EXTENDED RANGE FORECAST OF ATLANTIC SEASONAL HURRICANE ACTIVITY AND U.S. LANDFALL STRIKE PROBABILITY FOR 2006

We continue to foresee another very active Atlantic basin tropical cyclone season in 2006. Landfall probabilities for the 2006 hurricane season are well above their long-period averages.

(as of 4 April 2006)

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

with special assistance from William Thorson[3]

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 and Brad Bohlander, Colorado State University Media Representatives, (970-491-6432) are available to answer various questions about this forecast

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ATLANTIC BASIN SEASONAL HURRICANE FORECAST FOR 2006

Forecast Parameter and 1950-2000 Climatology (in parentheses)	Issue Date 6 December 2005	Issue Date 4 April 2006
Named Storms (NS) (9.6)	17	17
Named Storm Days (NSD) (49.1)	85	85
Hurricanes (H) (5.9)	9	9
Hurricane Days (HD) (24.5)	45	45
Intense Hurricanes (IH) (2.3)	5	5
Intense Hurricane Days (IHD) (5.0)	13	13
Net Tropical Cyclone Activity (NTC) (100%)	195	195

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

1) Entire U.S. coastline - 81% (average for last century is 52%)

2) U.S. East Coast Including Peninsula Florida - 64% (average for last century is 31%)

3) Gulf Coast from the Florida Panhandle westward to Brownsville - 47% (average for last century is 30%)

4) Above-average major hurricane landfall risk in the Caribbean

Notice of Author Changes

By William Gray

The order of the authorship of these forecasts has been reversed from Gray and Klotzbach to Klotzbach and Gray. After 22 years (since 1984) of making these forecasts, it is appropriate that I step back and have Phil Klotzbach assume the primary responsibility for our project's seasonal, monthly and landfall probability forecasts. Phil has been a member of my research project for the last five years and has been second author on these forecasts for the last four years. I have greatly profited and enjoyed our close personal and working relationships.

Phil is now devoting 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 five years ago. I foresee an outstanding future for him in the hurricane field. I expect he will make many new forecast innovations and skill improvements in the coming years. I plan to continue to be closely involved in the issuing of these forecasts for the next few years.

ABSTRACT

Information obtained through March 2006 continues to indicate that the 2006 Atlantic hurricane season will be much more active than the average 1950-2000 season. We estimate that 2006 will have about 9 hurricanes (average is 5.9), 17 named storms (average is 9.6), 85 named storm days (average is 49.1), 45 hurricane days (average is 24.5), 5 intense (Category 3-4-5) hurricanes (average is 2.3) and 13 intense hurricane days (average is 5.0). The probability of U.S. major hurricane landfall is estimated to be about 55 percent above the long-period average. We expect Atlantic basin Net Tropical Cyclone (NTC) activity in 2006 to be about 195 percent of the long-term average. This early April forecast is based on a newly devised extended range statistical forecast procedure which utilizes 52 years of past global reanalysis data. Analog predictors are also utilized. We have maintained our forecast from our early December prediction as the Atlantic Ocean, although cooling slightly with respect to climatology, remains anomalously warm and central and eastern tropical Pacific sea surface temperatures anomalies have continued to cool. Currently, weak La Niña conditions are observed. We expect either neutral or weak La Niña conditions to be present during the upcoming hurricane season.

Acknowledgment

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The second author gratefully acknowledges valuable input to his CSU 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.

DEFINITIONS

Atlantic Basin – The area including the entire North Atlantic Ocean, the Caribbean Sea, and the Gulf of Mexico.

El Niño – (EN) 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 estimated to have hurricane intensity winds.

Hurricane Destruction Potential – (HDP) A measure of a hurricane's potential for wind and storm surge destruction defined as the sum of the square of a hurricane's maximum wind speed (in 10^4 $knots^2$) for each 6-hour period of its existence.

Intense Hurricane - (IH) 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 (also termed a "major" hurricane).

Intense Hurricane Day – (IHD) Four 6-hour periods during which a hurricane has an intensity of Saffir/Simpson category 3 or higher.

Named Storm – (NS) A hurricane or a tropical storm.

Named Storm Day – (NSD) As in HD but for four 6-hour periods during which a tropical cyclone is observed (or is estimated) to have attained tropical storm intensity winds.

NTC – Net Tropical Cyclone Activity –Average seasonal percentage mean of NS, NSD, H, HD, IH, IHD. Gives overall indication of Atlantic basin seasonal hurricane activity.

ONR – Previous year October-November SLPA of subtropical Ridge in eastern Atlantic between 20-30°W.

QBO – Quasi-Biennial Oscillation – A stratospheric (16 to 35 km altitude) oscillation of equatorial east-west winds which vary with a period of about 26 to 30 months or roughly 2 years; typically blowing for 12-16 months from the east, then reversing and blowing 12-16 months from the west, then back to easterly again.

