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

A downturn is expected from the recent five (1995-96-98-99-00) very busy seasons. Above average probability of US landfall is forecast.

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

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[Both this and prior forecasts are available at the following World Wide Web address: http://tropical.atmos.colostate.edu/forecasts/index.html] — also you may contact:

David Weymiller and Thomas Milligan, Colorado State University media representatives who are available to answer various questions about this forecast (970-491-6432).

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2001 ATLANTIC BASIN SEASONAL HURRICANE FORECAST

Tropical Cyclone Seasonal	7 December 2000 Forecast for 2001	Updated 7 April 2001 Forecast
Named Storms (NS) (9.3)	9	10
Named Storm Days (NSD) (46.9)	45	50
Hurricanes (H)(5.8)	5	6
Hurricane Days (HD)(23.7)	20	25
Intense Hurricanes (IH) (2.2)	2	2
Intense Hurricane Days (IHD)(4.7)	4	4
Hurricane Destruction Potential (HDP) (70.6)	65	65
Maximum Potential Destruction (MPD) (61.7)	60	60
Net Tropical Cyclone Activity (NTC)(100%)	90	100

UPDATED PROBABILITY OF ONE OR MORE MAJOR (CATEGORY 3-4-5) HURRICANE LANDFALL

1) Entire U.S. coastline – 65% (average for last century is 52%)

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

3) Gulf Coast from the Florida Panhandle westward to Brownsville – 37% (average for last century is 30%)

4) Expected average major hurricane landfall risk in the Caribbean

Landfall probabilities for 2001 are above-average even though forecast NTC is average (100). This is due to the expected ongoing contribution of the recent six-year positive North Atlantic SSTA trend which is a proxy representation of the strength of the Atlantic thermohaline circulation – see discussion in section 6. A full report on the methodology for estimating these landfall probabilities is in preparation and will be made available on this Website.)

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 or so 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 kt 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 intensity of Saffir/Simpson category 3 or higher.

MATL - Sea surface temperature anomaly in the sub-tropical Atlantic between 30-50°N, 10-30°W

MPD - Maximum Potential Destruction - A measure of the net maximum destruction potential during the season compiled as the sum of the square of the maximum wind observed (in knots) for each named storm. Values expressed in 10^3kt.

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.

NATL - Sea surface temperature anomaly in the Atlantic between 50-60°N, 10-50°W

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 (see Appendix B).

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 reverse 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 5 is the most intense hurricane.

SLPA - Sea Level Pressure Anomaly - The deviation of Caribbean and Gulf of Mexico 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.

TATL - Sea surface temperature anomaly in Atlantic between 8-22°N, 10-50°W.

ZWA - Zonal Wind Anomaly - A measure of upper level ($\sim$ 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 = .515 meters per second.

ABSTRACT

Information obtained through March 2001 indicates that the 2001 Atlantic hurricane season will be less active than the recent, very busy 1995, 1996, 1998, 1999 and 2000 seasons but more active than the average for seasons during the recent multi-decadal period of low activity which extended from 1970 through 1994. Collectively, Atlantic basin Net Tropical Cyclone (NTC) activity during 2001 is expected to be about the average for the last 50 years. Predictive signals in the Atlantic basin including Sea Surface Temperature Anomalies (SSTAs) and surface pressure are quite positive (meaning favorable for more activity). The primary suppressing influences of this year's activity are the anticipated development of a weak to moderate El Niño this summer and an easterly QBO. We estimate that 2001 should see about 6 hurricanes (average is 5.7), 10 named storms (average is 9.3), 50 named storm days (average is 47), 25 hurricane days (average is 24), 2 intense (category 3-4-5) hurricanes (average is 2.2), 4 intense hurricane days (average is 4.7) and a Hurricane Destruction Potential (HDP) of 65 (average is 71) and overall average NTC activity of 100, or equal to the average year for the period between 1950–1990. U.S. landfall probability is forecast to be 5-10 percent above the long term average owing to the effects of the anticipated continuation of a strong Atlantic Ocean thermohaline circulation.

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 activity and landfall probability. This paper presents details of our observations as well as the rationale for this 2 to 8-month (1 June to 30 November) extended range seasonal forecast for 2001. The forecast is based on both statistical and analog analyses of prior hurricane seasons with atmospheric and oceanic conditions similar to what we anticipate to be in place during the 2001 hurricane season.

Useful long-range predictive signals exist for seasonal tropical cyclone activity in the Atlantic basin. Our research has shown that a sizeable portion of the season-to-season variability of Atlantic tropical cyclone activity can be forecast with skill exceeding climatology by early December of the prior year. Qualitative adjustments are added to accommodate additional processes which are not yet incorporated into our statistical models. Two influences which will largely determine this year's Atlantic hurricane activity are:

1. The status of El Niño-Southern Oscillation (ENSO) and
2. The configuration of Atlantic Sea Surface Temperature Anomaly (SSTA) conditions which provide proxy signals for the strength of the Atlantic Ocean thermohaline circulation.

Presently, we anticipate that a weak to moderate El Niño event will act as an inhibiting influence on 2001 activity whereas North Atlantic SSTA patterns will continue to be a positive enhancing influence, as they have been for the last six years. Other lesser factors include the following:

3. The phase of the stratospheric Quasi-Biennial Oscillation (QBO) of zonal winds at 30 mb and 50 mb (which can be extrapolated six months into the future).
4. Two measures of West African rainfall during the prior year (Figs. 1 and 2).
5. The strength of the Azores high surface pressure anomaly in March of this year and October-November of last year and the configuration of current and forecast future broad scale Atlantic sea surface pressure and temperature anomaly patterns (see Fig. 3).

