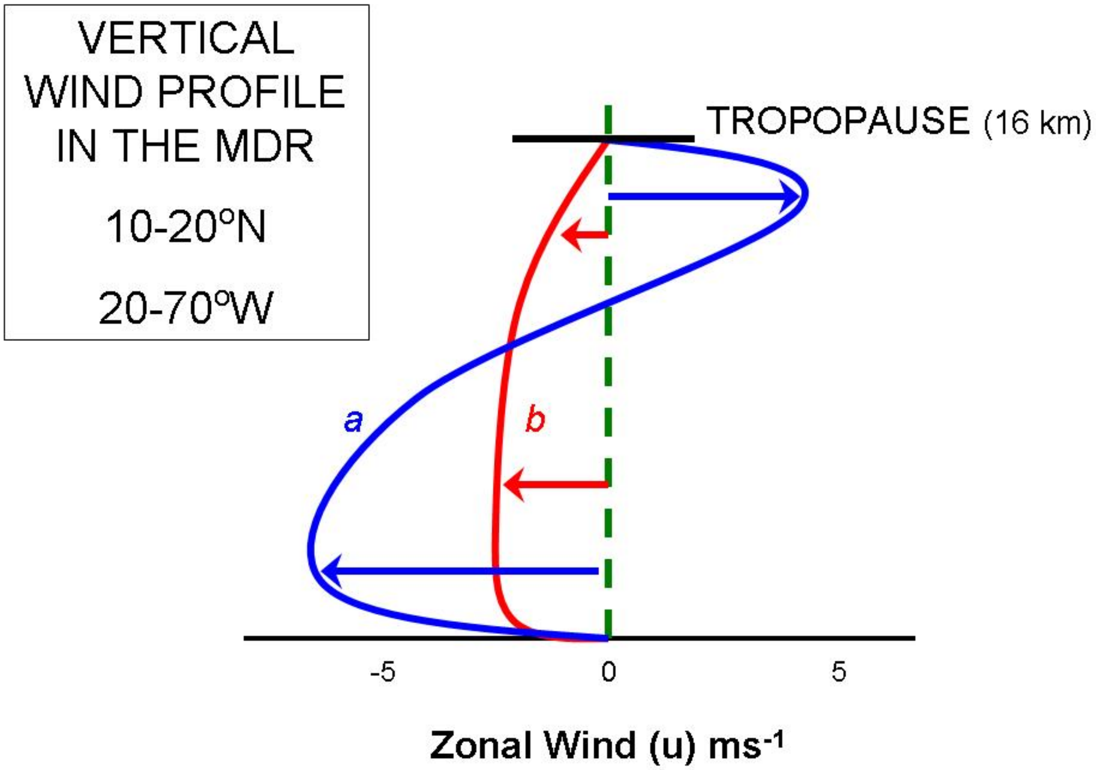


Figure 3: Vertical wind profile typically associated with (a) inactive Atlantic basin hurricane seasons and (b) active Atlantic basin hurricane seasons. Note that (b) has reduced levels of vertical wind shear.

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 850 mb zonal wind, respectively. In general, higher values of SSTS, lower values of SLPA, anomalous westerlies at 850 mb and anomalous easterlies at 200 mb are associated with active Atlantic basin hurricane seasons. SST correlations are displayed using the NOAA Optimum Interpolation (OI) SST, SLP and 850 mb zonal wind correlations are displayed using the Climate Forecast System Reanalysis (CFSR), while 200 mb zonal wind correlations are displayed using the NCEP/NCAR Reanalysis, as there are questions about the quality of the upper-level wind reanalysis in the CFSR.

Predictor 1. January-March SST in the Tropical and Subtropical Eastern Atlantic (+)

(5°S-35°N, 10-40°W)

Warmer-than-normal SSTs in the tropical and subtropical Atlantic during the January-March time period are associated with a weaker-than-normal subtropical high and reduced trade wind strength during the boreal spring (Knaff 1997). Positive SSTs in January-March are correlated with weaker trade winds and weaker 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. Predictor 1 correlates quite strongly (~0.6) with NTC. Predictor 1 also strongly correlates (r = 0.65) with August-October values of the Atlantic Meridional Mode (AMM) (Kossin and Vimont 2007) over the period from 1982-2010. 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 (-)

(20-40°N, 20-35°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 increased 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.

Predictor 3. February-March SLP in the southeastern tropical Pacific (+)

(5-20°S, 85-120°W)

High pressure in the southeastern tropical Pacific during the months of February-March correlates strongly with a positive Southern Oscillation Index and strong trades blowing across the eastern tropical Pacific. Strong trade winds help prevent eastward propagating Kelvin waves from transporting warmth from the western Pacific warm pool region and triggering El Niño conditions. During the August-October period, positive values of this predictor are associated with weaker trades, lower sea level pressures, and relatively cool SST anomalies in the eastern Pacific (typical of La Niña conditions) (Figure 6). The combination of these features is typically associated with more active hurricane seasons.

Predictor 4. ECMWF 1 March SST Forecast for September Nino 3 (-)

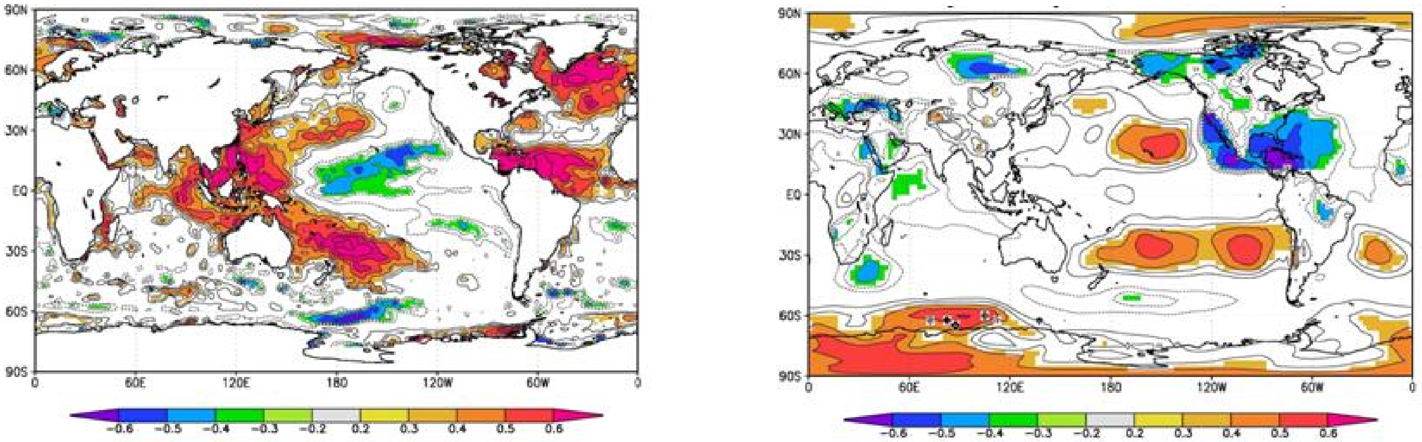
(5°S -5°N, 90-150°W)

The ECMWF seasonal forecast system 3 has shown skill at being able to forecast SST anomalies associated with ENSO several months into the future (Stockdale et al. 2011). ENSO has been documented in many studies to be one of the primary factors associated with interannual fluctuations in Atlantic basin and U.S. landfalling hurricane activity (Gray 1984, Goldenberg and Shapiro 1996, Bove et al. 1998, Klotzbach 2011), primarily through alterations in vertical wind shear patterns. The ensemble-averaged ENSO forecast for September values of the Nino 3 region from a 1 March issue date correlates with observations at 0.63, which is impressive considering as this forecast goes through the springtime predictability barrier, where fluctuations in ENSO lead to greatly reduced forecast skill. When the ECMWF model predicts cool SST anomalies for September, it strongly correlates with observed cool anomalies throughout the tropical Pacific associated with La Niña conditions, as well as reduced vertical wind shear, especially across the Caribbean (Figure 7).

