# UPDATED EARLY AUGUST FORECAST OF ATLANTIC SEASONAL HURRICANE ACTIVITY AND US LANDFALL STRIKE PROBABILITIES FOR 2001

## Conditions affecting hurricane activity indicate somewhat above average activity and above normal U.S. landfall probability

This forecast is based on ongoing research by the authors along with meteorological information through August 2001

By


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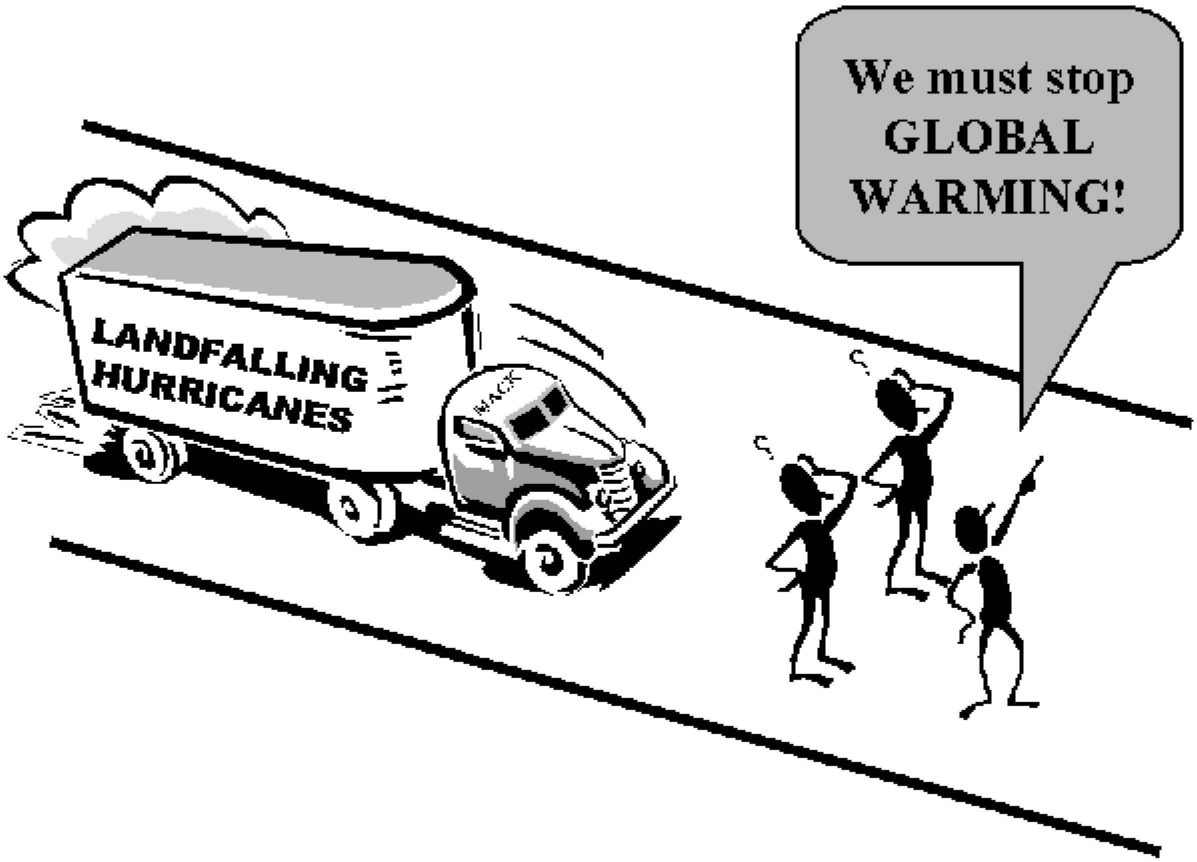
7 August 2001




# 2001 ATLANTIC BASIN SEASONAL HURRICANE FORECAST

| | 7 December 2000 Forecast for 2001 | Updated 7 April 2001 | Updated 7 June 2001 | Updated 7 August 2001 |
|---|---|---|---|---|
| **Tropical Cyclone Seasonal Named Storms (NS) (9.3)** | 9 | 10 | 12 | 12 |
| **Named Storm Days (NSD) (46.9)** | 45 | 50 | 60 | 60 |
| **Hurricanes (H)(5.8)** | 5 | 6 | 7 | 7 |
| **Hurricane Days (HD)(23.7)** | 20 | 25 | 30 | 30 |
| **Intense Hurricanes (IH) (2.2)** | 2 | 2 | 3 | 3 |
| **Intense Hurricane Days (IHD)(4.7)** | 4 | 4 | 5 | 5 |
| | | | | |

| | | | | |
|---|---|---|---|---|
| **Hurricane Destruction Potential (HDP) (70.6)** | 65 | 65 | 75 | 75 |
| **Maximum Potential Destruction (MPD) (61.7)** | 60 | 60 | 70 | 70 |
| **Net Tropical Cyclone Activity (NTC)(100%)** | 90 | 100 | 120 | 120 |

Forecast for August 2001 alone: 3 Named Storms, 1 Hurricane, 1 Major Hurricane

(See discussion in Section 5)

## UPDATED PROBABILITY FORECAST OF LANDFALL BY ONE OR MORE MAJOR (CATEGORY 3-4-5) HURRICANES:

1) Probability for landfall somewhere on the U.S. coastline: 69% (average for last century is 52%)
2) On the U.S. East Coast Including Peninsular Florida: 50% (average for last century is 31%)
3) On the Gulf Coast from the Florida Panhandle to Brownsville: 39% (average for last century is 30%)

# DEFINITIONS

**ABSTRACT**

**Information obtained through July indicates that the 2001 Atlantic hurricane season will likely be above average though not as busy as the recent 1995, 1996, 1998, 1999 and 2000 hurricane seasons. However, the 2001 season should be considerably more active than the average for the hurricane seasons during the recent multi-decadal period of low activity from 1970 through 1994. Collectively, Atlantic basin Net Tropical Cyclone (NTC) activity during 2001 is expected to be about 20 percent above an average hurricane season. Predictive signals in the Atlantic basin including Sea Surface Temperature Anomalies (SSTAs) and Sea Level Pressure Anomalies (SLPA) are favorable for above-average hurricane activity. The only obvious suppressing influence for this year's activity is the persistence of an easterly stratospheric QBO. We estimate that the 2001 season will bring about 7 hurricanes (average is 5.8), 12 named storms (average is 9.3), 60 named storm days (average is 47), 30 hurricane days (average is 24), 3 intense (category 3-4-5) hurricanes (average**

**is 2.2), 5 intense hurricane days (average is 4.7), a Hurricane Destruction Potential (HDP) value of 75 (average is 71) and, as noted previously, an overall NTC activity of 120 percent of the average season for the period between 1950-1990. U.S. landfall probability is estimated to be 10-20 percent above the long-term mean.**

# 1 Introduction

Our evolving forecast techniques are based on a variety of global and regional predictors previously shown to be related to forthcoming seasonal Atlantic tropical cyclone (TC) activity and landfall probability. This paper presents details of our observations and rationale for this four-month (1 August to 30 November) extended range seasonal forecast for 2001. The forecast is based on both statistical analyses and on prior hurricane seasons with atmospheric and oceanic conditions analogous to those which we anticipate to be in place during the 2001 hurricane season.

Useful long-range global predictive signals exist for seasonal TC activity in the Atlantic basin. Our research has shown that a sizeable portion of the season-to-season variability of Atlantic TC activity can be forecast with skill exceeding climatology by early December of the prior year. Qualitative adjustments to predictions from regression equations are added to accommodate additional perspectives related to seasonal activity which are not yet incorporated into our statistical models. The variable climate influences whose current conditions will largely determine this year's Atlantic basin hurricane activity are as follows:

1. The status of the El Niño-Southern Oscillation (ENSO),

2. The configuration of Atlantic Sea Surface Temperature Anomalies (SSTA) which also provide proxy signals for the strength of the Atlantic Ocean thermohaline circulation,

3. The phase of the stratospheric Quasi-Biennial Oscillation (QBO) of zonal winds at 30 mb and 50 mb which can be accurately extrapolated months into the future,

4. Two measures of West African rainfall during the prior year (see Figs. 1 and 2),

5. The West minus East gradient of the temperature and surface pressure over West Africa during February through May of the current year.

6. The strength of the Azores High surface pressure anomaly during March through July of the current year and the configuration of the current and forecast future (late summer) broad scale Atlantic sea level pressure and surface temperature anomaly patterns (see Figs. 2 and 3).