Saffir/Simpson (S-S) Category – 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.

SLPA – Sea Level Pressure Anomaly – The deviation of sea level pressure from observed long-term average conditions.

SOI – Southern Oscillation Index – A normalized measure of the surface pressure difference between Tahiti and Darwin.

SST(s) – Sea Surface Temperature(s)

SSTA(s) – Sea Surface Temperature(s) Anomalies

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 Storm – (TS) A tropical cyclone with maximum sustained winds between 39 (18 ms^{-1} or 34 knots) and 73 (32 ms^{-1} or 63 knots) miles per hour.

ZWA – Zonal Wind Anomaly – A measure of the upper level (~200 mb) west to east wind strength. Positive anomaly values mean winds are stronger from the west or weaker from the east than normal.

1 knot = 1.15 miles per hour = 0.515 meters per second

1 Introduction

This is the 23rd 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 52 years of past data and a separate study of analog years which have similar precursor circulation features to the current season. 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 tropical cyclone 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.

A variety of atmosphere-ocean conditions interact with each other to cause year-to-year and month-to-month hurricane variability. The interactive physical linkages between these many physical parameters and hurricane variability are complicated and cannot be well elucidated to the satisfaction of the typical forecaster making short range (1-5 days) predictions where changes in the momentum fields are the crucial factors. Seasonal and monthly forecasts, unfortunately, must deal with the much more complicated interaction of the energy-moisture fields with the momentum fields.

We find that there is a rather high (50-60 percent) degree of year-to-year hurricane forecast potential if one combines 4-5 semi-independent atmospheric-oceanic parameters together. The best predictors (out of a group of 4-5) 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 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 4-5 other predictors.

In a five-predictor empirical forecast model, the contribution of each predictor to the net forecast skill can only be determined by the separate elimination of each parameter from the full five predictor model while noting the hindcast skill degradation. When taken from the full set of predictors, one parameter may degrade the forecast skill by 25-30 percent, while another degrades the forecast skill by only 10-15 percent. An individual parameter that, through elimination from the forecast, degrades a forecast by as much as 25-30 percent may, in fact, by itself, show much less direct correlation with the predictand. A direct correlation of a forecast parameter may not be the best measure of the importance of this predictor to the skill of a 4-5 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. It follows that any seasonal or climate forecast scheme showing significant hindcast skill must be empirically derived. No one can completely understand the full complexity of the atmosphere-ocean system or develop a reliable scheme for forecasting the myriad non-linear interactions in the full-ocean atmosphere system.

2 Early April Forecast Methodology

Our initial early April seasonal hurricane forecast scheme demonstrated hindcast skill for the period of 1950-1995. Our new, recently developed early April forecast scheme uses more hindcast years (1950-2001) and shows improved hindcast skill and better physical insights into why such precursor relationships have an extended period memory.

Through extensive analysis of NOAA-NCEP reanalysis products, we have recently developed a new set of 1 April extended range predictors which shows superior hindcast prediction skill over our previous 1 April forecast scheme. The location of each of these new predictors is shown in Fig. 1. The pool of six predictors for this extended range forecast is given in Table 1. Strong statistical relationships can be extracted via combinations of these predictors (which are available by the end of March) and the amount of Atlantic basin hurricane activity occurring later in the year.

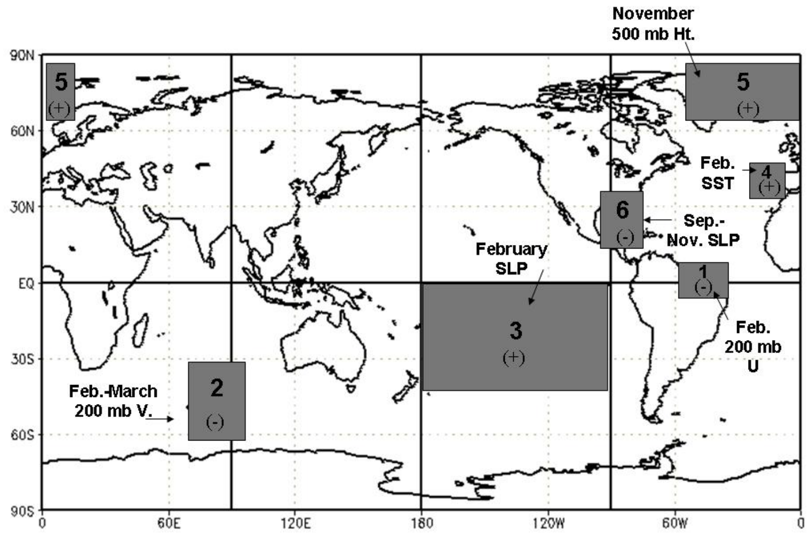

Figure 1: Location of predictors for the early April forecast for the 2006 hurricane season. A plus (+) means that positive values of the parameter indicate increased hurricane activity this year, and a minus (-) means that positive values of the parameter indicate decreased hurricane activity this year.