August-October Correlations w/ Predictor 1

(a) SST

(b) SLP



(c) 850 mb U

(d) 200 mb U

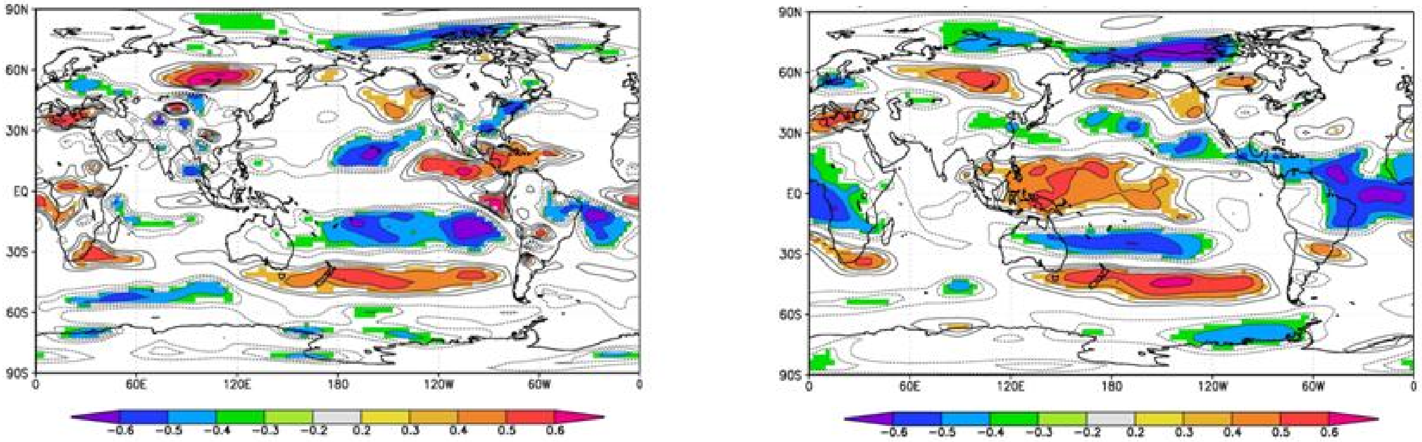


Figure 4: Linear correlations between January-March SST in the tropical and subtropical Atlantic (Predictor 1) and August-October sea surface temperature (panel a), August-October sea level pressure (panel b), August-October 850 mb zonal wind (panel c) and August-October 200 mb zonal wind (panel d). All four of these parameter deviations in the tropical Atlantic are known to be favorable for enhanced hurricane activity.

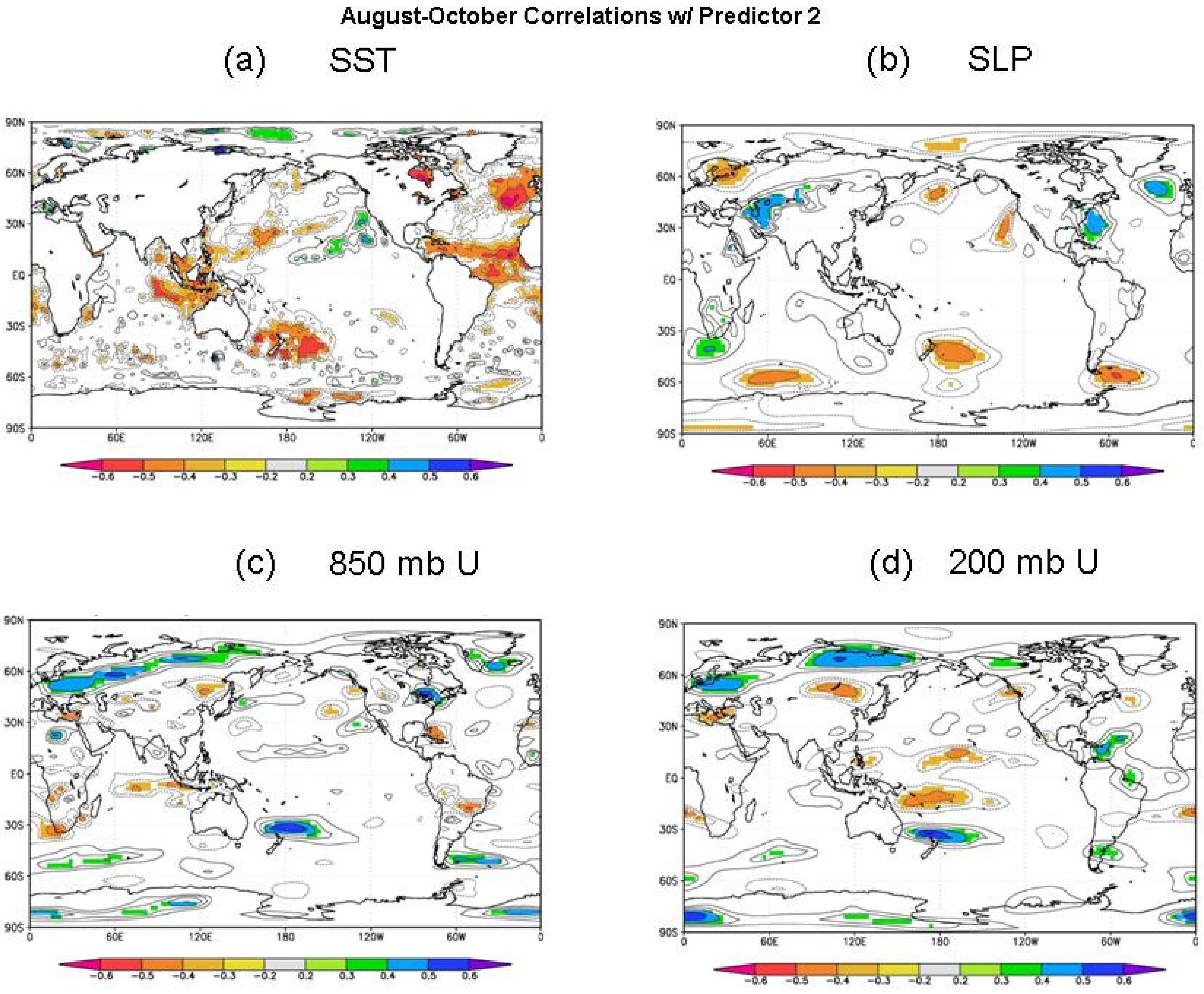


Figure 5: Linear correlations between March SLP in the subtropical Atlantic (Predictor 2) and August-October sea surface temperature (panel a), August-October sea level pressure (panel b), August-October 850 mb zonal wind (panel c) and August-October 200 mb zonal wind (panel d). The predictor's primary impact during the hurricane season appears to be with MDR-averaged SST. The correlation scale has been flipped to allow for easy comparison of correlations for all four predictors.

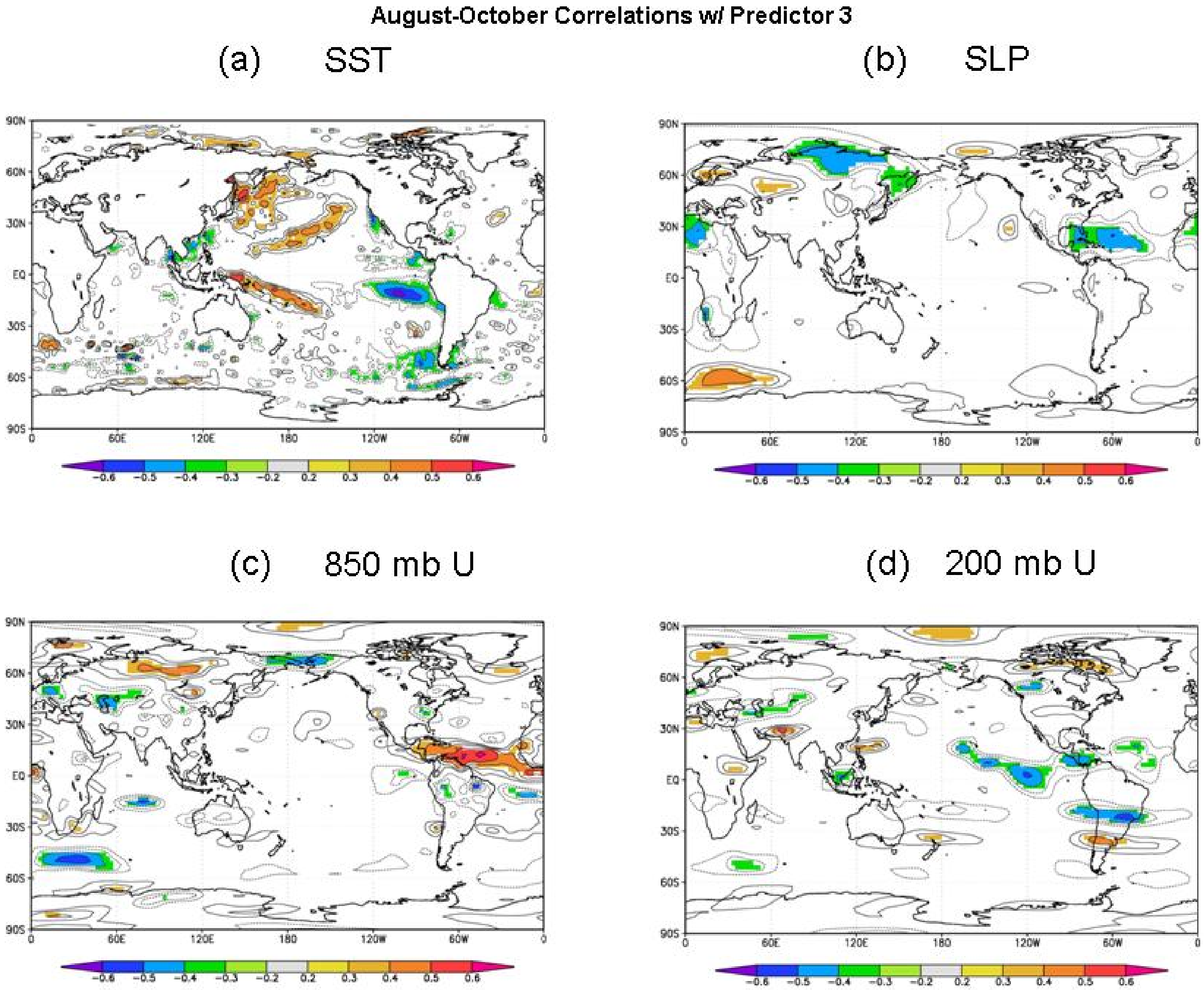
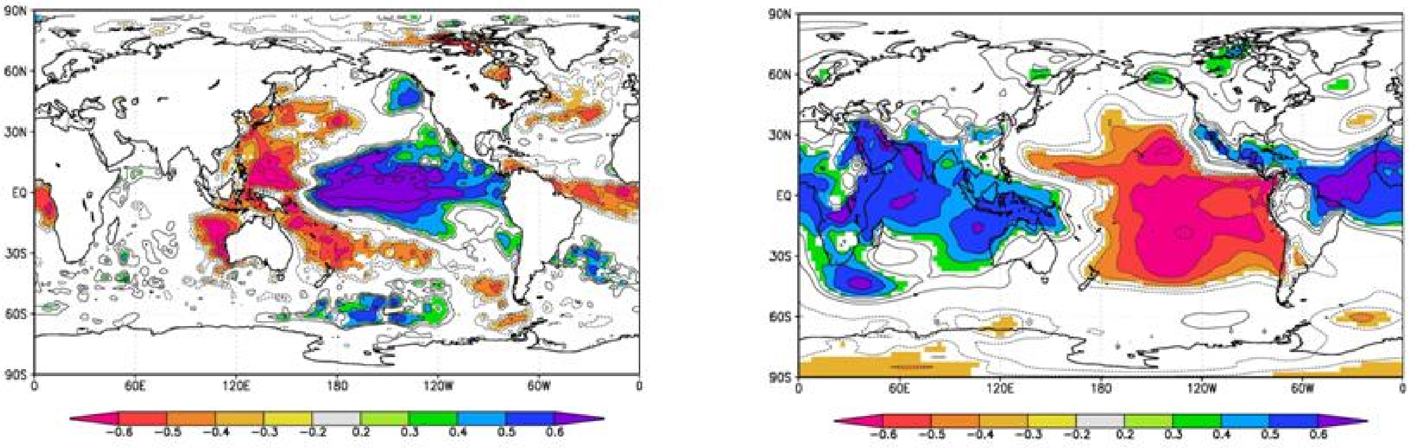