A brief summary of these predictor indices and their specific current implications for the 2001 season follows:

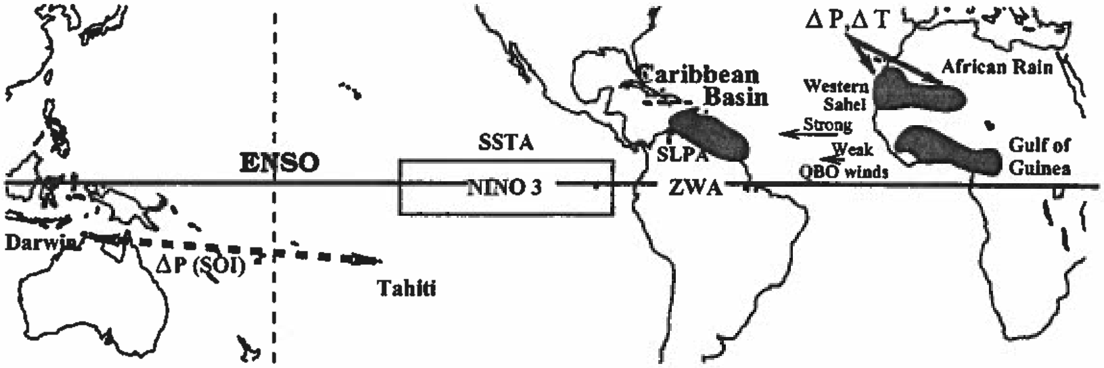

Figure 1: Meteorological parameters used in various versions of our older early August (Gray et al. 1994a) seasonal forecast.

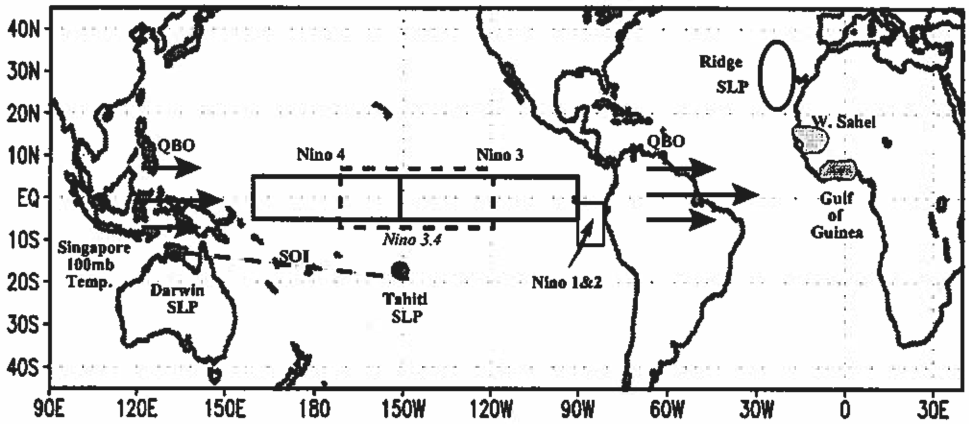

Figure 2: Additional parameters used or consulted in our extended-range forecasts.

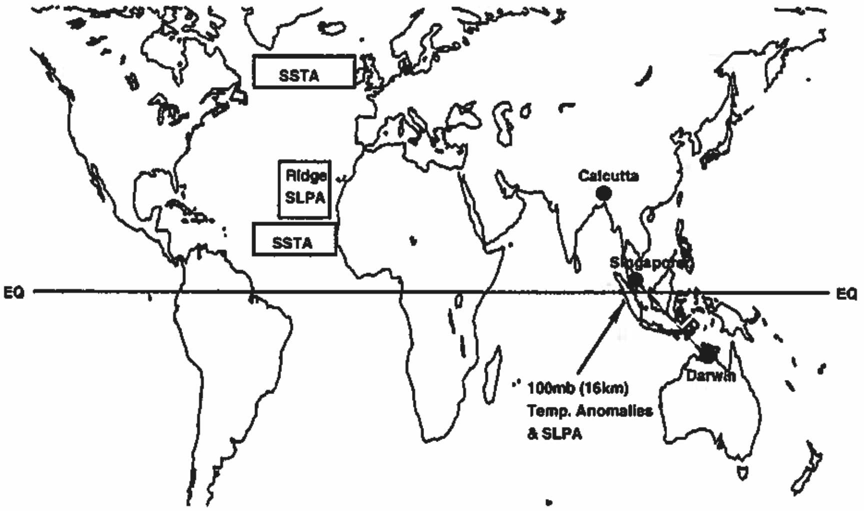

Figure 3: Additional (new) predictors which have recently been noted to be related to the upcoming Atlantic hurricane activity.

a) ENSO

ENSO is one of the principal global-scale environmental factors affecting Atlantic seasonal hurricane activity. Hurricane activity is usually suppressed during El Niño events (e.g., 1997 when the strongest El Niño ever observed for the August to October period occurred in the equatorial eastern and central Pacific). Conversely, activity tends to be enhanced during seasons with cold (or La Niña) water conditions, as occurred during 1998–2000. We expect that the recent cool ENSO conditions are now being replaced by a weak to moderate El Niño which will be in place during the 2001 hurricane season. This should be a modest suppressing influence on 2001 hurricane activity but not nearly as strong as the extremely intense event of 1997.

Warming of the tropical east Pacific Ocean sea surface during El Niño events suppresses hurricane activity by contributing to stronger deep cumulus convective activity in this region. A portion of the upper-level wind outflow from this enhanced convection moves into the tropical Atlantic where it simultaneously sinks and dries the upper troposphere and strengthens upper-level ($\sim$ 200 mb) westerly winds. The latter effects strongly inhibit the intensification of organized westward moving (African) disturbances through enhanced vertical shear. We anticipate that during 2001, these effects (particularly in combination with the easterly QBO at 50 mb, as described below) will be a constraint on Atlantic TC activity.