Table 1: Listing of 1 April 2006 predictors for this year's hurricane activity. A plus (+) means that positive values of the parameter indicate increased hurricane activity this year, and a minus (-) means that positive values of the parameter indicate decreased hurricane activity this year. The combination of these six predictors calls for an active hurricane season.

Predictor	Values for 2006 Forecast
1) February 200 mb U (5°S-10°N, 35-55°W) (-)	+0.6 SD
2) February-March 200 mb V (35-62.5°S, 70-95°E) (-)	+0.3 SD
3) February SLP (0-45°S, 90-180°W) (+)	-1.4 SD
4) February SST (35-50°N, 10-30°W) (+)	+1.2 SD
5) Previous November 500 MB Ht. (67.5-85°N, 50°W -10°E) (+)	+0.6 SD
6) Previous September-November SLP (15-35°N, 75-95°W) (-)	-1.4 SD

2.1 Physical Associations among Predictors Listed in Table 1

Brief descriptions of our early April predictors follow:

Predictor 1. February 200 mb U in Equatorial East Brazil (-)

(5°S-10°N, 35-55°W)

Easterly upper-level zonal wind anomalies off the northeast coast of South America imply that the upward branch of the Walker Circulation associated with ENSO remains in the western Pacific and that cool ENSO or La Niña conditions are likely to be present in the eastern equatorial Pacific for the next 4-6 months. El Niño conditions shift the upward portion of the Walker Circulation to the eastern Pacific and cause 200 mb westerly wind anomalies over the tropical Atlantic. These anomalies inhibit Atlantic hurricane activity.

Predictor 2. February-March 200 MB V in the Southern Indian Ocean (-)

(35-62.5°S, 70-95°E)

Anomalous winds from the north at 200 mb in the southern Indian Ocean are associated with a northeastward shift of the South Indian Convergence Zone (SICZ) (Cook 2000), a more longitudinally concentrated upward branch of the Hadley Cell near Indonesia and warm sea surface temperatures throughout most of the Indian Ocean. This also implies that warm ENSO conditions have likely been prevalent throughout the past several months due to the lag teleconnected effect of a warm Indian Ocean with a warm eastern Pacific Ocean. Strong lag correlations ($r > 0.4$) with this predictor indicate that a change in phase of ENSO from warm to cool is likely during the latter part of the spring/early summer.

Predictor 3. February SLP in the Southeast Pacific (+)

(0-45°S, 90-180°W)

High sea level pressure in the eastern Pacific south of the equator indicates a positive Southern Oscillation Index (SOI) and stronger-than-normal trade winds across the Pacific. Increased trades drive enhanced upwelling off the west coast of South America that is typical of La Niña and hurricane-enhancing conditions in the Atlantic. Cool sea surface temperatures in the eastern Pacific are associated with these higher surface pressures and tend to persist throughout the spring and summer thereby reducing vertical wind shear over the tropical Atlantic and providing more favorable conditions for tropical cyclone development.

Predictor 4. February SST off the Northwestern European Coast (+)

(35-50°N, 10-30°W)

Warm sea surface temperatures off the northwest coast of Europe correlate quite strongly with warm sea surface temperatures across the entire North Atlantic Ocean. A warm North Atlantic Ocean indicates that the thermohaline circulation is likely stronger than normal, the subtropical high near the Azores is weaker than normal and consequently trade wind strength across the Atlantic is also reduced. Weaker trade winds induce less upwelling which keeps the tropical Atlantic warmer than normal. This pattern tends to persist throughout the spring and summer implying a warmer tropical Atlantic during the hurricane season which is an enhancing factor for developing tropical waves.

Predictor 5. Previous November 500 MB Geopotential Height in the far North Atlantic (+)

(67.5-85°N, 50°W-10°E)

Positive values of this predictor correlate very strongly (r = -0.7) with negative values of the Arctic Oscillation (AO) and the North Atlantic Oscillation (NAO). Negative AO and NAO values imply more ridging in the central Atlantic and likely also a warm North Atlantic Ocean (50-60°N, 10-50°W). Also, on decadal timescales, weaker zonal winds in the sub-polar areas are indicative of a relatively strong thermohaline circulation which is favorable for hurricane activity. Positive values of this November index are negatively correlated with both 200 mb zonal winds and trade winds the following September in the tropical Atlantic. The associated reduced tropospheric vertical wind shear enhances conditions for TC development. Other features that are directly correlated with this predictor are low sea level pressure in the Caribbean and a warm North and Tropical Atlantic the following summer. Both of the latter are also hurricane-enhancing factors.