A listing of all of our potential predictors is provided in Table 4. A brief summary of these predictor indices and their specific current implications for the 2001 season follows.

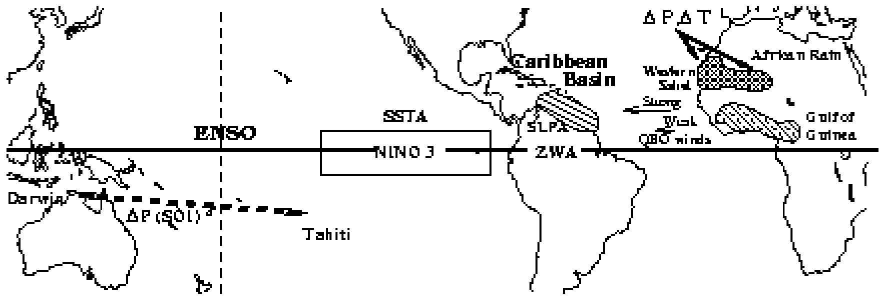



Figure 1: Meteorological parameters used in various prior versions of our early August (Gray et al. 1994a) seasonal forecast.

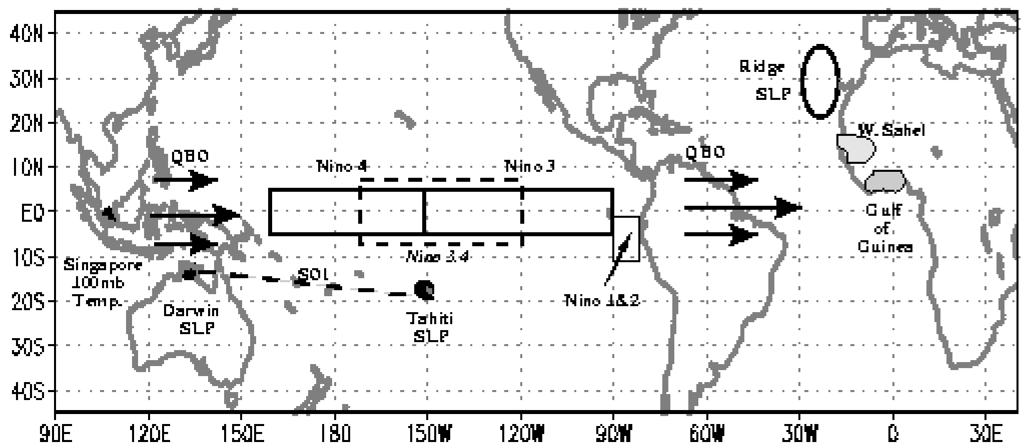



Figure 2: Additional parameters used or consulted in making the actual extended-range forecasts.

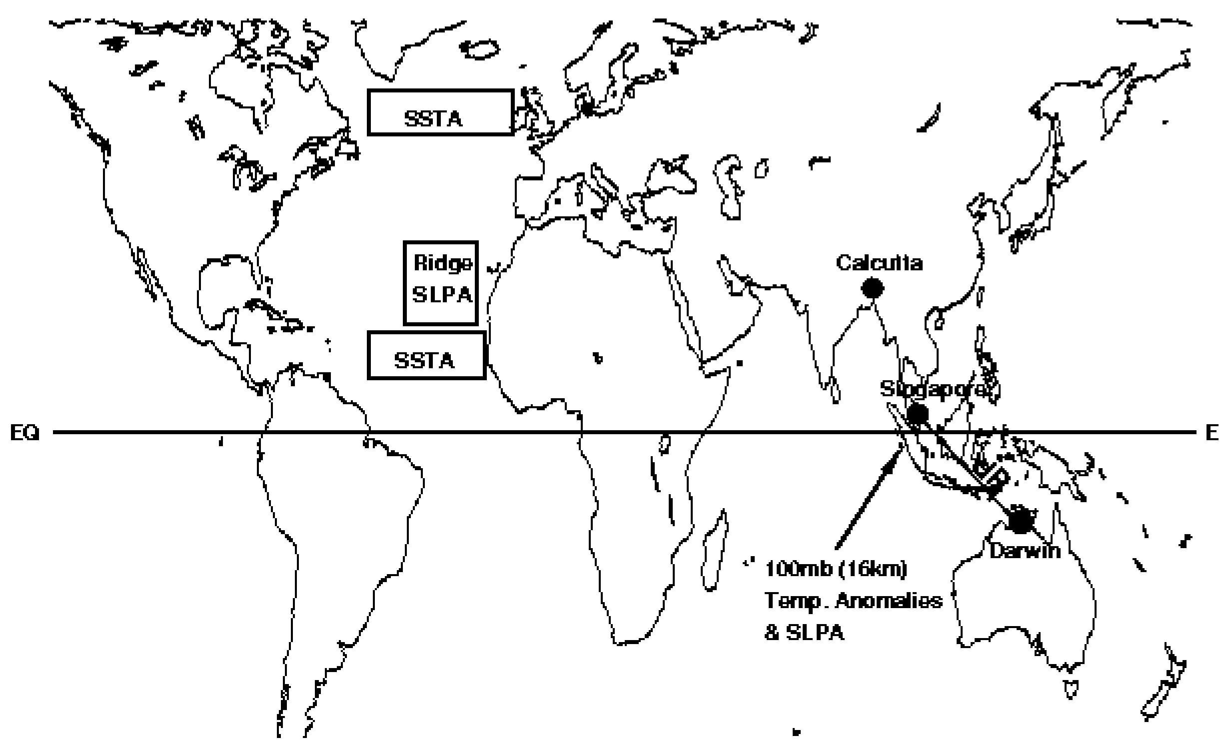


Figure 3: Additional (new) predictors which have recently been noted to be useful for predicting Atlantic hurricane activity.

a) El Niño-Southern Oscillation (ENSO). ENSO is one of the principal global-scale environmental factors affecting Atlantic seasonal hurricane activity. Hurricane activity tends to be suppressed during El Niño events (1997 is a good recent example). This strongest El Niño ever observed for the August to October period caused hurricane activity to be very suppressed that year only one hurricane occurred from August to October 1997 (average 4.9). Conversely, activity tends to be enhanced during seasons with cold water (La Niña) conditions, as occurred during 1995-1996 and 1998-2000. Warming of the sea surface in the tropical east Pacific Ocean during El Niño events decreases Atlantic hurricane activity by enhancing deep cumulus convective activity in the East Pacific region. A portion of the increased upper-level outflow wind from this enhanced Pacific convection spreads through the tropical Atlantic where it eventually sinks and dries the upper troposphere while also strengthening upper-level ( £#200 mb) westerly winds. These effects inhibit the intensification of organized westward moving African disturbances by enhancing subsidence and vertical shear in the intensification region of the tropical Atlantic. The recent cool ENSO conditions are now being replaced by neutral equatorial Pacific SST conditions. We expect ENSO conditions during the 2001 hurricane season to be close to neutral, slightly warm in western Nino-4 region, but somewhat cooler in the eastern Ninos 1-2 region (see Fig. 3). Table 1 lists analog years wherein such conditions (i.e., warm SSTA in the west and cool in the east) were present during August through October.

Table 1: Analog years to 2001 when ENSO conditions were cool in Ninos 1-2 and neutral to warm in Nino-4. On average there was reasonable hurricane activity during these years of near neutral to warm in the west and cool in the east conditions.

| | SSTA (˙C) in Nino 4 | SSTA (˙C) in Ninos 1 and 2 | |
|---|---|---|---|
| **Year** | **During Aug-Oct** | **During Aug-Oct** | **NTC** |
| 1952 | .08 | -0.33 | 97 |
| 1966 | .35 | -0.32 | 140 |
| 1977 | .45 | -0.13 | 46 |
| 1990 | .71 | -0.37 | 104 |
| 1992 | .44 | -0.42 | 62 |
| 1996 | .01 | -0.92 | 204 |
| Mean | .34 | -0.42 | 109 |

## 2 Recent ENSO Conditions Through July 2001

Table 2 shows changes in Pacific equatorial SSTA conditions during the last seven months. We do not expect the net change associated with this recent warming trend to be of sufficient strength to cause a significant reduction in this season's hurricane activity. Note that most of the recent SST warming has been in the Nino-4 area of the central Pacific.