We also anticipate the El Niño characteristics during 2001 will be more typical of the El Niño events of the 1950s and 1960s (i.e., 1951-53-57-63-65) wherein equatorial Pacific SST warming trends begin along the coast of Peru and spread westward with time to the Dateline (as originally discussed by Rasmussen and Carpenter 1982). The comparatively strong and persistent multi-year El Niño events observed during the 1970s, 1980s and mid-1990s (i.e., 1972, 1982–1983, 1986–1987 and 1997) are believed to be less likely at present owing to the recent (since mid-1990s) multi-decadal rearrangement of SSTA patterns in the Atlantic and Pacific Oceans. This re-configuration of SSTs is also reflected as concurrent changes of the North Atlantic Oscillation (NAO), the Pacific Decadal Oscillation (PDO) and the Pacific North America pattern (PNA).

It is estimated that El Niño SSTAs during August to October 2001 will be about the average amplitude of the five one-year El Niño events that occurred between 1942 and 1968 (1951, 1953, 1957, 1963 and 1965). Table 1 shows that the SSTAs associated with these 1950s and 1960s El Niño events were generally less intense than those El Niño events of 1972, 1982, 1986, 1987 and 1997 when long term global ocean SSTA patterns were different from what are expected this year or occurred in the 1950s and 1960s.

The five strong El Niño events which occurred during the 1970 through the mid-1990s period (1972, 1982, 1986, 1987, 1997) had average August-October NINO 3.4 SSTAs which were 60 percent warmer than observed for the five events between 1950s through 1965 (1951, 1953, 1957, 1963, 1965); this, is in addition to having numerous individual maximum monthly values which were often more than twice as strong. Consistent with these more recent (1970–1997) stronger El Niño events, average Atlantic basin NTC was only about 40 percent of the average using the five earlier (1951–1965) El Niños. NINO 3.4 SSTAs during the four-year (off-and-on) 1991 through 1994 El Niño event were, on average, not as warm as the average for the five individual one-year events of the 1950–1960s. However, the average of the maximum individual months during this 1991–1994 period were greater. Regardless of the strength of the El Niño warming events during 1970–1995, all nine El Niño years (i.e., 1972-82-86-87-97 and 1991 through 1994) had Atlantic basin NTC activity (average NTC of nine recent El Niño years) of 46 versus 105 for the five El Niño years of during the 1950s and 1960s).

ENSO Is Not the Only Consideration

Although ENSO conditions are the single most important parameter dictating Atlantic seasonal hurricane variability, other properties of the atmosphere and ocean can be preeminent in some years. Table 2 shows years when active hurricane seasons occurred during El Niño conditions as well as when inactive hurricane seasons occurred during La Niña conditions. Note in the lower panel of Table 2 that despite NINO 3.4 SSTA conditions which are, on average, nearly 2°C warmer, NTC

Table 1: August through October NINO 3.4 SSTA in °C, and the individual monthly maximum anomaly observed that year (from Kaplan as provided by A. Mestas-Nuzes). Comparative NTC values are also listed for each year.

Net Tropical Cyclone (NTC) Activity During El Niño Years When Strong Atlantic Ocean Thermohaline Conditions Were Present and Atlantic SSTA's Were Generally Positive (Warm) as Expected In 2001

	Aug-Oct SSTA	Max Monthly Value During Year	NTC
1951	0.60	0.71 (Aug)	120
1953	0.57	0.80 (Aug)	120
1957	1.20	1.26 (Dec)	85
1963	1.13	1.28 (Dec)	115
1965	1.55	1.80 (Nov)	85
Mean	1.01	1.17	105

Net Tropical Cyclone (NTC) Activity During El Niño Years When Weak Atlantic Ocean Thermohaline Conditions Were Present and Atlantic SSTA's Were Generally Negative (Cool) Conditions Not Expected to Be Present This Year

1972	1.59	2.32 (Nov)	28
1982	1.35	2.39 (Dec)	37
1986	0.82	1.42 (Dec)	38
1987	1.73	2.07 (Sept)	47
1997	2.51	2.98 (Nov)	54
Mean	1.60	2.24	41

4-Year Long Continuous "Hemorrhage" Type El Niño Events During Which Weak Atlantic Ocean Thermohaline Conditions Were Present – Conditions Not Anticipated For This Year

1991	0.44	1.82 (Dec)	59
1992	0.07	2.10 (Feb)	66
1993	0.44	1.36 (May)	53
1994	0.77	1.51 (Dec)	36
Mean	0.43	1.70	53

Table 2: Unusual years in which warm El Niño and cool La Niña (NINO 3.4) conditions occur but with TC activity trends opposite to what is typically observed.

Cool (La Niña) Seasons With Below Average NTC Activity

Year	Aug-Oct NINO 3.4 SSTA (°C)	NS	H	NTC
1890	−1.00	1	1	13
1892	−1.07	9	4	78
1956	−0.61	8	4	69
1970	−1.01	10	5	64
1973	−1.56	7	4	51
Average	−1.05	7	3.6	55

Warm (El Niño) Seasons With Above Average NTC Activity

1896	1.22	6	6	141
1899	1.07	6	5	144
1951	0.60	10	8	120
1953	0.64	14	6	120
1969	0.68	17	12	155
Average	0.84	10.6	7.4	136

activity was 2.6 times greater during this collection of exceptionally warm years compared to the exceptionally cold years shown in the top panel.