Predictor 6. Previous September-November SLP in the Gulf-SE USA (-)

(15-35°N, 75-95°W)

Low pressure in this area during September-November of the previous year correlates quite strongly with the positive phase of the PNA. According to Horel and Wallace (1981), the PNA is positive during the final year of most warm ENSO events. Therefore, a change to neutral or cool ENSO conditions is to be expected the following year. This feature is also strongly correlated with the following year's August-September sea level pressure in the tropical and subtropical Atlantic. August-September SLP in the tropical Atlantic is one of the most important predictors for seasonal activity, that is, lower-than-normal sea level pressures in the tropical Atlantic provide more favorable conditions for TC activity. In addition, easterly anomalies at 200 mb throughout the tropical Atlantic are typical during the following year's August-September period with low values of this predictor.

2.2 Hindcast Skill

Table 2 shows the degree of hindcast variance explained by our 1 April forecast scheme based upon our 52-year developmental dataset (1950-2001). To reduce over-fitting, we use no more than five predictors. Note that there is substantial skill for predictions of HD and NTC.

Table 2: Variance explained based upon 52 years (1950-2001) of hindcasting.

Variables Selected	Variance (r^2) Explained	Jackknife (r^2)
NS – 1, 2, 4, 5	0.45	0.34
NSD – 1, 2, 4, 5	0.59	0.50
H – 2, 3, 5, 6	0.53	0.41
HD – 1, 2, 5, 6	0.65	0.57
IH – 2, 3, 4, 5	0.61	0.53
IHD – 1, 2, 4, 5, 6	0.55	0.46
NTC – 1, 2, 4, 5, 6	0.71	0.64

3 Analog-Based Predictors for 2006 Hurricane Activity

Certain years in the historical record have global oceanic and atmospheric trends which are substantially similar to 2006. These years also provide useful clues as to trends in activity that the upcoming 2006 hurricane season may bring. For this early April extended range forecast, we project atmospheric and oceanic conditions for August through October 2006 and determine which of the prior years in our database have distinct trends in key environmental conditions which are similar to current February-March 2006 conditions. Table 3 lists our analog selections.

We select prior hurricane seasons since 1949 which have similar atmospheric-oceanic conditions to those currently being experienced. Analog years for 2006 were selected primarily on how similar they are to conditions that are currently observed such as warm tropical and North Atlantic sea surface temperatures and cool ENSO conditions. In addition, we look for analogs with similar conditions to what we project for August-October 2006 including warm Atlantic sea surface temperatures, neutral to cool ENSO conditions and west phase QBO conditions.

There were four hurricane seasons since 1949 with characteristics similar to what we observe in February-March and what we project for August-September. The best analog years that we could find for the 2006 hurricane season are 1964, 1996, 1999 and 2003. We anticipate that 2006 seasonal hurricane activity will have slightly more activity than what was experienced in the average of these four years. We believe that 2006 will be a very active season in the Atlantic basin.

Table 3: Best analog years for 2006 with the associated hurricane activity listed for each year.

Year	NS	NSD	H	HD	IH	IHD	NTC
1964	12	71.25	6	43.00	5	9.75	160
1996	13	79.00	9	45.00	6	13.00	192
1999	12	78.50	8	41.00	5	14.25	182
2003	16	79.25	7	32.75	3	16.75	174
Mean	13.3	77.0	7.5	40.4	4.8	13.4	177.0
2006 Forecast	**17**	**85**	**9**	**45**	**5**	**13**	**195**

4 ENSO

We believe that neutral or weak La Niña conditions are likely to be present during August-October 2006. A La Niña event is now in place in the tropical Pacific according to the Climate Prediction Center. SOI values continue to remain positive, and trade winds in the central Pacific are anomalously strong. In addition, oceanic heat content in the tropical Pacific remains below normal. These features will likely contribute to keeping waters from becoming anomalously warm over the next few months. In addition, most forecast models call for either neutral or La Niña conditions to persist for the next 4-6 months. When the tropical Atlantic is warm and neutral or La Niña conditions are present, Atlantic basin hurricane activity is greatly enhanced.

5 Adjusted 2006 Forecast

Table 4 shows our final adjusted early April forecast for the 2006 season which is a combination of our derived full 52-year statistical forecast, our analog forecast and qualitative adjustments for other factors not explicitly contained in either scheme. We foresee another very active Atlantic basin hurricane season. We anticipate that ENSO will likely be somewhat cool and will therefore play an enhancing role for the 2006 season. Warm sea surface temperatures are likely to continue being present in the tropical and North Atlantic during 2006, due to the fact that we are in a positive phase of the Atlantic Multidecadal Oscillation (AMO) (i.e., a strong phase of the Atlantic thermohaline circulation).