Figure 6: Linear correlations between February-March SLP in the southern tropical Pacific (Predictor 3) and August-October sea surface temperature (panel a), August-October sea level pressure (panel b), August-October 850 mb zonal wind (panel c) and August-October 200 mb zonal wind (panel d). The predictor's primary impacts appear to be on sea level pressure and trade wind strength across the tropical Atlantic.

August-October Correlations w/ Predictor 4 (1982-2010)

(a) SST (b) SLP



(c) 850 mb U (d) 200 mb U

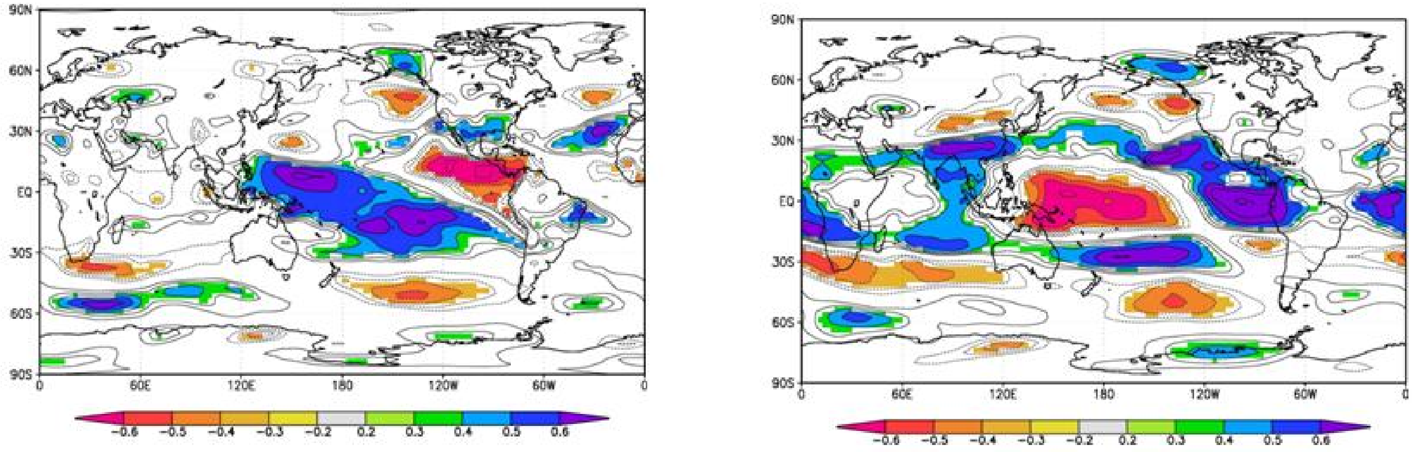


Figure 7: Linear correlations between a 1 March ECMWF SST forecast for September Nino 3 (Predictor 4) and August-October sea surface temperature (panel a), August-October sea level pressure (panel b), August-October 850 mb zonal wind (panel c) and August-October 200 mb zonal wind (panel d). The predictor correlates very strongly with ENSO as well as vertical shear in the Caribbean. The correlation scale has been flipped to allow for easy comparison of correlations for all four predictors.

3 Forecast Uncertainty

One of the questions that we are asked regarding our seasonal hurricane predictions is the degree of uncertainty that is involved. Our predictions are our best estimate, but 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 the 1982-2010 cross-validated hindcast error. 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 2011 hurricane forecast. Uncertainty ranges are given in one standard deviation (SD) increments.

Parameter	Hindcast Error (SD)	2011 Forecast	Uncertainty Range – 1 SD (67% of Forecasts Likely in this Range)
Named Storms (NS)	3.4	16	12.6 – 19.4
Named Storm Days (NSD)	21.5	80	58.5 – 101.5
Hurricanes (H)	2.4	9	6.6 – 11.4
Hurricane Days (HD)	12.7	35	22.3 – 37.7
Major Hurricanes (MH)	1.5	5	3.5 – 6.5
Major Hurricane Days (MHD)	5.5	10	4.5 – 15.5
Accumulated Cyclone Energy (ACE)	53	160	107 – 213
Net Tropical Cyclone (NTC) Activity	50	175	125 – 225

4 Analog-Based Predictors for 2011 Hurricane Activity

Certain years in the historical record have global oceanic and atmospheric trends which are similar to 2011. These years also provide useful clues as to likely trends in activity that the forthcoming 2011 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 2011 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 weak to moderate La Niña conditions and above-average tropical Atlantic and 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 2011. Four of these analog years (1955, 1996, 1999, and 2008) had either neutral or La Niña conditions during the hurricane season, and all four of these were active years. In 2006, February-March conditions were similar to February-March 2011, but that year experienced an unexpected El Niño which greatly reduced hurricane activity. We anticipate that the 2011 hurricane season will have slightly more activity than what was experienced in the average of these five years, due to the very active season predicted by our new statistical model. We believe that this season should experience well above-average activity.

Table 5: Best analog years for 2011 with the associated hurricane activity listed for each year.

Year	NS	NSD	H	HD	MH	MHD	ACE	NTC
1955	12	82.75	9	46.75	6	17.25	199	207
1996	13	79.00	9	45.00	6	13.00	166	192
1999	12	78.50	8	41.00	5	14.25	177	182
2006	10	52.75	5	21.25	2	2.00	79	85
2008	16	88.25	8	30.50	5	7.50	146	162
Average	12.6	76.3	7.8	36.9	4.8	10.8	153	166
2011 Forecast	**16**	**80**	**9**	**35**	**5**	**10**	**160**	**175**

5 ENSO

Moderate-to-strong La Niña conditions were in place during the winter of 2010-2011. This event has rapidly weakened in magnitude over the past couple of months, as warm sub-surface temperature anomalies have translated eastward associated with a Kelvin wave. Upper-ocean (top 300 meters) heat content anomalies in the eastern and central tropical Pacific have just recently become positive (Figure 8). From a climatological perspective, La Niña events tend to weaken during the late winter and early spring, although this event has weakened even more than the typical La Niña.