Thus, even if our projection of a weak to moderate El Niño event of next summer-fall is exactly correct, this in itself would not guarantee an inactive hurricane season; exceptionally strong anomalies for other large scale atmosphere/ocean features (such as Atlantic basin SST, SLPA and zonal winds) can play a dominant role in some years.

b) QBO–Tropical Cyclone Lag Relationship

The easterly and westerly modes of stratospheric QBO zonal winds which encircle the globe over the equatorial regions have a substantial influence on Atlantic tropical cyclone activity (Gray, 1984a; Shapiro, 1989). Typically, 50 to 75 percent more hurricane activity (depending on the specific activity index considered) occurs 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 large vertical wind shear conditions between 30 and 50 mb.

During 2001, we anticipate that the easterly QBO phase will be in place in the lower stratosphere below 30 mb throughout the hurricane season. This should be a modest inhibiting influence on this year's hurricane activity.

c) African Rainfall-Tropical Cyclone Lag Relationship

As discussed by Landsea (1991), Gray and Landsea (1992) and Gray et al. (1992), predictive signals for seasonal hurricane activity occur in West African rainfall data during the mid-summer to fall period of the prior year. Two such rainfall-linked signals include:

(1) June–September Western Sahel Rainfall. The Western Sahel area (see Fig. 2) experiences large year-to-year persistence of rainfall 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 the first half of the 1990s) and suppressed hurricane

activity. Since the rainfall in this region is positively related to Atlantic hurricane activity, year-to-year persistence alone tends to provide a moderate amount of skill for forecasting next season's African rainfall as well as the associated Atlantic hurricane activity. Last year's (2000) rainfall over the Western Sahel during June-September was –0.70 SD below average and thus is a negative factor for 2001 hurricane activity.

(2) August–November Rainfall in the Gulf of Guinea. Landsea (1991) and Gray and Landsea (1992) documented a strong African rainfall - intense hurricane lag relationship using August through November rainfall along the Gulf of Guinea (see Fig. 2). Intense hurricane activity during seasons following the ten wettest August–November Gulf of Guinea years is many times greater than occurs during hurricane seasons following the ten driest August-November periods in the Gulf of Guinea. Since 1994 West Sahel rainfall has been generally higher than it was during the 1970 to 1993 period, however. The 2000 August-November Gulf of Guinea rainfall was below average (–0.50 SD), implying a negative influence on next year's hurricane activity. However, it is notable that these two rainfall relationships have not worked as well during the active hurricane seasons of the last few years (1995–2000) as it had in earlier decades and we judge them to be of little influence in dictating how the coming hurricane season will evolve.

d) October–November 2000 and March 2001 Atlantic Subtropical Ridge (Azores High) Between 20-30°W

High surface pressure between 20-30°W associated with the Azores high is positively related to stronger east 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 often associated with higher surface pressures during the following spring which can then create a self-enhancing (positive feedback) process ultimately resulting in higher Caribbean pressures during the summer (Knaff 1999). By this mechanism, positive ridge index values in fall and in March are thus associated with an enhanced Azores high the following spring, stronger trade winds and, thereby, generally reduced hurricane activity. The long-term memory and feedback effects of this association make it a useful parameter for predicting next year's seasonal hurricane activity. Ridge strength during October-November 2000 was high, +1.1 SD above the long-term mean. But, March 2001 ridge values have been very low (-1.6 SD). These March ridge pressure values are more dominant than the October-November values. The very low March values are an indication of enhanced 2001 hurricane activity.

2 Prediction Methodology

We forecast nine measures of seasonal Atlantic basin tropical cyclone activity including 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 3). For each of these measures, we choose the three to six best predictors (i.e., those resulting in optimum prediction skill) from a group of 13 possible forecast parameters which are known to be related to tropical cyclone activity. The current set of potential predictors used to develop our early April forecast is shown in Table 3. The specific values of these parameters for this year's April forecast are shown in the right hand column of this table.

The statistical skill of this forecast in hindcast data is summarized in Table 4. The number of forecast parameters is given in parentheses. We make every attempt to minimize the skill degradation (i.e., limit statistical "overfitting") of these equations when making independent forecasts by choosing the least number of predictors for the highest amount of hindcast skill. We stop adding predictors when the hindcast improvement owing to inclusion of the next best predictor adds less than a 0.025 variance improvement to the total variance explained.

We have also studied schemes which use various fixed numbers of predictors. This procedure investigates how hindcast variance (not necessarily true skill) increases as the number of predictors increases from 4 to 6. Although independent forecast skill (i.e., "true skill") typically degrades in approximate proportion to the increased number of predictors, it is of interest to determine 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. Additional forecast parameters representing conditions in the Atlantic and Pacific Ocean basins and in the Asia-Australia regions (Figs. 1 to 3) are also consulted for further qualitative perspective and add influence to our final "adjusted" forecast.

Table 3: Pool of predictors (and their values as of 1 April 2001) used to develop the 2001 prediction based on meteorological data available through March 2001. See Figs. 1–3 for the locations of these predictors.