Table 4: Summary of our new early April statistical forecast, our analog forecast and our adjusted final forecast for the 2006 hurricane season.

Forecast Parameter and 1950-2000 Climatology (in parentheses)	New Statistical Scheme	Analog Scheme	Adjusted Final Forecast
Named Storms (9.6)	10.6	13.3	17
Named Storm Days (49.1)	54.0	77.0	85
Hurricanes (5.9)	6.2	7.5	9
Hurricane Days (24.5)	28.2	40.4	45
Intense Hurricanes (2.3)	2.3	4.8	5
Intense Hurricane Days (5.0)	7.8	13.4	13
Net Tropical Cyclone Activity (100%)	125.9	177.0	195

6 Skill and Verification of 1 April Forecasts

We define forecast skill as the degree to which we are able to predict the variation of seasonal hurricane activity parameters above that specified by a long-term climatology. The latter is expressed as the ratio of our forecast error to the observed difference from climatology or:

Forecast Error / Seasonal Difference from Climatology

For example, if there were a year with five more tropical storms than average and we had predicted two more storms than average, we would give ourselves a skill score of 2 over 5 or 40 percent. By this measure, each of the seven parameters of our seasonal forecasts has shown some degree of skill from 1 April. Table 5 shows our skill based on 52 years of hindcasts from 1950-2001, and Table 6 displays our skill score in real-time forecasting for the last seven years. All parameters of our real-time forecasts have shown skill from 1 April.

Table 5: Average percent of variation explained of 1 April hindcasts above that of climatology (in percent) for the 52-year period 1950-2001. A value of 40 means that we hindcast 40 percent of the variability from climatology or that we were unable to explain 60 percent of the variability from climatology.

Tropical Cyclone Parameter	Early April Hindcast Skill
NS	31
NSD	38
H	36
HD	40
IH	40
IHD	34
NTC	47

Table 6: Last seven years' (1999-2005) average percent of variation explained of our 'real-time' forecasts issued on 1 April above that of climatology (in percent). A value of 30 means that we hindcast 30 percent of the variability from climatology or that we were unable to explain 70 percent of the variability from climatology.

Tropical Cyclone Parameter	Early April Forecast Skill
NS	35
NSD	27
H	20
HD	40
IH	24
IHD	22
NTC	36

Another way to consider the skill of our forecasts is to evaluate whether the forecast for each parameter successfully forecast above- or below-average activity. Table 7 displays how frequently our forecasts have been on the right side of climatology in hindcasts from 1950-2001 and in real-time forecasts for the past seven years (1999-2005). Note that our early April scheme has been successful at determining whether various hurricane parameters will be above- or below-average over 75% of the time at the extended lead time of 1 April in both hindcasts and real-time forecasts.

Table 7: The number of years that our tropical cyclone forecasts issued on 1 April has correctly predicted above- or below-average activity for each predictand in (A) hindcast mode (1950-2001) and in (B) real-time forecast mode (1999-2005).

Tropical Cyclone Parameter	(A) Hindcast	(B) Forecast
NS	38/52	7/7
NSD	40/52	7/7
H	41/52	6/7
HD	38/52	6/7
IH	42/52	5/7
IHD	37/52	5/7
NTC	41/52	6/7
Total	277/364	42/49
Correct Prediction of Above or Below Climatology	**76%**	**86%**

Of course, there are significant amounts of unexplained variance in a number of the individual parameter forecasts. Even though the skill for some of these parameter forecasts is somewhat low, there is a great curiosity in having some objective measure as to how active the coming hurricane season is likely to be. Therefore, even a forecast that has shown only modest skill in past years should be considered worthwhile when the only other information available is climatology.

7 Landfall Probability

7.1 Landfall Probability for 2006

A significant focus of our recent research involves efforts to develop forecasts of the probability of hurricane landfall along the U.S. coastline. 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 last 100 years (1900-1999). Specific landfall probabilities can be given for all tropical cyclone intensity classes for a set of distinct U.S. coastal regions.