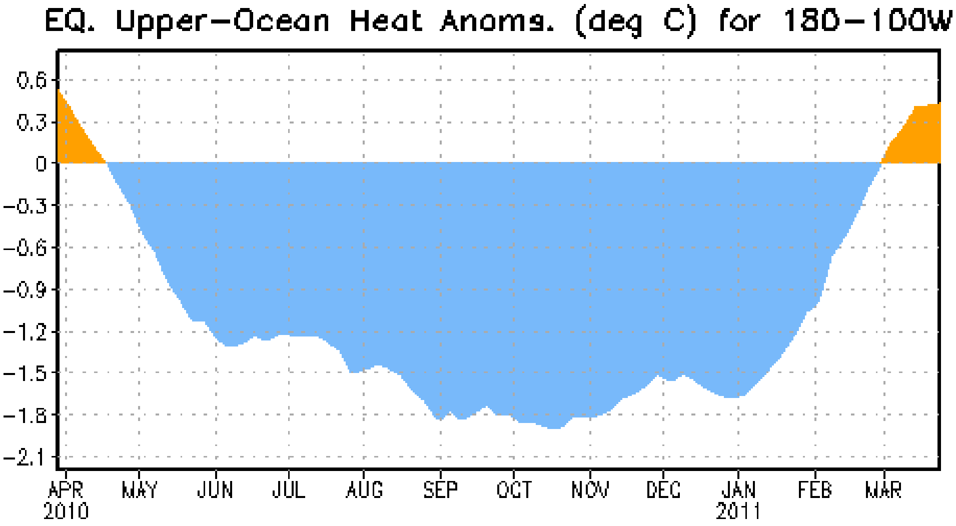


Figure 8: Central and eastern tropical Pacific upper ocean (0-300 meters) heat content anomalies over the past year. Note the significant warming of these anomalies that has occurred over the past three months.

Currently, SSTs are generally 0.5°C – 1.0°C below average across most of the eastern and central tropical Pacific. Table 6 displays January and March SST anomalies for several Nino regions. Note that most of the central and eastern tropical Pacific has experienced considerable warming 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	-0.4	-0.4	0.0
Nino 3	-1.3	-0.8	+0.5
Nino 3.4	-1.6	-1.0	+0.6
Nino 4	-1.6	-0.8	+0.8

There is considerable uncertainty as to what is going to happen with the current weak La Niña event. The spring months are known for their ENSO predictability barrier. 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. There is a very wide spread in both the statistical and dynamical model guidance for the August-October period (Figure 9). 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 correlation skill between a 1 March forecast from the ECMWF model and the observed September Nino 3.4 anomaly is 0.71, based on hindcasts/forecasts from 1982-2010, explaining half of the variance in Nino 3.4 SST. This is a very skillful forecast, considering that the prediction goes through the springtime predictability barrier. The average of the various ECMWF ensemble members is calling for a September Nino 3.4 SST anomaly of -0.3°C, giving us increased confidence in our neutral ENSO prediction for the upcoming hurricane season. Only one of the 41 ensemble members is calling for SSTs to approach El Niño levels (anomaly >= 0.5°C) for September (Figure 10).

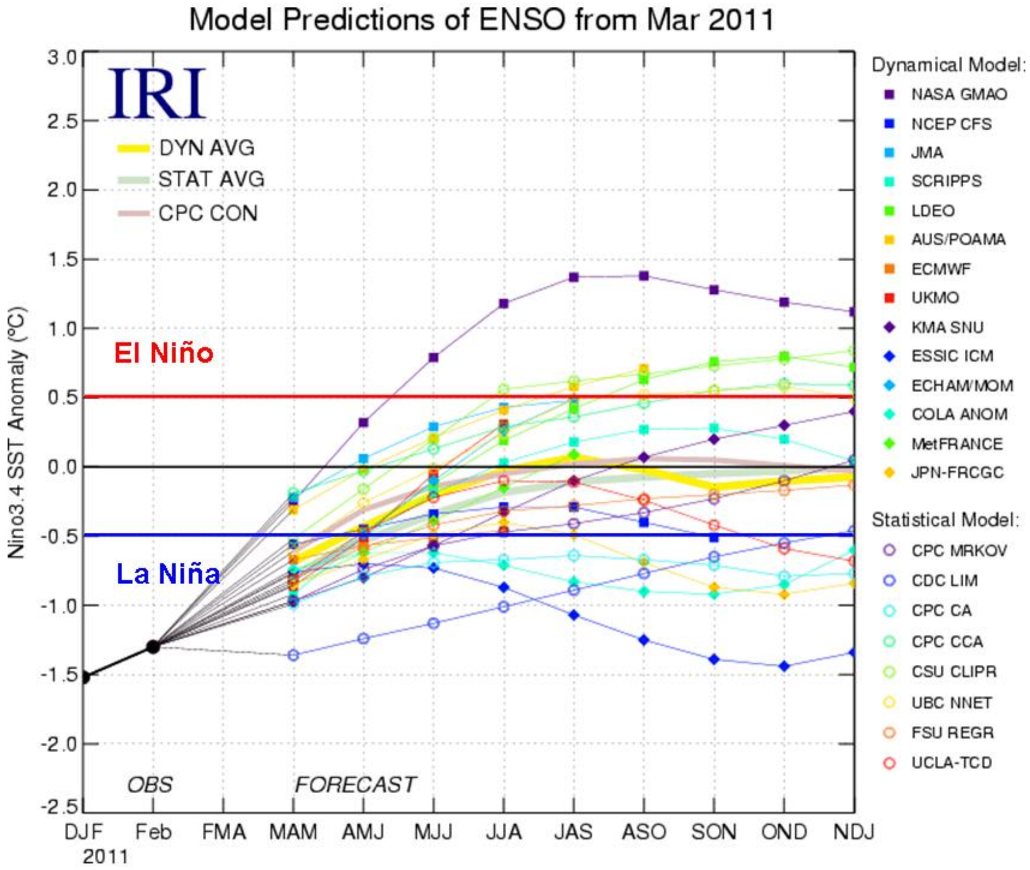


Figure 9: ENSO forecasts from various statistical and dynamical models. Figure courtesy of the International Research Institute (IRI). There is a very wide spread in the model guidance for the August-October period, with several models calling for either El Niño or La Niña conditions and the rest calling for neutral conditions.

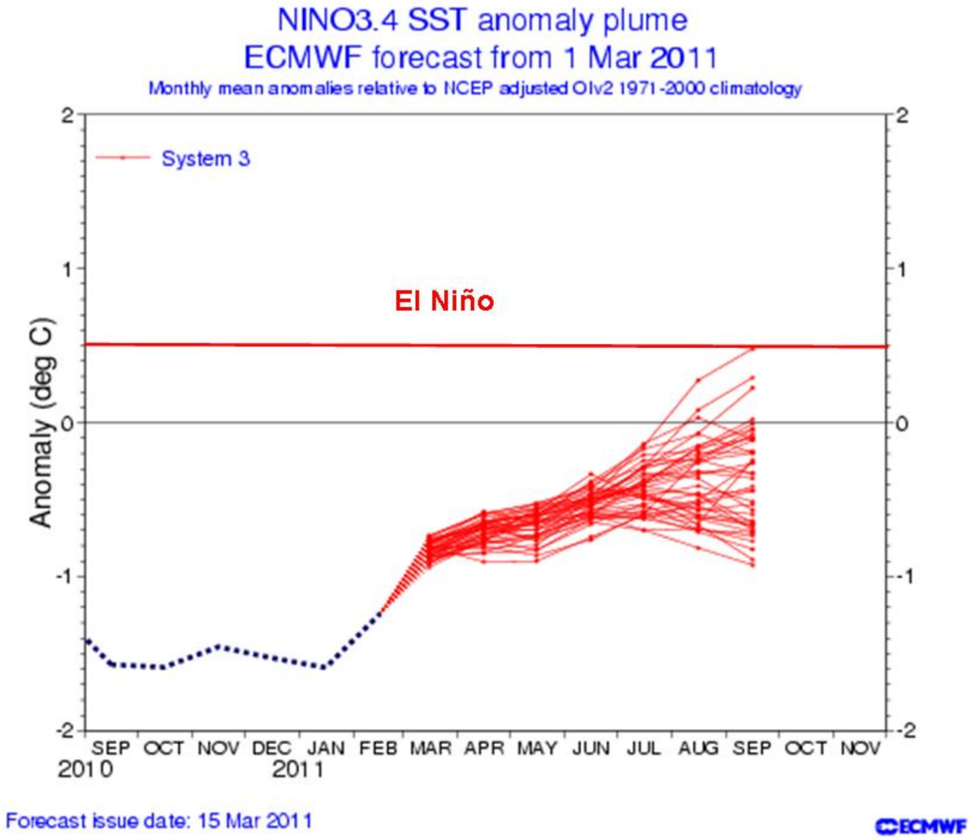


Figure 10: ECMWF ensemble model forecast for the Nino 3.4 region. Only one ensemble member has SSTs approaching El Niño conditions by September.

Another reason why we believe that we are not likely to see a rapid transition to El Niño is that the atmosphere is still in a La Niña-like state, with strongly positive values of the Southern Oscillation Index (SOI). The SOI is a normalized pressure differential between Tahiti and Darwin, Australia. When the SOI is positive, it implies strong trade winds across the tropical Pacific and overall, conditions typically associated with La Niña. Figure 11 displays the 30-day moving SOI since January 2009. Note the strong positive values of the SOI since August of last year.