Table 2: SSTA in (˙C) in the equatorial central and east Pacific during the last three-months. See Figure 2 for the locations of the Nino domains.

| Month (2001) | Nino 4 | Nino 3.4 | Nino 3 | Nino 1-2 |
|---|---|---|---|---|
| **January** | -0.6 | -0.7 | -0.5 | -0.5 |
| **February** | -0.8 | -0.5 | -0.2 | 0.1 |
| **March** | -0.5 | -0.3 | 0.3 | 1.3 |
| **April** | -0.2 | 0.0 | 0.3 | 1.3 |
| **May** | 0.0 | 0.0 | 0.1 | -0.1 |
| **June** | 0.2 | 0.2 | 0.1 | -0.7 |
| **July** | 0.5 | 0.3 | -0.1 | -0.8 |
| **April-July Warming** | 0.7 | 0.3 | -0.4 | -2.1 |

Table 3: Years with neutral Nino 3.4 SSTA (¶0.5˙C) conditions grouped into active and inactive hurricane seasons.

| **Neutral Nino-3.4 SSTA (¶0.5˙C) with active hurricane seasons.** | | | | |
|---|---|---|---|---|
| Year | NS | H | IH | NTC |
| 1887 | 17 | 10 | 2 | 180 |
| 1932 | 11 | 6 | 4 | 154 |
| 1958 | 10 | 7 | 4 | 139 |
| 1996 | 13 | 9 | 6 | 204 |
| 2000 | 14 | 8 | 3 | 134 |
| Average | 13 | 8 | 3.8 | 162.2 |
| **Neutral Nino-3.4 SSTA (¶0.5˙C) with inactive hurricane seasons.** | | | | |
| 1907 | 4 | 0 | 0 | 13 |
| 1939 | 5 | 3 | 1 | 44 |
| 1962 | 5 | 3 | 0 | 33 |
| 1968 | 7 | 4 | 0 | 40 |
| 1983 | 4 | 3 | 1 | 32 |
| Average | 5 | 2.6 | 0.4 | 32.4 |
| **Ratio: Active/Inactive** | 2.6 | 3.1 | 9.5 | 5.0 |

**ENSO Is Not the Only Consideration**. Although ENSO conditions tend to be the single most important parameter dictating strong seasonal trends in Atlantic seasonal hurricane activity, other properties of the atmosphere and ocean can be preeminent in some years, especially years with near neutral ENSO conditions in the tropical Pacific as 2001 is expected to be. Table 3 lists sets of years wherein either active or inactive hurricane seasons occurred with neutral ENSO conditions. Note in Table 3 that despite NINO 3.4 SSTA conditions during August through September near neutral (SSTA ¶0.5˙C), wide variations of tropical activity occurs. The averages of these two contrasting sets of five seasons differ by large amounts of activity including ratios of 2.6 (for NS), 3.1 (for H), 9.5 (for IH) and 5.0 times (for NTC). Factors other than ENSO caused these large contrasting seasonal differences.

b) The QBO. The easterly and westerly modes of the stratospheric QBO zonal winds which encircle the globe over the equatorial regions also have an influence on Atlantic tropical cyclone activity (Gray, 1984a; Shapiro, 1989). Typically, 30 to 50 percent more hurricane activity (depending on the specific activity index considered) occurs at low latitudes during those seasons when stratospheric QBO winds between 30 mb and 50 mb are anomalously westerly (hereafter, the ``westerly QBO''). Conversely, seasonal hurricane activity is typically reduced during the easterly QBO phase and/or when large vertical wind shear conditions exist between 30 and 50 mb. We anticipate that the current easterly QBO phase will persist in the lower stratosphere below 30 mb throughout the 2001 hurricane season and vertical wind shear between these two levels will be small. Overall these conditions should be a modest inhibiting influence for this year's low latitude hurricane activity.

c) Rainfall in western Africa. As discussed by Landsea (1991), Gray and Landsea (1992) and Gray et al. (1992), predictive signals for this year's seasonal hurricane activity occur in last year's western African rainfall data during the mid-summer to fall period. One such rainfall-linked signal is June-September western Sahel Rainfall. The western Sahel area (see Fig. 2) experiences large year-to-year persistence of anomalous rainfall trends. Reflecting long-term trends, wet years tend to be followed by wet years (e.g., in the 1950s and 1960s) with enhanced hurricane activity, while dry years are typically followed by dry years (e.g., during the 1970s, 1980s and first half 1990s) and suppressed hurricane activity. A second western African rainfall index involves August-November Rainfall in the Gulf of Guinea. Landsea (1991) and Gray and Landsea (1992) documented a strong African rainfall - intense hurricane multi-year lag relationship using August through November rainfall along the Gulf of Guinea (see Fig. 2). There is typically more major (category 3-4-5) hurricane activity in year's following wet August-November seasons in the Gulf of Guinea and reduced activity following the driest August-November periods in the Gulf of Guinea. Last year's value was -0.5 SD.

Since the upswing in hurricane activity since 1995, western African rainfall data as specified by the rain gauge observations has, surprisingly, been below average. This is atypical of all our prior measurement networks since 1900. We suspect that a degradation has occurred in the rain gauge measurements. Rainfall estimates from satellite data have implied higher rainfall than that measured by the gauges. In recent years it is not infrequent to find that a number of individual stations report no daily rainfall under satellite reported areas of heavy rain producing convective clouds. Recent year satellite rainfall estimates have been notably higher than those reported by the rain gauges in recent years. We believe the rain gauge network is now less reliable than it was previously. For this reason we have decided to assume that our western African rainfall values for this forecast show no deviation from the average and more in line with the satellite observations. This discrepancy needs further study.

d) October-November 2000 and March 2001 Atlantic Subtropical Ridge (Azores High) Between 20-30°W. High surface pressure associated with the Azores High between 20-30°W is positively related to stronger eastern Atlantic trade winds which, in turn, enhance upwelling of cold water off the coast of northwest Africa. Colder sea surface temperatures created by this enhanced ocean upwelling are typically associated with higher surface pressures during the following spring-summer. This condition often creates a self-enhancing (positive feedback) process, ultimately resulting in higher Caribbean pressures during the subsequent summer (Knaff 1999). By this mechanism, positive ridge index values during the prior fall and spring (i.e., March) are linked to an enhanced Azores High during the following summer with stronger trade winds. Stronger trade winds have the effect of reducing hurricane activity the following summer and fall. Although ridge strength during October-November 2000 was high (+1.1 SD above the long-term mean), March 2001 ridge values were very low (-1.6 SD). March ridge pressure values are more closely associated with TC trends than the October-November values. Hence, the very low March 2001 SLPA values indicate enhanced 2001 hurricane activity.

e) June-July SLPA - Combined Neutral Influence. Two Caribbean basin parameters which contribute to the early August hurricane forecast are the Caribbean Basin SLPA and 200 mb (12 km) Zonal Wind Anomalies (ZWA). The mean June-July 2001 five-station tropical (Trinidad, Barbados, Curacao, San Juan and Cayenne) SLPA was near neutral. June SLPA was +0.5 mb above average and July SLPA was near average. Following the Knaff (1998) 1 April 2001 forecast of June through September 2001 SLPA of -0.79 mb, we anticipate, however, that this SLPA index to be below average during the August-September period and thus be a positive influence for an active 2001 hurricane season. Table 4 provides details of these Caribbean-West Atlantic SLPA forecasts which are based on anomaly information concerning the March Atlantic subtropical ridge, January through March SSTs in the North Atlantic (50-60°N, 10-50°W) and January through March Niño 3.4 (5°N-5°S, 120°W-170°W) SST anomalies. This combination of factors in separate regression equations leads to a forecast of reduced Caribbean-western tropical Atlantic SLPA for the months of August-September 2001. Hindcasts by this method using data since 1903 show good skill and a significant association with variations of seasonal hurricane activity. Knaff finds that additional April-May and June-July predictors do not improve on this forecast.

Table 4: April 1, 2001 multi-month independent statistical prediction of Caribbean basin and Western tropical Atlantic Sea Level Pressure Anomaly (SLPA) for the 2001 summer (Knaff 1998). Separate regression analyses are made for each monthly category. SLPA predictions are expressed in mb.

| | August-September | June through September |
|---|---|---|
| **SLPA** | -0.66 | -0.79 |

f) 200 mb Zonal Wind (ZWA). Five-station mean June-July (Trinidad, Curacao, Barbados, Kingston and Balboa) ZWA values for 200 mb zonal winds at these lower Caribbean locations were averaged to obtain a value near zero (+0.2 m/s) for 2001. We anticipate a change to somewhat more negative ZWA values as the season progresses and, if this happens, it should be an enhancing influence on this season's hurricane activity.