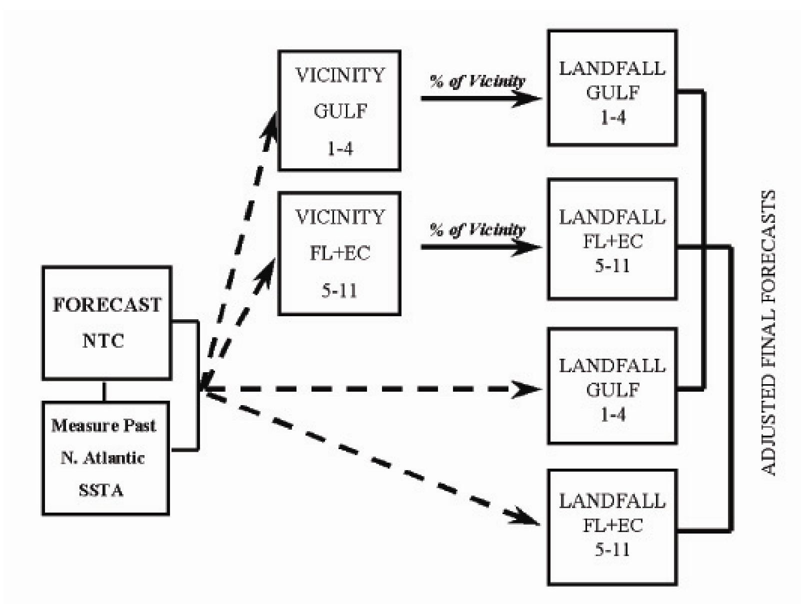

Figure 2: Flow diagram illustrating how forecasts of U.S. hurricane landfall probabilities are made. Forecast NTC values and an observed measure of recent North Atlantic (50-60°N, 10-50°W) SSTA* are used to develop regression equations from U.S. hurricane landfall measurements of the 20th century. Separate equations are derived for the Gulf and for Florida and the East Coast (FL+EC).

Figure 2 provides a flow diagram showing how these forecasts are made. Net landfall probability is shown linked to the overall Atlantic basin Net Tropical Cyclone activity (NTC; see Table 8) and to climate trends linked to multi-decadal variations of the Atlantic Ocean thermohaline circulation as inferred from recent past years of North Atlantic SSTA*.

Higher values of SSTA* generally indicate greater Atlantic hurricane activity, especially for intense or major hurricanes. Atlantic basin NTC can be skillfully hindcast, and the strength of the Atlantic Ocean thermohaline circulation can be inferred from the value of SSTA* which is North Atlantic SST anomalies (in the region 50-60°N, 10-50°W) from current and prior years. See our previous papers located online at http://hurricane.atmos.colostate.edu/Forecasts for further discussion of SSTA*. The forecast relationship we use to make probability estimates for U.S. landfall is as follows:

Landfall Probability = Forecast NTC + Measured SSTA   (1)*

The current (March 2006) value of SSTA* is 69. Hence, in combination with a prediction of NTC of 195 for 2006, a combination of NTC + SSTA* of (195 + 69) yields a value of 264.

As shown in 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. For example, landfall observations during the 20th century show that a greater number of intense hurricanes strike the Florida and U.S. East Coast during years of (1) increased NTC and (2) above-average North Atlantic SSTA* conditions.

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 IH, and 5 IHD 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)	Intense Hurricanes (IH)	2.3
6)	Intense Hurricane Days (IHD)	5.0

Table 9 lists strike probabilities for the 2006 hurricane season for different TC categories for the entire U.S. coastline, the Gulf Coast, and the East Coast including the

Florida peninsula. The mean annual probability of one or more landfalling systems is given in parentheses. Note that Atlantic basin NTC activity in 2006 is expected to be well above its long-term average of 100, and North Atlantic SSTA* values are measured to be well above average (69 units). The long-period SSTA* average is 0. During periods of positive North Atlantic SSTA, a higher percentage of Atlantic basin major hurricanes cross Florida and the eastern U.S. coastline for a given level of NTC. U.S. hurricane landfall probability is thus expected to be well above average owing to both predicted above-average NTC and above-average North Atlantic SSTAs.

Please visit our website at http://www.e-transit.org/hurricane for landfall probabilities for 11 U.S. coastal regions, 55 subregions and 205 coastal and near-coastal counties from Brownsville, Texas to Eastport, Maine.

Table 9: Estimated probability (expressed in percent) of one or more U.S. landfalling tropical storms (TS), category 1-2 hurricanes (HUR), category 3-4-5 hurricanes, and 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 2006. The long-term mean annual probability of one or more landfalling systems during the 20th century is given in parentheses.

Coastal Region	TS	Category 1-2 HUR	Category 3-4-5 HUR	All HUR	Named Storms
Entire U.S. (Regions 1-11)	91% (80%)	88% (68%)	81% (52%)	98% (84%)	99% (97%)
Gulf Coast (Regions 1-4)	74% (59%)	61% (42%)	47% (30%)	79% (61%)	95% (83%)
Florida plus East Coast (Regions 5-11)	64% (51%)	69% (45%)	64% (31%)	89% (62%)	96% (81%)

7.2 Forthcoming Revised Landfall Prediction Scheme

We have recently been investigating the potential predictability of steering current patterns likely to be present during the upcoming hurricane season. No individual or group can accurately predict exactly where or when a particular storm will make landfall months in advance; however, we have found that using a combination of our NTC forecast and several April-May steering current predictors, we can improve our landfall probability scheme considerably. We are currently working on documentation of this revised landfall prediction scheme, and it will debut with our 31 May update of the 2006 hurricane forecast.