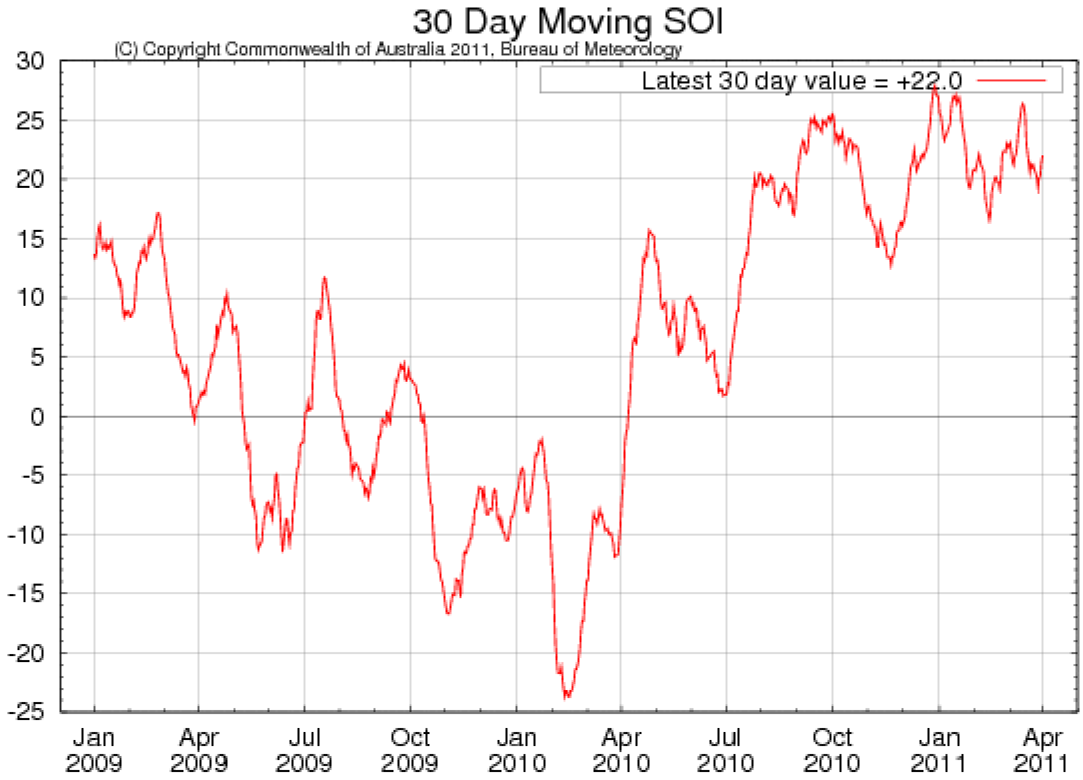


Figure 11: 30-day moving SOI since January 2009. Note how the SOI remains strongly positive, indicating that the tropical Pacific atmosphere is still responding like a well-developed La Niña is underway

Based on this information, our best estimate is that we will likely experience neutral ENSO conditions during the 2011 hurricane season. Since we expect to continue to see a warm tropical Atlantic (discussed in detail in the next section), we believe that ENSO will not be a significant detrimental factor for this year's hurricane season. However, there remains a need to closely monitor these conditions in the next few months. We should be more confident about ENSO conditions for the upcoming hurricane season by the time of our next forecast on June 1.

6 Current Atlantic Basin Conditions

Conditions in the Atlantic are favorable for an active season. SSTs across the tropical Atlantic remain at above-average levels (Figure 12). However, these anomalies have cooled somewhat over the past several months, likely due to a mid-winter switch from a negative phase of the North Atlantic Oscillation (NAO) to a positive phase of the NAO (Figure 13). A positive phase of the NAO is associated with anomalously strong trades across the tropical Atlantic, which promotes enhanced mixing and upwelling resulting in anomalous cooling. Figure 14 displays the cooling in SSTs observed in the tropical Atlantic from the latter part of March minus the latter part of January. The anomalous cooling has been on the wane over the past couple of weeks as the NAO has migrated back towards a neutral state. The atmospheric state across the tropical Atlantic looks quite favorable for an active season, as wind shear anomalies across the basin have been well below average over the past two months (Figure 15).

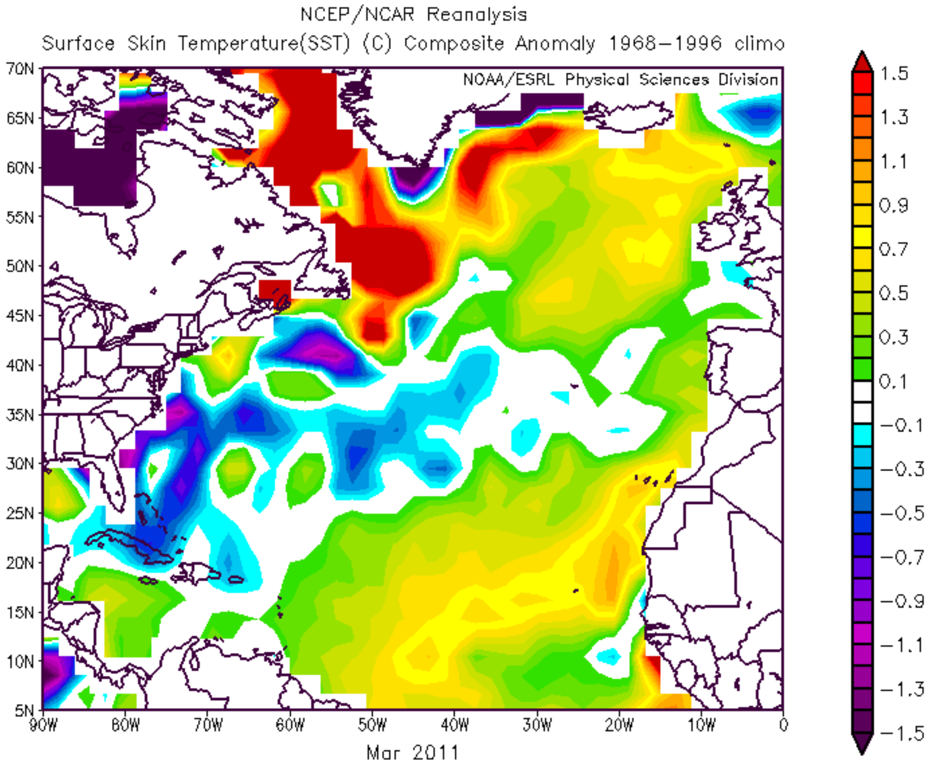


Figure 12: March 2011 SST anomaly pattern across the Atlantic Ocean.

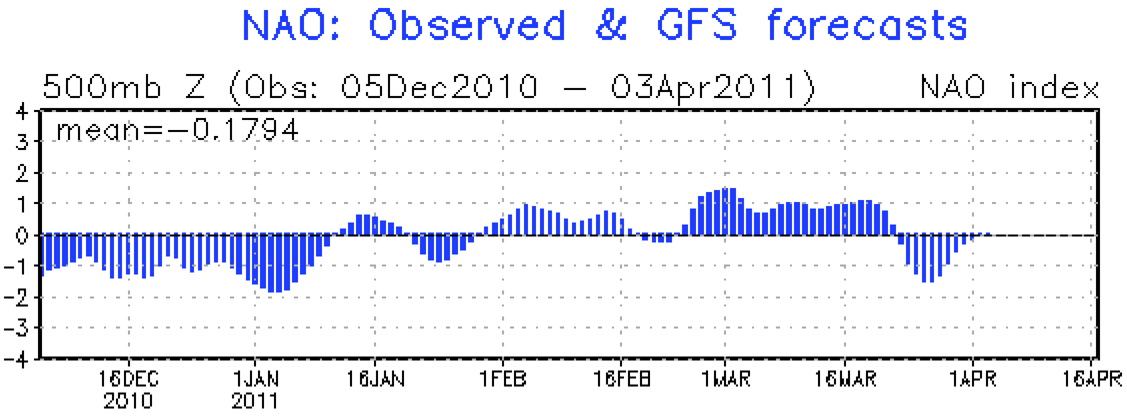


Figure 13: Observed NAO since December 2010. Note the change in NAO from a predominately negative phase through the middle of January to a predominately positive phase since that time.