# 3 Prediction Methodology

We forecast nine measures of seasonal Atlantic basin tropical cyclone activity including seasonal numbers of the following: Named Storms (NS), Named Storm Days (NSD), Hurricanes (H), Hurricane Days (HD), Intense Hurricanes (IH), Intense Hurricane Days (IHD), Hurricane Destruction Potential (HDP), Net Tropical Cyclone Activity (NTC), and Maximum Potential Destruction (MPD). Definitions for these indices are given on page 4. For each of these measures of activity, we choose the best three to six predictors (i.e., those resulting in optimum prediction skill) from a group of 15 potential forecast parameters known to be related to tropical cyclone activity. The current set of potential predictors used to develop our early August forecast is shown in Table 5. The specific values of these parameters used for 2001 are shown in the right-hand column.

Table 5: Listing of the pool of predictive parameters and their estimated values for the early August 2000 prediction, based on meteorological data available through July 2001. See Figs. 2 through 4 for the locations of the sources of these predictor data.

| **Predictive Parameter** | |
|---|---|
| 1 = QBO 50 mb 2-month extrapolation of zonal wind at 12˙N to Sept. 2001 | -18 m s$^{01}$ |
| 2 = QBO 30 mb 2-month extrapolation of zonal wind at 14˙N to Sept. 2001 | -17 m s$^{01}$ |
| 3 = QBO absolute value of shear between 50 and 30 mb at 8˙N to Sept. 2001 | 1 m s$^{01}$ |
| 4 = Rgc AN Gulf of Guinea rainfall anomaly (Aug-Nov of 2000) | -0.5 SD |
| 5 = Rws West Sahel rainfall anomaly (June-July 2001) | (assume) 0.0 SD |
| 6 = SST3.4 Nino 3.4 SSTA in June-July 2001 | +0.3˙C |
| 7 = ZWA June-July 2001 Caribbean basin zonal wind anomaly | +0.2 m/s |
| 8 = SLPA June-July 2001 Caribbean basin sea level pressure anomaly | +0.2 mb |
| 9 = Temp West-East Sahel temperature gradient(Feb-May 2001) | +0.5 SD |
| 10 = NATL North Atlantic SSTA anomaly (50-60˙N,10-50˙W) (June-July) | +0.75˙C |
| 11 = SATL South Atlantic SSTA anomaly (5-18˙S,50˙W-10˙E) (June-July) | +0.2˙C |
| 12 = TATL Tropical Atlantic SSTA anomaly (10-22˙N,18-50˙W) (June-July) | +0.1˙C |
| 13 = R-M: Mar Azores surface pressure ridge strength in Mar 2001 | -1.60 SD |
| 14 = R-ON: Azores surface pressure ridge strength in Oct-Nov 2000 | +1.1 SD |
| 15 = D-SST3.4: Nino 3.4 SSTA for June-July minus April-May 2001 | +0.3˙C |
| 16 = NSD-S: Named storm days south of 23.5˙N and east of 75˙W before 1 August | 0 |

**Statistical Regression Models**. A number of statistical forecasts are made for each of several TC activity parameters. Table 6 lists the seasonal hurricane indices that we predict and the number and name of the forecast parameters we use for each forecast. Our hindcast skill (between 50-60 percent) for the 42-year period of 1950-1991 is shown in the right column. These prediction equations are established for our variable parameter forecast model. This represents our best statistical forecast where, so as to minimize the skill degradation of these equations when making independent forecasts via statistical ``overfitting", we include the least number of predictors for the highest amount of hindcast variance. We stop adding predictors when the hindcast improvement of the next best predictor adds less than a 0.025 improvement to the total variance explained. These equations are also constrained to have regression coefficients whose sign match those when analyzed in isolation.

Table 6: Details of our 1 August forecast scheme which utilizes variable selection of predictors so as to maximize forecast skill (hindcast variance explained) while limiting the number of predictors to minimize artificial skill. See Figs. 1-3 for the locations of the predictors. Data for the period 1950-1997 was used to develop these equations.

| Forecast Parameter | No. of Predictors | Expected Measure of Agreement | Independent Fcst Skill | Predictors |
|---|---|---|---|---|
| **(NS)** | 5 | .602 | .463 | $U_{50}$, Shear, $R_g$, R-ON, NSD-S |
| **(NSD)** | 3 | .518 | .363 | $U_{50}$, $R_g$, NSD-S |
| **(H)** | 5 | .560 | .406 | $U_{30}$, $R_g$, R-M, R-ON, NSD-S |
| **(HD)** | 4 | .513 | .341 | $U_{30}$, $R_g$ NATL, NSD-S |
| **(IH)** | 5 | .574 | .425 | $U_{50}$, $R_s$, $R_g$, D-T, R-M |
| **(IHD)** | 5 | .573 | .424 | $U_{50}$, $R_g$, D-T, R-M, NSD-S |
| **(HDP)** | 4 | .507 | .332 | $U_{30}$, $R_g$, NATL, NSD-S |
| **(NTC)** | 5 | .628 | .497 | $U_{30}$, $R_g$, R-M, R-ON, NSD-S |
| **(MPD)** | 6 | .672 | .548 | $U_{30}$, $R_g$, NATL, R-M, R-ON, NSD-S |

We have also studied a scheme which uses various fixed (maximum) numbers of the predictors listed in Table 5. This procedure considers how hindcast variance (not necessarily true skill) increases as the number of predictors increases from 4 to 6 to 8. Although independent forecast skill (i.e., ``true skill") typically degrades in approximate proportion to the increased number of predictors, it is of interest to assess the degree of hindcast improvement which occurs with added predictors. Individual year forecast skill degradation from application of hindcast statistics can never be accurately specified. Consequently, as the latter are purely random effects, the hazards of overfitting become obvious. Additional forecast parameters representing conditions in the Atlantic and Pacific Ocean basins and in the Asia-Australia regions (refer to Figs. 1-3) are also consulted for further qualitative inter-relations and possible influences on our final ``adjusted" forecast.

Probability dictates that, on average, a net degradation of this hindcast skill of between 10-20 percent of total variability will likely occur. The amount of degradation (if any) for an individual year forecast is a random process. In some years, when conditions include strong trends that are similar to past years, forecasts will do quite well, perhaps better than the skill of the hindcast scheme. In other years, a given forecast can perform quite poorly. This is because our 42-year (1950-1991) predictor database likely does not contain realizations expressing the full range of independent possibilities. Our 1997 forecast is a good example. No year in our 1950 through 1991 developmental data sets had experienced an El Niño event nearly as intense as 1997 (by a factor of two of any other on record).

In Table 7, column (1) lists each of our statistical forecasts, column 2 contains our best qualitatively adjusted ``final" forecasts and column 3 provides the climatological mean for each parameter for 1950-1990. Note in column (2) that we have made an upward adjustment to our 2001 statistical forecasts to reflect the expectation of a more active hurricane season.

Table 7: 1 August season statistical forecasts which have a variable number of predictors (column 1) . Column 2 is our final adjusted early August forecast of 2001 hurricane activity. Column 3 gives climatology.

| **Full Forecast Parameter** | **(1) Variable Predictor** | **(2) Adjusted Actual Fcst.** | **(3) 1950-1990 Climatology** |
|---|---|---|---|
| **Named Storms (NS)** | 8.7 | 12 | 9.3 |
| **Named Storm Days (NSD)** | 40.9 | 60 | 46.9 |
| **Hurricanes (H)** | 4.4 | 7 | 5.8 |
| **Hurricane Days (HD)** | 21.7 | 30 | 23.7 |
| **Intense Hurricanes (IH)** | 2.4 | 3 | 2.2 |
| **Intense Hurricane Days (IHD)** | 5.5 | 5 | 4.7 |
| **Hurricane Destruction Potential (HDP)** | 69.0 | 75 | 70.6 |
| **Maximum Potential Destruction (MPD)** | 61.9 | 70 | 61.7 |
| **Net Tropical Cyclone Activity (NTC)** | 107% | 120% | 100% |

**Forecast of Post-1 August Activity**. Table 8 lists both our original and revised quantitative forecasts for the post-1 August hurricane activity. Our forecast for the remainder of the hurricane season (i.e., August through November) is for above-average tropical storm and hurricane activity.