8 Is Global Warming Responsible for the Large Upswing in 2004-2005 US Hurricane Landfalls?

8.1 Background

The recent U.S. landfall of major hurricanes Dennis, Katrina, Rita and Wilma and the four Florida landfalling hurricanes of 2004 (Charley, Frances, Ivan and Jeanne) has raised questions about the possible role that global warming may be playing in these last two unusually destructive seasons.

The global warming arguments have been given much attention by many media references to recent papers claiming to show such a linkage. Despite the global warming of the sea surface of about 0.5^{o}C that has taken place over the last 3 decades, global numbers of hurricanes and their intensity have not shown increases in recent years except for the Atlantic.

The Atlantic has seen a very large increase in major hurricanes during the last 11-year period of 1995-2005 (average 4.0 per year) in comparison to the prior 25-year period of 1970-1994 (average 1.5 per year). This large increase in Atlantic major hurricanes is primarily a result of a multi-decadal increase in strength in the Atlantic Ocean thermohaline circulation (THC) which is not directly related to global temperature increase. Changes in ocean salinity are believed to be the driving mechanism. These multi-decadal changes have also been termed the Atlantic Multi-Decadal Oscillation (AMO).

There have been similar past periods (1940s-1950s) when the Atlantic was just as active as in recent years. For instance, when we compare Atlantic basin hurricane numbers of the last 15 years with an earlier 15-year period (1950-1964), we see little difference in hurricane frequency or intensity even though global surface temperatures were cooler and there was a general global cooling during 1950-1964 as compared with global warming during 1990-2004.

8.2 Discussion

There is no physical basis for assuming that global hurricane intensity or frequency is necessarily related to global mean surface temperature changes of less than $\pm 0.5^{o}$C. As the ocean surface warms, so too does global upper air temperatures to maintain conditionally unstable lapse-rates and global rainfall rates at their required values. Seasonal and monthly variations of sea surface temperature (SST) within individual storm basins show only very low correlations with monthly, seasonal, and yearly variations of hurricane activity. Other factors such as tropospheric vertical wind shear, surface pressure, low level vorticity, mid-level moisture, etc. play more dominant roles in explaining hurricane variability than do surface temperatures. Although there has been a general global warming over the last 30 years and particularly over the last 10 years, the SST increases in the individual tropical cyclone basins have been smaller than the overall global warming (about half) and, according to the observations, have not brought about any significant increases in global major tropical cyclones except for the Atlantic which as has been discussed, has multi-decadal oscillations driven primarily by changes in Atlantic salinity. No credible observational evidence is available or likely will be available in the next few decades which will be able to directly associate global surface temperature change to changes in global hurricane frequency and intensity.

Most Southeast coastal residents probably do not know how fortunate they had been in the prior 38-year period (1966-2003) leading up to 2004-2005 when there were only 17 major hurricanes (0.45/year) that crossed the U.S. coastline. In the prior 40-year period of 1926-1965, there were 36 major hurricanes (0.90/year or twice as many) that made U.S. landfall. It is understandable that coastal residents were not prepared for the great upsurge in landfalling major hurricanes in 2004-2005.

We should interpret the last two years of unusually large numbers of U.S. landfalling hurricanes as natural but very low probability years. During 1966-2003, U.S. hurricane landfall numbers were substantially below the long-term average. In the last two seasons, they have been much above the long-term average. Although the 2004 and 2005 hurricane seasons have had an unusually high number of major landfall events, the overall Atlantic basin hurricane activity has not been much more active than five of the recent hurricane seasons since 1995 (e.g., 1995-1996, 1998-1999, 2003). What has made the 2004-2005 seasons so unusually destructive is the higher percent of major hurricanes which moved over the U.S. coastline. These landfall events were not primarily a function of the overall Atlantic basin net major hurricane numbers, but rather of the favorable broad-scale Atlantic upper-air steering currents which were present the last two seasons. It was these favorable Atlantic steering currents which caused so many of the major hurricanes which formed to come ashore.

It is rare to have two consecutive years with such a strong simultaneous combination of high amounts of major hurricane activity together with especially favorable steering flow currents. The historical records and the laws of statistics indicate that the probability of seeing another two consecutive hurricane season like 2004-2005 is very low. Even though we expect to see the current active period of Atlantic major hurricane activity to continue for another 15-20 years, it is statistically unlikely that the coming 2006 and 2007 hurricane seasons, or the seasons which follow, will have the number of major hurricane U.S. landfall events as we have seen in 2004-2005.