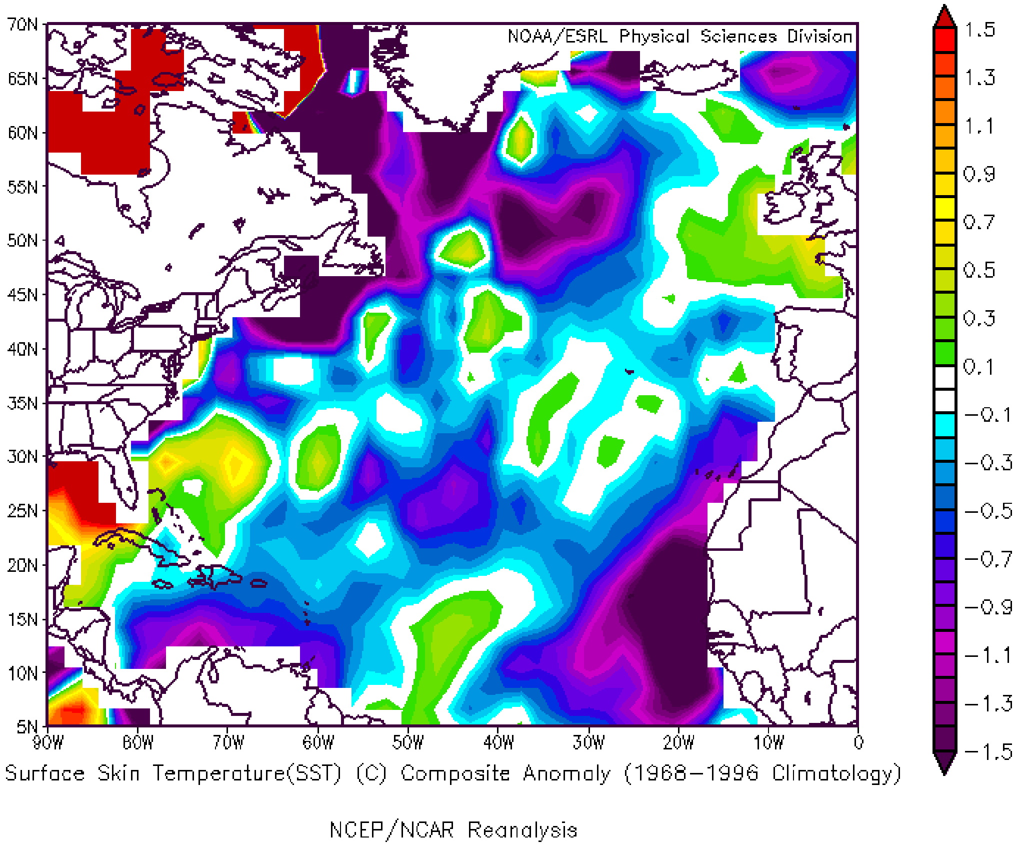


Figure 14: Late March 2011 – late January 2011 anomalous SST changes across the Atlantic Ocean. Note that anomalous cooling has taken place across most of the Atlantic.

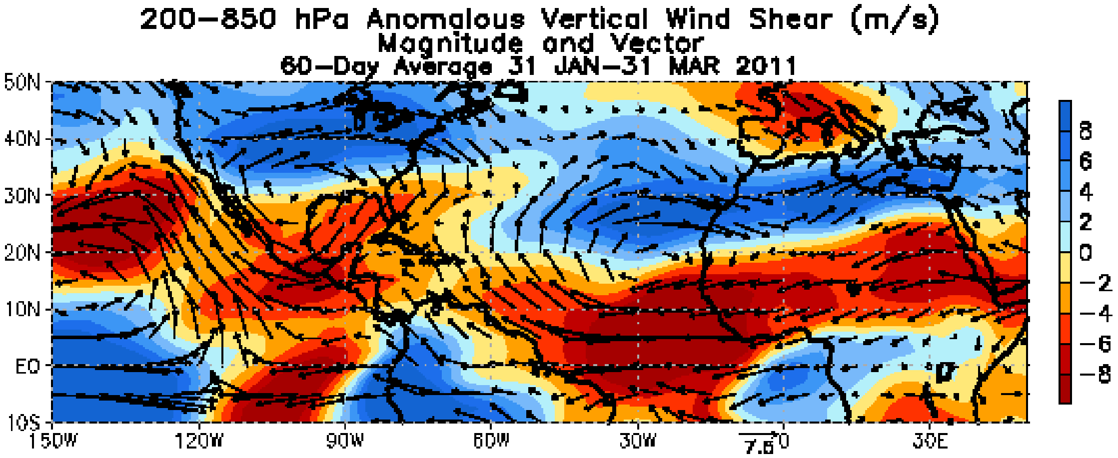


Figure 15: Anomalous 200-850 mb vertical wind shear from January 31 to March 31. Note the anomalously low vertical wind shear across the tropical Atlantic. Anomalies are calculated with respect to the 1971-2000 base period.

7 Adjusted 2011 Forecast

Table 7 shows our final adjusted early April forecast for the 2011 season which is a combination of our statistical scheme, our analog scheme and qualitative adjustments for other factors not explicitly contained in any of these schemes. Both our statistical and analog forecasts call for a very active Atlantic hurricane season.

We have reduced our forecast slightly from early December due to a combination of anomalous warming in the eastern and central tropical Pacific and anomalous cooling in the tropical Atlantic.

Table 7: Summary of our early April statistical forecast, our analog forecast and our adjusted final forecast for the 2011 hurricane season.

Forecast Parameter and 1950-2000 Climatology (in parentheses)	Statistical Scheme	Analog Scheme	Adjusted Final Forecast
Named Storms (9.6)	15.2	12.6	16
Named Storm Days (49.1)	85.7	76.3	80
Hurricanes (5.9)	9.5	7.8	9
Hurricane Days (24.5)	43.2	36.9	35
Major Hurricanes (2.3)	5.1	4.8	5
Major Hurricane Days (5.0)	13.4	10.8	10
Accumulated Cyclone Energy Index (96.1)	180	153	160
Net Tropical Cyclone Activity (100%)	192	166	175

8 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 accurately 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 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 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.

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. We suggest that all coastal residents visit the Landfall Probability Webpage for their individual probabilities.

As an example we find that the probability of Florida being hit by a major (Cat 3-4-5) hurricane this year is 34% 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 19%. For Duval County, the probability of being impacted by hurricane-force wind gusts is only 5%. 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 50%, 26%, and 8%, respectively.

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 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)	94% (79%)	86% (68%)	72% (52%)	96% (84%)	99% (97%)
Gulf Coast (Regions 1-4)	79% (59%)	62% (42%)	47% (30%)	80% (60%)	96% (83%)
Florida plus East Coast (Regions 5-11)	71% (50%)	64% (44%)	48% (31%)	81% (61%)	94% (81%)
Caribbean (10-20°N, 60-88°W)	95% (82%)	77% (57%)	61% (42%)	91% (75%)	99% (96%)

9 Has Global Warming 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 16) 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.

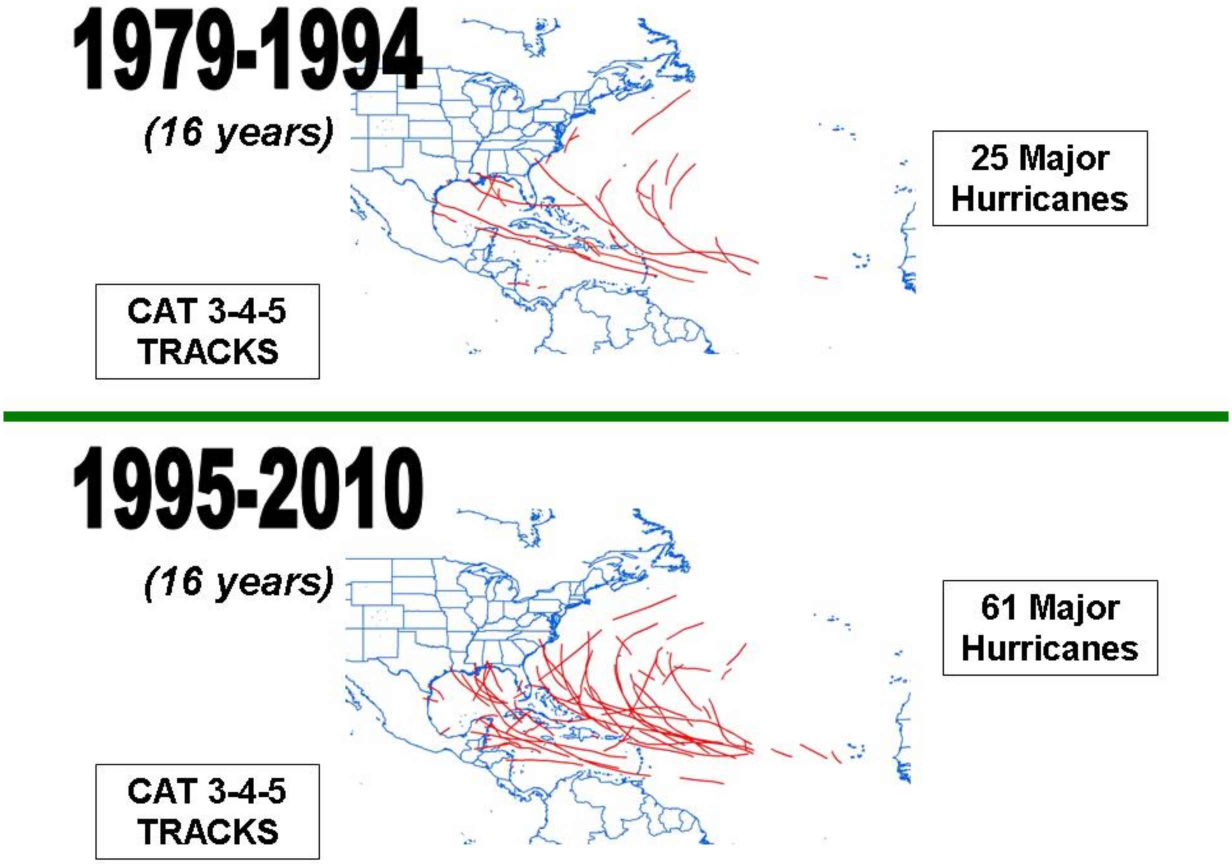


Figure 16: The tracks of major (Category 3-4-5) hurricanes during the 16-year period of 1995-2010 when the Atlantic thermohaline circulation (THC) was strong versus the prior 16-year period of 1979-1994 when the THC was weak. Note that there were approximately 2.5 times as many major hurricanes when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

Table 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 (3.7) 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 17). Similarly, Klotzbach (2006) found no significant change in global TC activity during the period from 1986-2005.