For 1 April 2001 Prediction (see Figs. 1–3 for location)	Specific 1 April Fcst Parameters
1) U50 (Mar extrapolated to Sep) – Actual	–22 m/s
2) U30 (Mar extrapolated to Sep) Actual	–10 m/s
3) AbsShe - absolute shear (Mar extrapolated to Sep)	12 m/s
4) Balboa - U50 (June-Aug, 2000)	–8.0 m/s
5) Rain - Aug-Nov Guinea Coastal Area	–0.50 SD
6) Rain - Aug-Sep West Sahel Area	–0.70 SD
7) R-ON - Ridge SLPA (Oct to Nov)	+1.10 SD
8) R-M - Ridge SLPA (Mar)	–1.60 SD
9) NATL (Jan to Mar) SSTA (50-60°N, 10-50°W)	+0.50°C
10) TATL (Jan to Mar) SSTA (8-22°N, 10-50°W)	+0.0°C
11) Nino 3.4 Mar SSTA	–0.30°C
12) Nino 3.4 (Mar minus Feb) SSTA	+0.24°C
13) Nino 4 (Jan, Feb, Mar minus Oct, Nov, Dec) SSTA	–0.25°C

On average, a net degradation of hindcast skill of between 5-15 percent of the variance is to be expected. Degradation (if any) for an individual forecast is a random process, however. In some years when conditions include strong trends that are similar to past years, forecasts will do quite well while in other years a given forecast can perform quite poorly. The latter is largely due to our 48-year (1950-1997) base of predictors which likely does not yet contain the full range of independent possibilities. Our 1997 forecast is a good example of this problem. No year in our 1950 through 1996 developmental data sets contained an El Niño event of comparable intensity (by a factor of 2) as the summer-fall 1997 El Niño – the most intense ENSO SST anomalies ever observed at that time of year, and our 1997 forecast failed.

3 Early April Forecast

Forecast signals for 2001 indicate a mix of positive and negative influences. Of the 13 potential predictors listed in Table 1, all but four are negative (i.e., indicating a below average hurricane season). However, we believe the positive regional Atlantic factors largely due to the new stronger Atlantic thermohaline circulation will act to balance out the negative parameters, leading to the prospect of a near average season.

Table 5 lists our April statistical prediction for the 2001 hurricane season. It contains variable (column 1) and fixed predictors (columns 2 and 3), along with what we consider our current best qualitatively adjusted forecast [Column (4)]. Climatology is given in the last column on the right. Note that we envisage the 2001 hurricane season to be more active than is specified by our statistical scheme. Since the apparent shift of Atlantic Ocean climate in 1995 our statistical forecasts have rather consistently underpredicted Atlantic basin hurricane activity (except for the unusually strong El Niño year of 1997). We believe that the 2001 hurricane season will again

Table 4: Hindcast (i.e., regression testing on data for past years) statistical predictor skill (measure of agreement or r^2) of our separate 1 April hindcasts for 1950-1997. Column (a) gives our best prediction with the minimum number of predictors shown in parentheses. Columns (b) and (c) give our hindcast skill obtained with the best 4 and 6 predictors, respectively.

		Fixed Number of predictors	
	Variable Predictors	4	6
	(a)	(b)	(c)
N	.531 (4)	.531	.569
NSD	.541 (5)	.489	.559
H	.459 (4)	.459	.506
HD	.505 (5)	.460	.517
IH	.510 (4)	.520	.552
IHD	.362 (3)	.378	.465
HDP	.504 (5)	.455	.518
NTC	.566 (6)	.490	.573
MPD	.613 (5)	.573	.630

be more active than is indicated by our statistical schemes, this owing to several new and likely hurricane enhancing features not fully incorporated in our statistical database. The latter include the persistence of warm north and tropical Atlantic SSTA patterns (associated with an enhanced Atlantic thermohaline circulation) which are expected to continue, as well as below average summer west Atlantic surface pressures.

Part of this statistical model underprediction problem is likely due to an apparent weakening of the strong West African rainfall – hurricane relationship which is an important component of our statistical forecast scheme. For this reason, we have recently expanded our studies to analog years with pre-season climate conditions similar to 2001.

Prediction of Caribbean Basin SLPA. Another 1 April predictor available to us but not yet quantitatively incorporated into our statistical forecast scheme is a prediction of the June through September Caribbean basin Sea Level Pressure Anomaly (SLPA). Lower SLPA is typically associated with enhanced hurricane activity, while higher SLPA values reduce it. This SLPA linked predictor was developed by J. Knaff (1998); a former project member. SLPA forecasts are based on information concerning the March Atlantic subtropical ridge, January through March SSTs in the North Atlantic (50-60°N, 10-50°W), and the January through March Niño 3.4 (5°N–5°S, 120°W–170°W) SST anomalies. Hindcasts using this predictive signal (since 1903) show good skill and a significant association with variations of seasonal hurricane activity. This year the 1 April prediction of the Caribbean and western Atlantic SLPA for June through September 2000 indicates below average SLPA (Table 6). This result suggests an enhancing influence for hurricane activity and further evidence that the 2001 hurricane season should be a reasonably active one.

Rationale for Upward Adjustments of 2001 Statistical Regression Forecast. We believe that the 2001 hurricane season will be more active than the values indicated by our statistical regression scheme. It appears that the training data sets for our statistical schemes, developed from 1950–1997 do not fully capture conditions associated with the unusually enhanced hurricane activity of the last six years. In addition, our statistical schemes have systematically underestimated the seasonal hurricane activity in five of the last six seasons (likely owing to effects of the changing of strength of the Atlantic thermohaline circulation). The one exception to this during this period was the year of 1997 when the most intense El Niño ever measured during a hurricane season was recorded. These considerations and the results of our analysis of analog years (discussed below)

Table 5: April statistical forecasts for 2001. These forecasts include one forecast obtained with a variable number of predictors and two other forecasts with 4 and 6 fixed predictors (columns 2 and 3). Column 4 presents our final adjusted early April forecast of 2000 hurricane activity. Column 5 gives climatology.