Table 8: Summary of forecasts for the entire season (column 1) using prior methodology and, for activity after August 1 (columns 2-3) using a new scheme.

| **Forecast Parameter** | **New Variable Predictor for Post 1 Aug. ActivityActivity** | **After 1 Aug Climatology** | **Qualitative Adjusted After 1 Aug Activity** | **Full Hurricane Season Average 1950-1999** |
|---|---|---|---|---|
| **(NS)** | 6.7 | 7.8 | 11 | 9.3 |
| **(NSD)** | 39.5 | 41.1 | 59 | 46.9 |
| **(H)** | 4.3 | 5.1 | 7 | 5.8 |
| **(HD)** | 17.7 | 21.4 | 30 | 23.7 |
| **(IH)** | 2.4 | 2.0 | 3 | 2.2 |
| **(IHD)** | 5.5 | 4.4 | 5 | 4.7 |
| **(HDP)** | 70.6 | 64.4 | 75 | 70.6 |
| **(MPD)** | 52.9 | 67 | 69 | 61.7 |
| **(NTC)** | 92.9 | 97 | 119 | 100 |

We have identified three other strong predictors that have not yet been quantitatively incorporated into our post 1 August statistical forecast scheme are expected to play a role. All of these indicate greater 2001 seasonal activity than that indicated by our current statistical schemes. New predictors include Caribbean basin SLPA (discussed previously) and the realization that the Atlantic and global climate features have shifted to a new mode favorable to increased Atlantic major hurricane activity (as experienced from the 1930s through the mid-1960s). This shift took place in the Atlantic in 1995 and appears to have now (2001) extended over most of the globe. Other new information includes the configuration of comparatively cold mid-latitude and tropical East Pacific SSTAs, indicative of a negative Pacific Decadal Oscillation (PDO) which is linked to enhanced hurricane activity.

These factors, in conjunction with additional qualitative information, suggest that our statistical forecast is underestimating the amount of hurricane activity likely to occur this season and we have chosen to make an upward adjustment in our forecast to values more in line with the values indicated by our analog (discussed next) analysis. Consequently, data through the end of July indicate that 2001 will experience above average hurricane activity and notably more than the average for seasons between 1970-1994 when major hurricane activity was greatly suppressed.

# 4 Analog-Based Estimates of Hurricane Activity During 2001

Certain years in the historical record have global oceanic and atmospheric trends which are notably analogous to those we have seen and expect to see during the 2001 hurricane season. These analog years provide useful clues to what the forthcoming 2001 hurricane season may bring. For this (1 August) extended range forecast, we project atmospheric and oceanic conditions forward through the August-October 2001 period and assess which prior years in our database have similar environmental conditions and consider the trends in hurricane activity during those years. In the record since 1949, we find five years wherein June-July conditions appear notably similar to June-July conditions of this year. The relevant properties of the analogs and their projection through the 2001 hurricane season include,

- Persistent North Atlantic (50-60°N, 10-50°W) warm SST anomalies during the prior six years are expected to remain warm through the 2001 season. This assumes a persistent strong multi-decadal thermohaline circulation in the Atlantic this year.
- The current condition of the North Atlantic Oscillation (NAO) and Pacific Decadal Oscillation (PDO) (i.e., in a global atmosphere and ocean circulation regime typical of the 1940s and 1950s).
- QBO winds in September 2001 will be from an easterly direction.
- Above average Atlantic SST anomalies.
- Negative tropical Atlantic SLP anomalies.

The analog years that have the best resemblance to 2001 appear to be 1951, 1952, 1960, 1996, and 2000. None of these five 2001 analogs seasons had strongly suppressed hurricane activity (see Table 9). Based on the values in Table 9, we expect the 2001 season to have tropical cyclone activity which is about the average that occurred during these five analogs. This analog technique is a reliable forecast technique for adjusting levels of activity predicted by our statistical schemes as discussed previously. Thus, based on this analysis, we expect that 2001 will be an above average hurricane year and distinctly more active than the average hurricane seasons during the inactive 1970-1994 period.

Table 9: Best analog years for 2001 with the associated tropical cyclone activity listed for each year.

| **Year** | **NS** | **NSD** | **H** | **HD** | **IH** | **IHD** | **HDP** | **NTC** |
|---|---|---|---|---|---|---|---|---|
| **1951** | 10 | 58 | 8 | 36 | 2 | 5 | 113 | 120 |
| **1952** | 7 | 40 | 6 | 23 | 3 | 4 | 70 | 97 |
| **1960** | 7 | 30 | 4 | 18 | 2 | 11 | 72 | 96 |
| **1996** | 13 | 78 | 9 | 45 | 6 | 6 | 135 | 204 |
| **2000** | 14 | 62 | 8 | 32 | 3 | 5 | 85 | 134 |
| **Mean** | 10.2 | 54 | 7.0 | 31 | 3.2 | 6.2 | 95 | 130 |
| **2001 Forecast** | 12 | 60 | 7 | 30 | 3 | 5 | 75 | 120 |

Table 10 gives all of our 2001 seasonal forecasts. Note that we anticipate the same seasonal numbers as we predicted in our early June forecast.

Table 10: Summary of forecasts for the entire season (column 1) using prior methodology and for activity after August 1 (columns 2-5) using a new scheme.

| **Tropical Cyclone Seasonal** | **7 Dec 2000 Fcst** | **Updated 7 April 2001 Fcst** | **Updated 7 June 2001 Fcst** | **Updated 7 August 2001 Fcst.** | **After 1 August Fcst.** |
|---|---|---|---|---|---|
| **Named Storms (NS) (9.3)** | 9 | 10 | 12 | 12 | 11 |

| | | | | | |
|---|---|---|---|---|---|
| **Named Storm Days (NSD) (46.9)** | 45 | 50 | 60 | 60 | 59 |
| **Hurricanes (H)(5.8)** | 5 | 6 | 7 | 7 | 7 |
| **Hurricane Days (HD)(23.7)** | 2 | 25 | 30 | 30 | 30 |
| **Intense Hurricanes (IH) (2.2)** | 2 | 2 | 3 | 3 | 3 |
| **Intense Hurricane Days (IHD)(4.7)** | 4 | 4 | 5 | 5 | 5 |
| **Hurricane Destruction Potential (HDP) (70.6)** | 65 | 65 | 75 | 75 | 75 |
| **Maximum Potential Destruction (MPD) (61.7)** | 60 | 60 | 70 | 70 | 70 |
| **Net Tropical Cyclone Activity (NTC)(100%)** | 90 | 100 | 120 | 120 | 119 |

# 5 Predictions for Individual Months

A new aspect of our climate research is the development of predictions for individual months. There are often periods within active and inactive Atlantic basin hurricane seasons which do not conform to the overall trend of the season. For example, 1961 was an active hurricane season (NTC of 222), but there was no TC activity during August; 1995 had 19 named storms but only one named storm developed during the 30-day period during the peak of the hurricane season, between 29 August and 27 September. By contrast, the inactive season of 1941 had only six named storms (average 9.3), but four of them developed during September. During the inactive hurricane season of 1968, three of the eight named storms formed in June (average 0.5).

We have started new research to see how well various sub-season or individual monthly trends can be forecast. This effort is being spearheaded by Eric Blake, a graduate student in the first author's project. Blake has been working to develop a scheme to skillfully predict August-only Atlantic basin tropical cyclone activity. On average, August has about 26 percent of the total season activity. Recent research is showing a surprising degree of August-only predictive skill (Table 11). The first August-only forecast was made last year (2000) and proved to be successful.

Table 11: Prediction of August 2001 Atlantic basin seasonal hurricane activity.

| Forecast Parameter | Statistical Forecast | Jacknife Hindcast Skill | Final Adjusted Forecast Numbers | August Climatology |
|---|---|---|---|---|
| **NS** | 1.60 | .41 | 3.00 | 2.76 |
| **NSD** | -1.66 | .59 | 7.00 | 11.80 |
| **H** | 0.62 | .43 | 1.00 | 1.55 |
| **HD** | -1.09 | .62 | 2.50 | 5.67 |
| **IH** | 0.77 | .48 | 1.00 | 0.57 |
| **IHD** | 0.59 | .70 | 0.50 | 1.18 |
| **NTC** | 12.6 | .73 | 21.80 | 26.1 |

At present, it is generally more difficult to predict shorter periods of hurricane activity than to predict the entire year's activity. Despite the inherent difficulties of these shorter period hindcast forecasts, Blake has devised a quite skillful August-only prediction scheme as determined by 51 years (1949-1999) of hindcast testing using a statistically independent jackknife approach. Predictors are largely derived from June and July NCEP global reanalysis data for 200 mb wind, SLP and 500 mb height anomalies to forecast a full list of August-only predictands (NS, NSD, H, HD, etc.) paralleling our seasonal forecasts.

**August Methodology and 2001 Forecast**. The August-only forecast is made using twelve different predictors from across the globe; mostly atmospheric signals in the months of June and July. These factors are inserted into a multiregression model with a different equation for each of the forecast parameters. About 50-60 percent of the variance can be explained in hindcast using this method, with the highest skills for NTC and IHD and lower skill for H and NS.