Table 10: 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

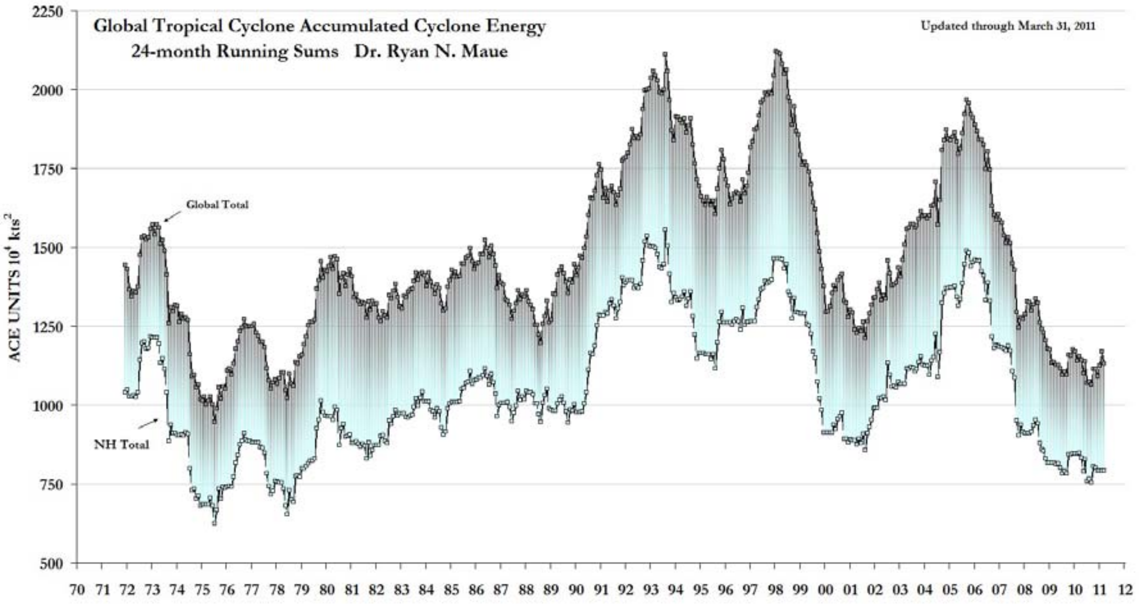


Figure 17: Northern Hemisphere and global Accumulated Cyclone Energy (ACE) over the period from December 1971-March 2011. Figure has been adapted from Ryan Maue, Center for Ocean-Atmospheric Prediction Studies, Florida State University.

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 18). 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 19) 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 20). 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.

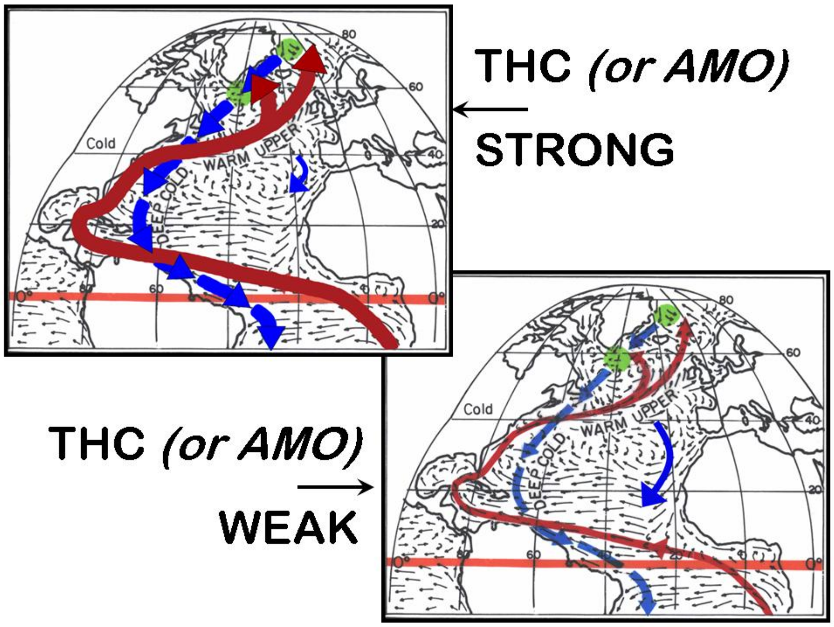


Figure 18: Illustration of strong (top) and weak (bottom) phases of the THC or AMO.

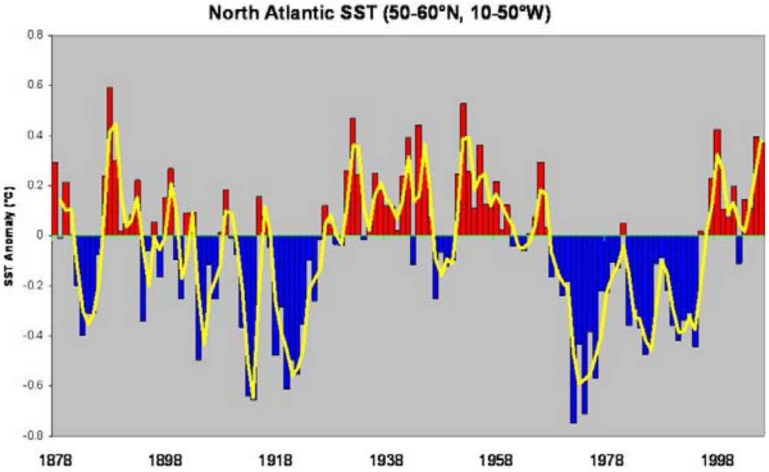


Figure 19: Long-period portrayal (1878-2006) of North Atlantic sea surface temperature anomalies (SSTA). The red (warm) periods are when the THC (or AMO) is stronger than average and the blue periods are when the THC (or AMO) is weaker than average.

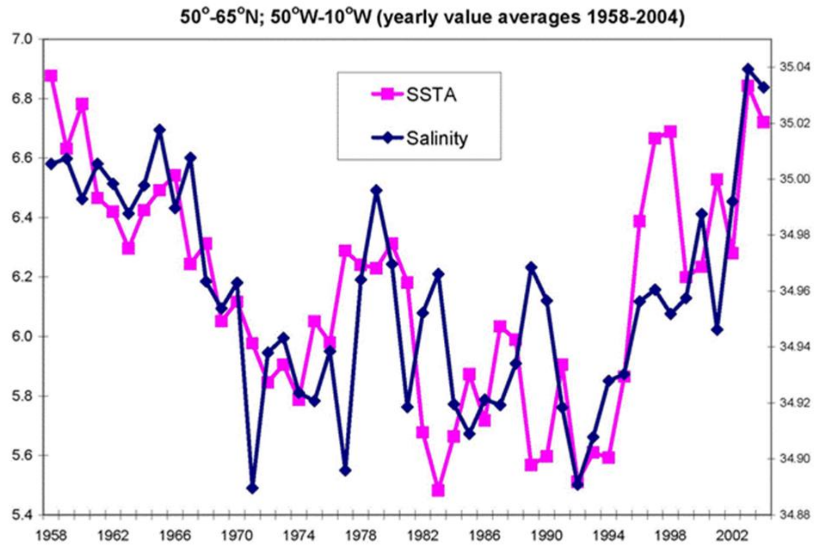


Figure 20: Illustration of the strong association of yearly average North Atlantic SSTA and North Atlantic salinity content between 1958 and 2004.

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.

CO_2 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/National Center for Atmospheric Research

(NCEP/NCAR) 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 21) 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^{-2} 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^{-2} 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.