	(1)	(2)	(3)	(4)	(5)
Full		Fixed predictors			
Forecast Parameter	Variable Predictor	4 Predictors	6 Predictors	Adjusted 1 Aug. Actual Fcst	1950-1990 Climatology
Named Storms (NS)	5.7 (4)	5.7	6.0	10	9.3
Named Storm Days (NSD)	32.0 (5)	56.4	35.5	50	46.9
Hurricanes (H)	5.7 (4)	5.7	4.8	6	5.8
Hurricane Days (HD)	15.8 (5)	3.5	18.8	25	23.7
Intense Hurricanes (IH)	2.6 (4)	2.8	3.5	2	2.2
Intense Hurricane Days (IHD)	4.6 (3)	5.0	6.8	4	4.7
Hurricane Destruction Potential (HDP)	40.5 (5)	14.7	42.6	65	70.6
Net Tropical Cyclone Activity (NTC)	76.4 (6)	35.3	109.1	100	100

Table 6: April 1 multi-month independent statistical prediction of 2001 summertime Caribbean basin and Western tropical Atlantic Sea Level Pressure Anomaly (SLPA) expressed in mb from Knaff (1998). Separate regression analyses are made for each monthly category.

	June-July	August-September	June through September
SLPA	–0.35	–0.66	–0.79

lead us to increase our 2001 forecast numbers beyond that specified by our statistical scheme. Our named storm statistical forecast is low because this forecast parameter is overly dependent on West African rainfall which has been anomalously low the last few years.

4 Anticipated Weak to Moderate El Niño Conditions During August-October 2001

We anticipate that a weak to moderate El Niño event will develop in the tropical Pacific this coming summer. Our reasoning is as follows:

1. Presently, eastern Pacific warm (Nino 1-2) water conditions have become quite warm. Two prominent westerly wind bursts have also occurred during the last four months in the Indonesia–tropical West Pacific region. These sorts of westerly wind events are known to be important in initiating at least some El Niños, especially in QBO easterly wind years. Table 7 shows changes in Pacific equatorial SSTA conditions during the last three months.
2. Various ENSO prediction groups have recently begun to predict an El Niño for 2001. Of the nine El Niño forecasts we have seen, about half are calling for weak to moderate conditions. The other half indicate little or no warming.
3. Four years will have passed since the onset of the very strong 1997 event and, El Niño's tend to be irregularly spaced at 3-5 year intervals. We do not anticipate this El Niño being a strong one because we are in a period of strong Atlantic Ocean thermohaline conditions during which El Niño frequency and strength tend to be diminished. For example, there were 10 El Niños (or 0.208 per year) during the aggregate 48-year period of 1926–1968 and 1995–1999 (and only a few of these were strong) when the Atlantic thermohaline circulation is inferred to have been relatively strong. By contrast, there were 26 El Niños (0.464 per year and more events strong) during the aggregate 56 year period (1896–1925 and 1969–1994) when the Atlantic thermohaline circulation is presumed to have been weak; the difference is greater than two-to-one. A discussion of these associations appears in a conference paper by the first author (Gray 1998) and in a more extended report (Gray et al. 1996). Allowing that we are in a period of relatively strong Atlantic thermohaline circulation, we expect that only a weak to moderate El Niño event is likely to occur during the 2001 hurricane season.

Table 7: 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
Warming From January to March	0.1	0.4	0.8	1.8

5 Analog Based Estimates of Hurricane Activity During 2001

Certain years in the historical record have global oceanic and atmospheric trends notably similar to 2000/2001. These analog years provide useful clues as to likely trends that the forthcoming 2001 hurricane season may bring. Although some of the physical associations involved with these relationships may be only partly understood, they are useful for extended range prediction. For this (1 April) extended range forecast, we project expected atmospheric and oceanic conditions for the coming August through October period and determine which of the prior years in our database have similar environmental conditions and then study the trends in hurricane activity during those years.

Analog Years Selected. Since 1949, we find six prior years wherein spring and the forthcoming summer-fall conditions appear similar to this year; that is now through November 2001 wherein

- the North Atlantic (50-60°N, 10-50°W) had persistent warm SST anomalies during the prior 5-6 years and (as is expected) remained warm through the following hurricane season. This assumes that a persistent strong decadal thermohaline circulation in the Atlantic this year.
- The current general conditions of the NAO, PNA, PDO, and AO will also persist in their present mode through fall 2001 (i.e., in a global atmosphere and ocean circulation regime typical of the 1940s and 1950s).
- QBO 50 mb winds in September 2001 are projected to be from an easterly direction. We view this as a enhancing factor for the development of an El Niño in 2001.
- Negative March East Atlantic subtropical SLPA ridge conditions are observed and are anticipated to continue through summer-early autumn 2001. This is a strong enhancing factor for tropical storm activity.

The analog years are 1951, 1952, 1953, 1957, 1963, and 1965. None of these six 2001 analogs seasons had strongly suppressed hurricane activity (see Table 8). Based on the values in Table 8, we expect the 2001 season to approximate the average value for these six analogs. This analog technique appears to be a more reliable forecast than the generally lower levels of activity predicted by our statistical schemes as discussed previously. Thus, based on this analysis we expect that 2001 should be about as active as an average of these six analog years but more active than the average seasons during the inactive 1970–1994 period.

Table 8: Best analog years for 2001 with the associated hurricane listed for each year.

	NS	NSD	H	HD	IH	IHD	HDP	NTC
1951	10	58	8	36	2	5.00	113	120
1952	7	40	6	23	3	3.75	70	97
1953	14	65	6	18	3	5.50	59	120
1957	8	38	3	21	2	5.25	67	85
1963	9	52	7	37	2	5.50	103	115
1965	6	40	4	27	1	6.25	73	85
Mean	9.4	50.6	5.6	27.8	2	5.5	83	105
2001 Forecast	10	50	6	25	2	4	65	100

6 Upward Adjustment of 7 December 2000 Forecast for 2001

We have chosen to make a one cyclone upward adjustment of our 7 December 2000 forecast because we believe that (1) the current incipient El Niño event will not be as strong as we anticipated in December and (2) regional Atlantic factors including SSTA and forecast SLPA now seem more favorable. We see the coming El Niño as being only a weak to moderate event that will not, as which the intense El Niño of 1997, strongly reduce Atlantic activity.