Blake finds that on a global scale, August NTC is increased when the Atlantic Ocean is more favorable for TC activity than the Pacific Ocean. In general, increasing August activity is noted with June high pressure in the north western tropical Pacific, southeast of Japan, July low pressure in the Bering Sea and low July subtropical pressures in the central Atlantic. The 200 mb winds across the equator just west of South America also play an important role in determining August TC activity. When these winds are anomalously from the north and east, low-latitude TC formation and longevity are greatly enhanced. These favorable August factors typically improve our overall seasonal forecast significantly.

The August forecast parameters for this year are mostly negative. July pressure over the subtropical Atlantic was well above normal, while June pressure in the western Pacific was below normal. The 200 mb winds west of South America were near normal, as was the Bering Sea SLPA. This combination of factors have, in the past, produced below-average August activity, irrespective of the whole season activity.

Table 11 lists Blake's prediction for August 2001 along with his jackknife determined hindcast skill for the 51-year period of 1949-1999, the August climatology, and his final adjusted August 2001 forecast numbers. Table 12 shows the best prior July analog years to 2001 that were used as an adjustment aid to the August 2001 forecast. This August-only forecast methodology will be fully explained and documented in a forthcoming paper.

Table 12: Best analog years for August 2001 forecast, or the prior years with the most similar June and July (mainly) global climate signals to June and July 2001.

| | NS | NSD | H | HD | IH | IHD | NTC |
|---|---|---|---|---|---|---|---|
| **1953** | 3 | 9.5 | 1 | 3.5 | 0 | 0 | 14.0 |
| **1960** | 2 | 4.5 | 1 | 1.75 | 0 | 0 | 9.2 |
| **1965** | 2 | 8.0 | 2 | 5.0 | 0 | 0 | 15.7 |
| **1970** | 3 | 8.5 | 1 | 2.25 | 1 | 0.5 | 22.1 |
| **1978** | 4 | 6.50 | 2 | 1.50 | 0 | 0 | 16.2 |
| **Average** | 2.8 | 7.4 | 1.4 | 2.8 | 0.2 | 0.1 | 15.4 |
| **2001 August Forecast** | 3 | 7.00 | 1 | 2.5 | 1 | 0.5 | 21.8 |

Blake expects August 2001 to have below-average hurricane activity (NTC about 21.8/26.1 or 84 percent). In round numbers, the August forecast is for three named storms, one hurricanes, and one intense or major hurricane.

Even though the forecast of H, NS, and IH is similar to 2000, we expect the longevity of TCs in August to be much less than 2000. This is due to a decrease in deep tropical systems from last year. Whereas two deep tropical hurricanes occurred during August 2000, we only expect one to form this August (2001). Table 13 shows August 2000 versus forecast August 2001. Note the large difference in NSD, HD and IHD.

**Separate September and October-Only Forecast**. Blake finds that August's hurricane activity is not well correlated to September activity; the correlation of August and September NTC for the period of 1949 to 1999 is only 0.2. By contrast, the correlation of September and October NTC for this same 51-year period is much higher (r = 0.51). This information is leading us to attempt development of separate and independent monthly forecasts for August and for September. These monthly forecasts are then compared with our seasonal forecast which we believe, they will improve.

MS graduate student, Philip Klotzbach, has recently been studying the possibility of making skillful monthly forecasts of September activity from data through July. This September predictive data consists of July Atlantic and East Pacific values of SSTA, SLPA, 850 and 200 mb ZWA, geopotential height and relative humidity at various global locations. This is also showing promise.

An analysis of these July 2001 predictors indicate that September 2001 is likely to have above-average hurricane activity. Given the positive correlation observed between September and October activity, it is thus likely that October 2001 activity will also be above average. This promising new research is not yet far enough along to be reported upon in detail except to reiterate that July 2001 data indicate that September-October 2001 TC activity will likely be above average which adds justification to our current 2001 seasonal forecast for about 120 percent of the long-term average.

Table 13: August 2000 versus August 2001 forecast.

| Predictors | August 2000 | Forecast August 2001 |
|---|---|---|
| **NS** | 4 | 3 |
| **NSD** | 24.75 | 7 |
| **H** | 2 | 1 |
| **HD** | 14 | 2.5 |
| **IH** | 1 | 1 |
| **IHD** | 1 | 0.5 |
| **NTC** | 42.6 | 21.8 |

# 6 Major Reconfiguration of Atlantic Basin SSTs and Long Term Trends in Hurricane Activity

For years we have been suggesting that the recent (1970-1994) era of reduced Atlantic intense (category 3-4-5) hurricane activity was likely ending and that Atlantic coastal residents should expect an eventual long-term increase of landfalling major hurricanes (eg., Gray 1990, Gray et al. 1996; Goldenberg et al. 2001). This outlook is especially ominous because, when normalized by increased coastal population, inflation, and wealth per capita, [see Pielke and Landsea (1999) and Gray (1999)] major hurricanes are observed to cause 80 to 85 percent of all US tropical cyclone-linked destruction.

Recent observations indicate increased salinity in upper ocean layers of the North Atlantic. Greater salinity increases the density of these surface layers which are then able to more readily sink to greater depths, thereby increasing the compensating northward flow of warm (and salty) replacement water at upper ocean levels. The resulting net enhanced northward transport of upper-layer warm water into the far North Atlantic (and compensating equatorward transport of deep cold water) is the principal manifestation of the Atlantic Ocean thermohaline conveyor circulation. A strong conveyor circulation thus transports greater quantities of heat to high latitudes. Slowly increasing upper-layer salinity values in the far North Atlantic during recent years indicate the development of a stronger thermohaline circulation and a warmer North Atlantic. The effects of a stronger thermohaline circulation have been evident in the region since the spring of 1995 where, as noted before, the best proxy for this increased circulation has been warm North Atlantic SST anomalies.

Despite El Niño-linked reductions of hurricane activity during 1997, the last six years (1995-2000) have together been the most active six consecutive year period on record. This enhanced level of activity includes the total number of named storms (79), hurricanes (49), major hurricanes (category 3-4-5) (23), major hurricane days (56.25) and Net Tropical Cyclone Activity (NTC, 976) which occurred during the last six years. Despite the El Nino diminished 1997 hurricane season, the annual average of NS, H, HD, IH, IHD and NTC during the last six years are 146, 163, 239, 329, 331 and 214 percent (respectively) of the average hurricane activity for the six-year period of 1989-1994. The annual average NS, H, IH, IHD and NTC values during the last six years are 153, 165, 247, 250, 373 and 217 percent respectively of the average for the previous 25-year period (1970-1994). The largest increases have come with IH and IHD activity. See our 21 November 2000 verification of our 2000 forecast (available on the web) for more documentation and discussion on this topic.

The general warming of the North Atlantic that has taken place during the last six years is in concurrence with increased incidence of major Atlantic hurricanes, an association similar to what occurred during the most active hurricane seasons of the 1930s to the 1960s. This active trend manifests itself primarily in the form of more hurricanes forming at low latitudes, more intense hurricanes, and more major hurricanes landfalling along the US East Coast, Florida, and the Caribbean region. We expect that this trend will continue for several decades. Hurricane activity in the Gulf Coast region is less effected by these changes.

# 7 Landfall Probabilities for 2001

A significant focus of our recent research involves efforts to develop seasonal estimates of hurricane landfall probability 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 determined with (useful) statistical skill. With the observation that, statistically, landfall is a function of varying climate conditions, a probability specification has been developed 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 cyclone intensity classes for a set of distinct U.S. coastal regions.

Net landfall probability is linked to the overall Atlantic basin NTC activity and to climate trends associated with multi-decadal variations of the Atlantic Ocean thermohaline circulation. The latter is measured by recent year North Atlantic SSTA*, an index of North Atlantic SSTA in the area between 50-60°N, 10-50°W. Higher values of SSTA* generally indicate greater Atlantic hurricane activity, especially for major hurricanes. Atlantic basin NTC can be skillfully predicted and the strength of the Atlantic Ocean thermohaline circulation can be inferred as SSTA* from North Atlantic SST anomalies from prior years. These values are then utilized to make probability estimates for U.S. landfall. The current (July 2001) value of SSTA* is 57. Hence, in combination with a prediction of NTC of 120 for 2001, a combination of NTC + SSTA* of (120 + 57) yields a value of 177.