9 Forecast Theory and Cautionary Note

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. It is 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. However, it must also be emphasized that a low landfall probability does not insure that hurricanes will not come ashore. Regardless of how active the 2006 hurricane season is, a finite probability always exists that one or more hurricanes may strike along the U.S. coastline or in the Caribbean and do much damage.

10 Forthcoming Updated Forecasts of 2006 Hurricane Activity

We will be issuing seasonal updates of our 2006 Atlantic basin hurricane forecasts on **Wednesday 31 May** (to coincide with the official start of the 2006 hurricane season on 1 June), **Thursday 3 August**, **Friday 1 September** and **Tuesday 3 October 2006**. The 3 August, 1 September and 3 October forecasts will include separate forecasts of August-only, September-only and October-only Atlantic basin tropical cyclone activity. A verification and discussion of all 2006 forecasts will be issued in late November 2006. Our first seasonal hurricane forecast for the 2007 hurricane season will be issued in early December 2006. All these forecasts will be available on the web at: http://hurricane.atmos.colostate.edu/Forecasts.

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13 Verification of Previous Forecasts

Table 10: Summary verification of the authors' six previous years of seasonal forecasts for Atlantic TC activity between 2000-2005.

2000	8 Dec. 1999	Update 7 April	Update 7 June	Update 4 August	Obs.
No. of Hurricanes	7	7	8	7	8
No. of Named Storms	11	11	12	11	14
No. of Hurricane Days	25	25	35	30	32
No. of Named Storm Days	55	55	65	55	66
Hurr. Destruction Potential	85	85	100	90	85
Intense Hurricanes	3	3	4	3	3
Intense Hurricane Days	6	6	8	6	5.25
Net Tropical Cyclone Activity	125	125	160	130	134

2001	7 Dec. 2000	Update 6 April	Update 7 June	Update 7 August	Obs.
No. of Hurricanes	5	6	7	7	9
No. of Named Storms	9	10	12	12	15
No. of Hurricane Days	20	25	30	30	27
No. of Named Storm Days	45	50	60	60	63
Hurr. Destruction Potential	65	65	75	75	71
Intense Hurricanes	2	2	3	3	4
Intense Hurricane Days	4	4	5	5	5
Net Tropical Cyclone Activity	90	100	120	120	142

2002	7 Dec. 2001	Update 5 April	Update 31 May	Update 7 August	Update 2 Sept.	Obs.
No. of Hurricanes	8	7	6	4	3	4
No. of Named Storms	13	12	11	9	8	12
No. of Hurricane Days	35	30	25	12	10	11
No. of Named Storm Days	70	65	55	35	25	54
Hurr. Destruction Potential	90	85	75	35	25	31
Intense Hurricanes	4	3	2	1	1	2
Intense Hurricane Days	7	6	5	2	2	2.5
Net Tropical Cyclone Activity	140	125	100	60	45	80

2003	6 Dec. 2002	Update 4 April	Update 30 May	Update 6 August	Update 3 Sept.	Update 2 Oct.	Obs.
No. of Hurricanes	8	8	8	8	7	8	7
No. of Named Storms	12	12	14	14	14	14	14
No. of Hurricane Days	35	35	35	25	25	35	32
No. of Named Storm Days	65	65	70	60	55	70	71
Hurr. Destruction Potential	100	100	100	80	80	125	129
Intense Hurricanes	3	3	3	3	3	2	3
Intense Hurricane Days	8	8	8	5	9	15	17
Net Tropical Cyclone Activity	140	140	145	120	130	155	173

2004	5 Dec. 2003	Update 2 April	Update 28 May	Update 6 August	Update 3 Sept.	Update 1 Oct.	Obs.
No. of Hurricanes	7	8	8	7	8	9	9
No. of Named Storms	13	14	14	13	16	15	14
No. of Hurricane Days	30	35	35	30	40	52	46
No. of Named Storm Days	55	60	60	55	70	96	90
Intense Hurricanes	3	3	3	3	5	6	6
Intense Hurricane Days	6	8	8	6	15	23	22
Net Tropical Cyclone Activity	125	145	145	125	185	240	229

2005	3 Dec. 2004	Update 1 April	Update 31 May	Update 5 August	Update 2 Sept.	Update 3 Oct.	Obs.
No. of Hurricanes	6	7	8	10	10	11	15
No. of Named Storms	11	13	15	20	20	20	27
No. of Hurricane Days	25	35	45	55	45	40	51
No. of Named Storm Days	55	65	75	95	95	100	125
Intense Hurricanes	3	3	4	6	6	6	7
Intense Hurricane Days	6	7	11	18	15	13	16.75
Net Tropical Cyclone Activity	115	135	170	235	220	215	275