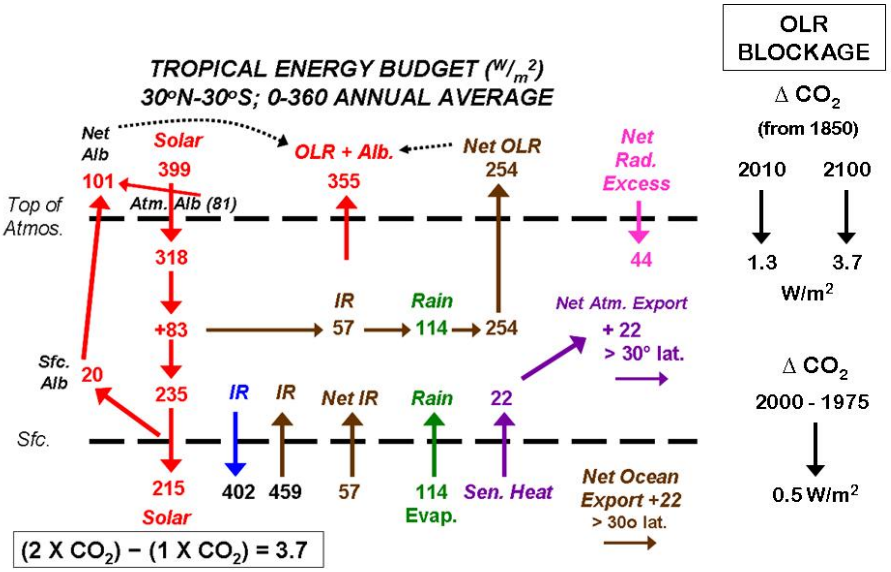


Figure 21: Vertical cross-section of the annual tropical energy budget as determined from a combination of ISCCP and NCEP/NCAR Reanalysis data over the period from 1984-2004. Abbreviations are **IR** for longwave infrared radiation, **Alb** for albedo and **OLR** for outgoing longwave radiation. The tropics receive an excess of about 44 Wm^{-2} radiation energy which is convected and exported as sensible heat to latitudes poleward of 30°. Estimates are about half (22 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 CO_2 increases (~ 1.3 Wm^{-2}) and a continued small blockage of 3.7 Wm^{-2} that will occur from a doubling of CO_2 by the end of this century.

It has been estimated that a doubling of CO_2 (from the pre-industrial period) without any feedback influences would result in a blockage of OLR to space of about 3.7 Wm^{-2}. The currently-measured value of CO_2 in the atmosphere is 385 parts per million by volume (ppmv). If we take the background pre-industrial value of CO_2 to be 285 ppmv, then by theory we should currently be having (from CO_2 increases alone) about (100/285)*3.7 = 1.3 Wm^{-2} less OLR energy flux to space than was occurring in the mid-19th century.

This reduced OLR of 1.3 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 CO_2-induced OLR blockage. For instance, an upper tropospheric warming of about 1°C with no change in moisture would enhance OLR sufficiently that it would balance the reduced OLR influence from a doubling of 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 by about 7 mb (~ 140 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_2. The 1.3 Wm^{-2} reduction in OLR we have experienced since the mid-19th century (about one-third of the way to a doubling of CO_2) is very small compared with the overall 399 Wm^{-2} of solar energy impinging on the top of the tropical atmosphere and the mostly compensating 356 Wm^{-2} of OLR and albedo energy going back to space. This 1.3 Wm^{-2} energy gain is much too small to ever allow a determination of its possible influence on TC activity. Any such potential CO_2 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_2 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. 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 22). Atlantic SSTs and hurricane activity do not follow global mean temperature trends.

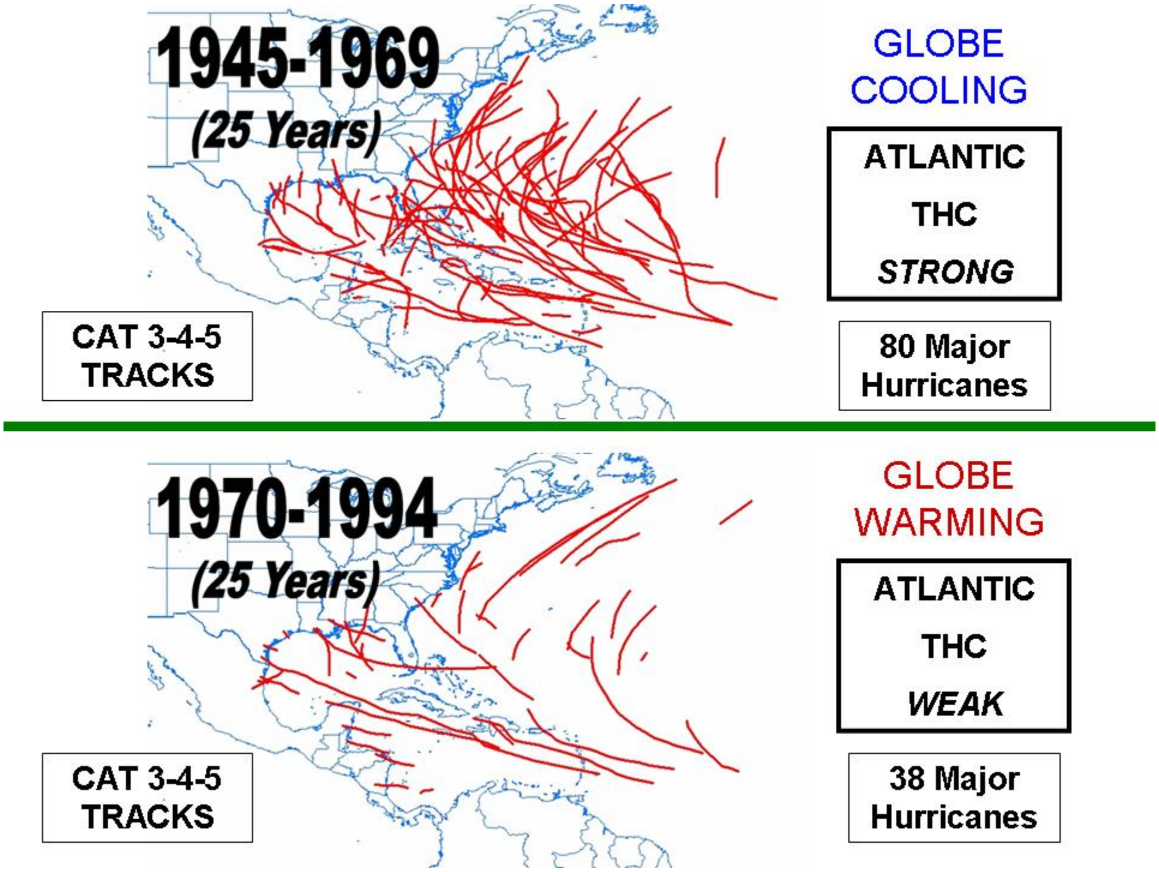


Figure 22: Tracks of major (Category 3-4-5) hurricanes during the 25-year period of 1945-1969 when the globe was undergoing a weak cooling versus the 25-year period of 1970-1994 when the globe was undergoing a modest warming. CO_2 amounts in the later period were approximately 18 percent higher than 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 11). 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 23). 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 11: 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.

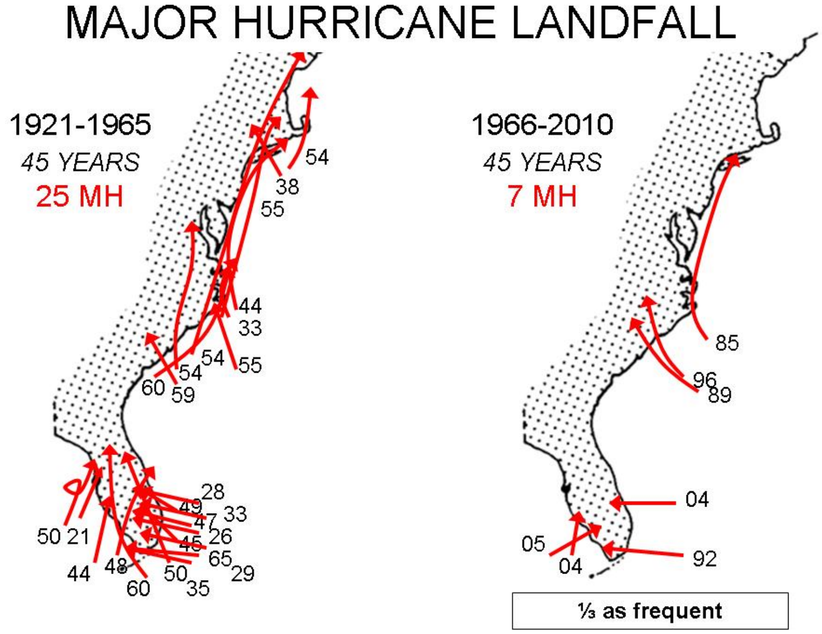


Figure 23: Contrast of tracks of East Coast and Florida Peninsula major landfalling hurricanes during the 45-year period of 1921-1965 versus the most recent 45-year period of 1966-2010.

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 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-19th 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 2011 Hurricane Activity

We will be issuing seasonal updates of our 2011 Atlantic basin hurricane forecasts on **Wednesday 1 June**, **and Wednesday 3 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 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.

11 Acknowledgments

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12 Citations and Additional Reading

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13 Verification of Previous Forecasts

Table 12: 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