As shown in Table 14, 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. Whereas many active Atlantic hurricane seasons feature no landfalling hurricanes, some inactive years have experienced one or more landfalling hurricanes. However, 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 last 100 years show that a greater number of intense hurricanes strike the Florida and U.S. East Coast during years of (1) highest NTC and (2) when above-average North Atlantic SSTA* conditions are in place. The 33 years with the combined highest NTC and strongest thermohaline circulation (during the last 100) had 24 category 3-4-5 hurricane strikes along the Florida and East Coast whereas the 33 years with the lowest NTC/weakest thermohaline circulation saw only three such intense hurricane landfall events; an 8 to 1 difference.

Table 14: 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: 10/9.3 = 108, 50/46.9 = 107, 6/5.8 = 103, 25/23.77 = 105, 3/2.2 = 130, 5/4.7 = 106, divided by six, yielding an NTC of 111.

| **1950-1990 Averages** | |
|---|---|
| Named Storms (NS) | 9.3 |
| Named Storm Days (NSD) | 46.9 |
| Hurricanes (H) | 5.8 |
| Hurricane Days (HD) | 23.7 |
| Intense Hurricanes (IH) | 2.2 |
| Intense Hurricane Days (IHD) | 4.7 |

Tables 15 and 16 summarize the links between hurricane and tropical storm landfall and the combined influences of NTC and thermohaline circulation (i.e., North Atlantic SSTA* effects) for Florida, the U.S. East Coast and for the Gulf Coast (Note: NTC only is used for this differentiation). Landfall characteristics for the Gulf Coast (Fig. 4) (or regions 1-4) from north of Tampa, FL westwards to Brownsville, TX (36 total category 3-4-5 hurricane landfalls of this century) are different from the rest of the U.S. coast from north of Tampa, FL to Eastport, ME (37 landfalls in regions 5-11). These differences are due primarily to the varying incidence of category 3-4-5 hurricanes in each of these areas. The locations of these 11 coastal zones for which regression equations have been developed relating forecasts of NTC ($NTC_f$) and measured values of SSTA* to landfall probability are shown (Fig. 4).

Table 15: Number of Florida Peninsula and U.S. East Coast (regions 5 through 11) hurricane landfall events by intensity class occurring in the years with 33 highest versus 33 lowest values of NTC plus Atlantic thermohaline circulation (SSTA) during the last century.

| **Intensity Category** | **Sum of Highest 33 Years** | **Sum of Lowest 33 Years** | **Ratio of Highest/Lowest 33 Years** |
|---|---|---|---|
| **IH (Category 3-4-5)** | 24 | 3 | 8.0 |
| **H (Category 1-2)** | 29 | 12 | 2.4 |
| **Tropical Storms** | 24 | 17 | 1.4 |

Table 16: Number of Gulf (regions 1 through 4) hurricane landfall events by intensity class during the seasons with the 33 highest and 33 lowest NTC values during this century.

| **Intensity Category** | **Sum of Highest 33 Years** | **Sum of Lowest 33 Years** | **Ratio of Highest/Lowest 33 Years** |
|---|---|---|---|
| **IH (Category 3-4-5)** | 18 | 5 | 3.6 |
| **H (Category 1-2)** | 22 | 11 | 2.0 |
| **Tropical Storms** | 28 | 27 | 1.0 |

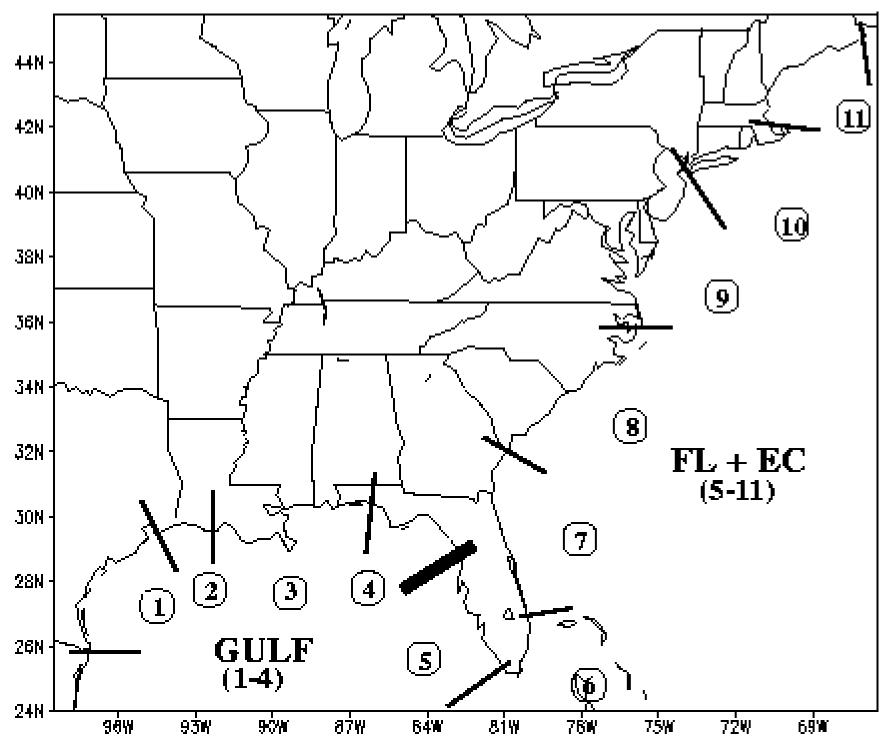



Figure 4: Location of the 11 coastal regions for which separate hurricane landfall probability estimates are made. The heavy bar delineates the boundary between the Gulf (regions 1-4) and the Florida Peninsula and East Coast (regions 5-11).

Figure 5 gives a flow diagram outlining the procedures by which these landfall forecasts are made. Using NTC alone, a similar set of regression relationships has been developed for the landfall probabilities of category 1-2 hurricanes and tropical storms along the Gulf Coast (regions 1-4) and along the Florida Peninsula and East Coast (regions 5-11). Table 17 lists strike probabilities for different TC categories for the whole U.S. coastline, the Gulf Coast and Florida, and the East Coast for 2001. The mean annual probability of one or more landfalling systems is given in parentheses. Note that although Atlantic basin NTC activity in 2001 is expected to be slightly greater than the long term average (120), U.S. hurricane landfall probability is expected to be well above-average owing to North Atlantic SSTAs being above average in recent years (Fig. 5). During periods of positive North Atlantic SSTA, a higher percentage of Atlantic basin major hurricanes cross the U.S. coastline for a given level of NTC.

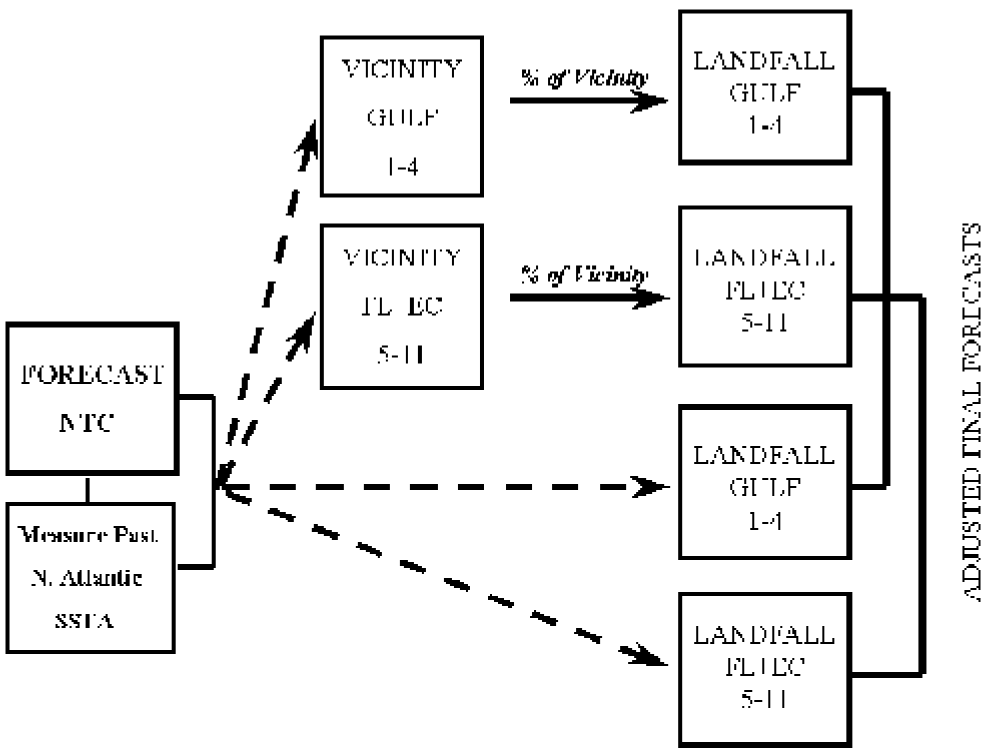



Figure 5: Flow diagram illustrating how forecasts of U.S. hurricane landfall probabilities are made. Forecast NTC values and an observed measure of recent North Atlantic (50-60°N, 10-50°W) SSTA* are used to develop regression equations from U.S. hurricane landfall measurements of the last 100 years. Separate equations are derived for the Gulf and for Florida and the East Coast (FL+EC).