7 General Characteristics of the 2001 Season

We anticipate that the 2001 hurricane season will differ from the last three (very active) hurricane seasons (1998-2000) with less intense hurricane activity at lower latitudes and more and weaker forming at higher latitudes. We also foresee more early season activity. (The last three seasons have been largely devoid of tropical cyclone activity prior to mid-August.)

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

For years we have been suggesting (eg., Gray 1990, Gray et al. 1996) that the recent (1970–1994) era of reduced Atlantic intense (category 3-4-5) hurricane activity was likely ending and that Atlantic coastal residence should expect an eventual long-term increase of landfalling major hurricanes. 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 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 high 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 transports greater quantities of heat to high latitudes. Hence, slowly rising 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.

Three decades ($\sim$ 1965–1995) passed wherein these SST anomaly patterns were comparatively cool. Figure 4 shows changes in the mean SST anomalies from 1990 to 1994 versus 1995 to 1999. During June through September 1999 SSTA values in the North Atlantic (50-60°N, 10-50°W) were nearly 1°C warmer than during the earlier five-year (1990–1994) period. These warmer SSTAs are presumably a result of a stronger Atlantic Ocean thermohaline circulation which has also led to a 0.5°C warming of the tropical Atlantic (6-22°N, 18-50°W) during the last 10 years. It is presumed that the current warm conditions will continue through 2001.

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 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 (976) which occurred during the last six years. Despite the weak 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 hurricanes, an association similar to what occurred during the most active hurricane seasons of the 1930s to the 1960s. This 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. The Gulf Coast is less effected by these changes. We expect that this trend will continue for several decades.

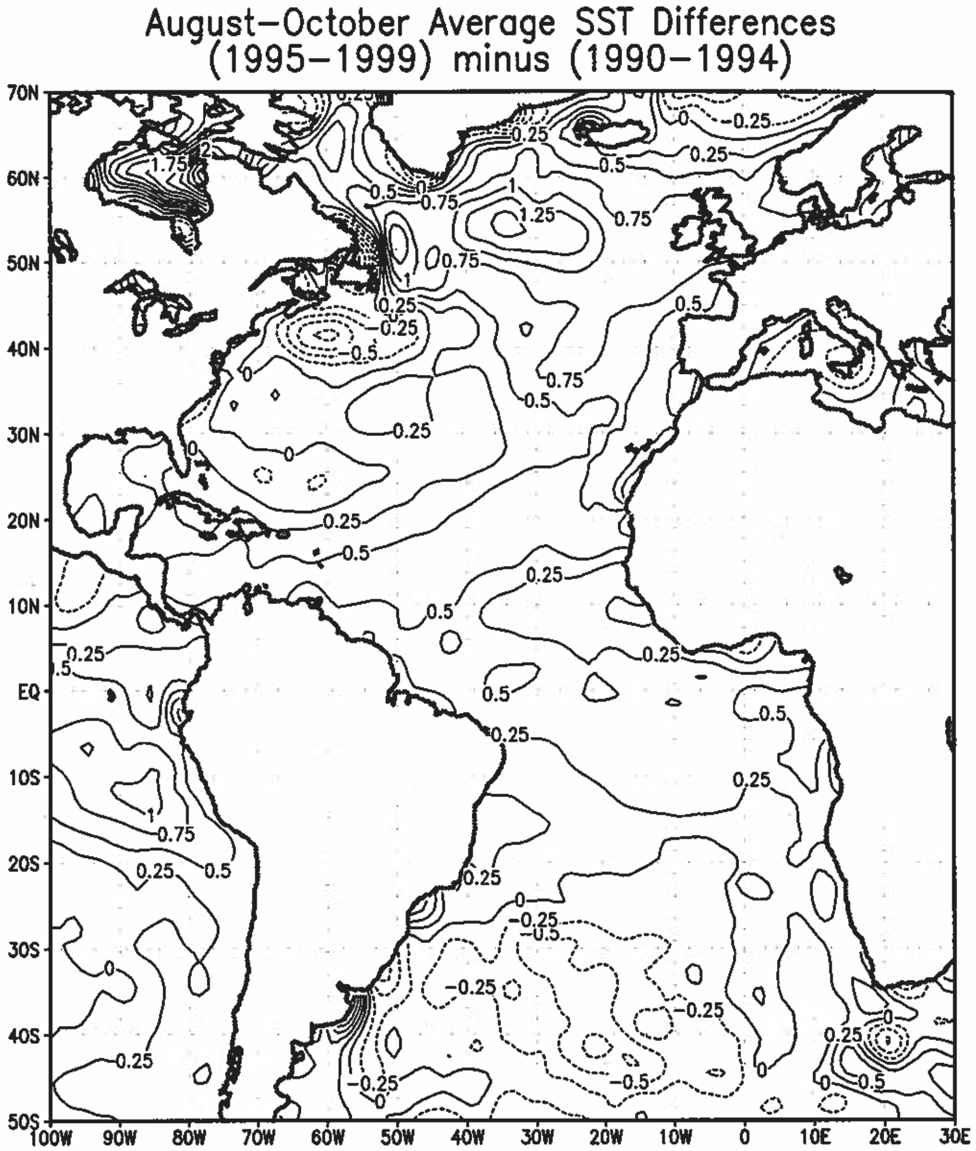

Figure 4: Differences (in °C) for August through October SST between the five-year periods 1995 to 1999 minus 1990 to 1994. Warm (positive) differences are analyzed with solid contours.

9 Landfall Probabilities for 2001

A recent focus of our 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 cyclone intensity classes for a set of distinct U.S. coastal regions.