Table 17: 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, total hurricanes and named storms along the entire U.S. coastline, along the Gulf Coast (region 1-4), and along the Florida and the East coastline (Regions 5-11) for 2001. The long-term mean annual probability of one or more landfalling systems during the last 100 years 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)** | 86% (80) | 79% (68) | 69% (52) | 94% (84) | 98% (97) |
| **Gulf Coast (Regions 1-4)** | 67% (59) | 52% (42) | 39% (30) | 71% (61) | 90% (83) |
| **Florida plus East Coast (5-11)** | 57% (51) | 58% (45) | 50% (31) | 78% (62) | 91% (81) |

# 8 Unusual Decrease in U.S. Major Hurricane Landfall During the Last Four Decades

Official records indicate that over the last century (1900-1999), 218 major hurricanes developed in the Atlantic basin and of these category 3-4-5 storms, about one-third (73) came ashore along the U.S. coastline. During the last six years (1995-2000), 23 major hurricanes developed in the Atlantic basin but only three (Opal, 1995; Fran, 1996; and Bret, 1999) came ashore. If the typical long-term one-of-three landfalling-to-total events ratio of major hurricanes observed during the last six years had occurred, then we should have experienced 7-8 major hurricane landfall events versus the three that actually came ashore.

We owe our good fortune to a persistent upper-air trough which has been located along the U.S. East Coast during a high percentage of the time during the last six hurricane seasons. This fortuitous trend has caused a large portion of otherwise northwest moving major hurricanes to be recurved to the north before they reached the U.S. coastline. However, our good luck cannot be expected to continue forever.

Given the U.S. major hurricane landfall numbers during the last century, our luck at beating the long-term climatological odds has now persisted for about four decades. For example, during the 30-year period of 1971-2000, the U.S. experienced 15 major landfall events, or 0.50 per year. This rate of incidence is only 62 percent of the annual incidence of major hurricane landfall events which occurred during the previous 72 years, 1900-1971. Very few residents of the southeastern U.S. coastline are likely aware of how fortunate they have been during the last 3-4 decades.

Regarding the Florida Peninsula and U.S. East Coast, the situation is even more skewed. In the last 40 years (1961-2000), only six major hurricanes (average 0.15 per year) made landfall on the Florida Peninsula and U.S. East Coast. Between 1900-1960, 31 major landfall events occurred along this same coastline (or 0.51 per year). Thus, the first six decades of the 20th century had 3.4 times the annual average incidence of major hurricane landfall events that occurred during the last four decades. It is highly likely that climatology will eventually right itself, and we must therefore expect a great increase in landfalling major hurricanes in the coming decades. With exploding coastal populations in the southeast U.S., we must also prepare for levels of hurricane damage never before experienced.

# 9 Forecast Theory and Cautionary Note

Our forecasts are based on the premise that those global environmental conditions which precede comparatively active or inactive hurricane seasons in the past provide meaningful information about likely similar trends in future seasons. Nevertheless, 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 explicitly predict specifically where within the Atlantic basin these storms will strike. Landfall probability estimates for any one location along the coast are very low and reflect the fact that, in any one season, most US 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 probability does not insure that a hurricane will not come ashore. Regardless of how active the 2001 hurricane season is, a finite probability always exists that one or more hurricanes may strike along the US or Caribbean Basin coastline and do much damage.

# 10 The 1995-2000 Upswing in Atlantic Hurricanes and Global Warming

Some may choose to interpret the recent large upswing in Atlantic hurricane activity (since 1995) as being in some way related to increased man-made greenhouse gases such as carbon dioxide ($CO_2$). There is no scientifically reasonable way that such an interpretation of this recent upward shift can be made. Anthropogenic greenhouse gas warming, even if a physically valid hypothesis, is a very slow and gradual process that, at best, might be expected to bring about small changes in global circulation over periods of 50 to 100 years and could not cause an abrupt and dramatic upturn in hurricane activity as occurred between 1994 and 1995. Also, the large downturn in Atlantic basin major hurricane activity between 1970-1994 must be reconciled with proposed global warming scenarios during this period. Atlantic intense (or category 3-4-5) hurricane activity showed a 40 percent decrease during 1970-1994 versus that which occurred during the 1950-1969 or the 1995-2000 periods. There were 78 Atlantic basin major hurricanes in the 26 years of 1950-1969, 1995-2000 versus 38 in the 25 years of 1970-1994. This is an annual ratio difference of two to one. Even if human-induced greenhouse gas increases were shown to be causing global temperature increases over the last 25 years, there is no way to relate such a small global temperature increase to more hurricane activity.

In contrast with the large increase in Atlantic basin major hurricane activity during the last five years, total hurricane and typhoon activity in the (East and West) North Pacific region during the 1995-2000 period has decreased. When we combine total Atlantic and North Pacific tropical cyclone activity, we observe a net downward trend for the recent 1995-2000 period (Table 18). Hence, we should not interpret the recent enhancement of major hurricanes in the Atlantic as indicative of the changes of hurricane activity around the globe. It is only in the Atlantic where hurricane activity has shown a sharp rise, and this rise is in conformity with the changes in Atlantic sea surface temperature patterns and the diagnosed increase in the thermohaline circulation. Such up and down multi-decadal changes in Atlantic sea surface temperature and tropical cyclone activity have been observed to take place many times in the past and are considered to be naturally occurring modes of multi-decadal variability.

Table 18: Comparison of North Pacific and Atlantic tropical cyclone activity during 1989-1994 versus 1995-2000.

| **(1989-1994)** | **No. of Systems >= TS Intensity** | **No. of Systems >= HUR Intensity** | **No. of Major Hurricanes** |
|---|---|---|---|
| **North Pacific (East and West)** | 301 | 230 | 100 |
| **Atlantic** | 54 | 30 | 7 |
| **Total** | 355 | 260 | 107 |
| **(1995-2000)** | | | |
| **North Pacific (East and West)** | 252 | 183 | 73 |
| **Atlantic** | 79 | 49 | 23 |
| **Total** | 331 | 232 | 96 |
| **Ratio of Total North Pacific + Atlantic 1995-2000/1989-1994** | 0.93 | 0.89 | 0.90 |

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# 11 Verification of 2001 Forecasts

A verification of this forecast will be issued in late November 2001, and a seasonal forecast for the 2002 hurricane season will be issued in early December 2001.

# 12 Acknowledgments

The authors are indebted to a number of meteorological experts who have furnished us with the data necessary to make this forecast or who have given us valuable assessments of the current state of global atmospheric and oceanic conditions. John Knaff, John Sheaffer and Todd Kimberlain have made many important contributions to the conceptual and scientific background for these forecasts. We are particularly grateful to Arthur Douglas, Richard Larsen, Ray Zehr and Mark DeMaria for very valuable climate discussions and input data. We thank Colin McAdie and Jiann-Gwo Jiing who have furnished data necessary to make this forecast and to Gerry Bell, James Angell, and Stan Goldenberg for input data and helpful discussions. Richard Taft has provided valuable data development and computer assistance. We wish to thank Tom Ross of NCDC and Wassila Thiao of the African Desk of CPC who provided us with West African and other meteorological information. In addition, Barbara Brumit and Amie Hedstrom have provided excellent manuscript and data analysis assistance. We have profited over the years from many in-depth discussions with most of the current NHC hurricane forecasters. These include Lixion Avila, Miles Lawrence, Richard Pasch, Jack Beven, James Franklin, and Stacy Stewart. The first author would further like to acknowledge the encouragement he has received for this type of forecasting research application over the last two decades from Neil Frank, Robert Sheets, Robert Burpee, Jerry Jarrell, former directors of the National Hurricane Center (NHC), and from the current director, Max Mayfield. We also thank Bill Bailey of the Insurance Information Institute, Inc. for his sage advice and encouragement.

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## 13

## Additional Reading

## APPENDIX A: Verification of Past Seasonal Forecasts