Net landfall probability is linked to the overall Atlantic basin Net Tropical Cyclone Activity (NTC; see explanation in caption of Table 9) and to climate trends linked to multi-decadal variations of the Atlantic Ocean thermohaline circulation as measured by recent past years of North Atlantic SSTA*, an index of recent year 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 relationships are then utilized to make probability estimates of U.S. landfall. The current (March 2001) value of SSTA* is 57. Hence, in combination with a new prediction of NTC of 100 for 2001, a combination of NTC+SSTA* of (100 + 57) yields a value of 157.

As shown in Table 9, 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. 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 (Saffir-Simpson category 3-4-5) 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; a difference of 8 to 1.

Table 9: 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, 50/46.6 = 107, 6/5.8 = 103, 25/23.9 = 105, 3/2.3 = 130, 5/4.7 = 106, divided by six, yielding an NTC of 110.

	1950-1990 Average	
1)	Named Storms (NS)	9.3
2)	Named Storm Days (NSD)	46.6
3)	Hurricanes (H)	5.8
4)	Hurricane Days (HD)	23.9
5)	Intense Hurricanes (IH)	2.3
6)	Intense Hurricane Days (IHD)	4.7

Tables 10 and 11 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 (NTC only) for the Gulf Coast.

Landfall characteristics for the Gulf Coast (Fig. 5) (or regions 1-4) from north of Tampa, FL westwards to Brownsville, TX (36 total category 3-4-5 hurricane landfalls of this century) and the rest of the U.S. coast from north of Tampa, FL to Eastport, ME (37 landfalls in regions 5-11).

Table 10: Number of Florida Peninsula and U.S. East Coast (regions 5 through 11) hurricane landfall events by intensity class occurring in the 33 highest versus the 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
NS	24	17	1.4

Table 11: 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
NS	28	27	1.0

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. 5).

Figure 6 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 TSs along the Gulf Coast (regions 1-4) and along the Florida Peninsula and East Coast (regions 5-11). Table 12 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 approximately that of the long term average (100), U.S. hurricane landfall probability is expected to be above average. This is due to North Atlantic SSTAs being above average in recent years (Fig. 4). 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 activity.

Table 12: 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)	84% (80)	76% (68)	65% (52)	92% (84)	98% (97)
Gulf Coast (Regions 1-4)	70% (59)	50% (42)	37% (30)	68% (61)	89% (83)
Florida plus East Coast (5-11)	56% (51)	55% (45)	46% (31)	75% (62)	89% (81)

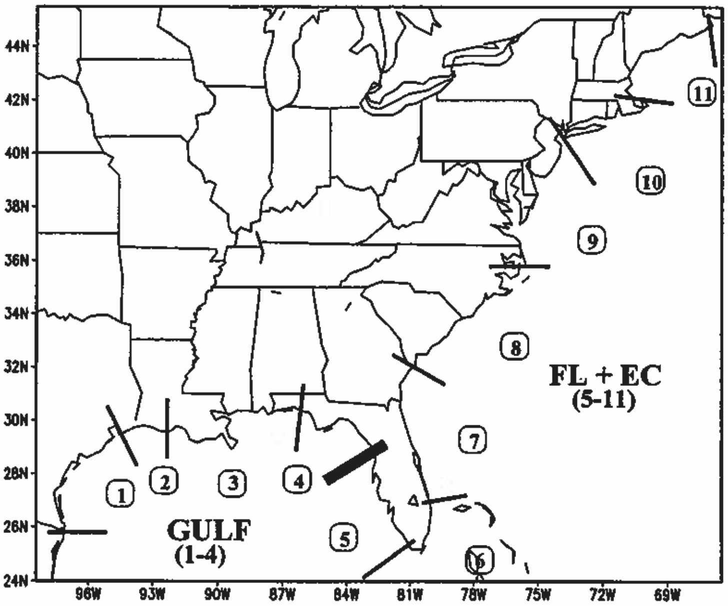

Figure 5: Location of the 11 coastal regions for which separate hurricane landfall probability estimates are made. The heavy bar delineates the boundary between the Gulf (regions 1-4) and the Florida Peninsula and East Coast (regions 5-11).

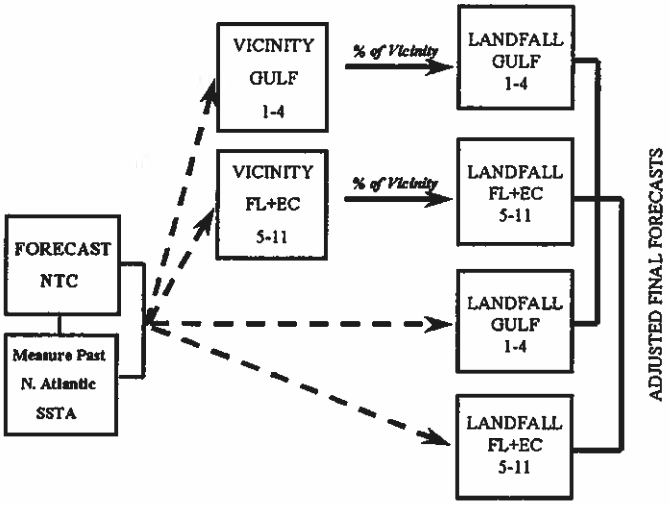

Figure 6: Flow diagram illustrating how forecasts of U.S. hurricane landfall probabilities are made. Forecast NTC values and an observed measure of recent North Atlantic (50-60°N, 10-50°W) SSTA* are used to develop regression equations from U.S. hurricane landfall measurements of the last 100 years. Separate equations are derived for the Gulf and for Florida and the East Coast (FL+EC).

10 Abnormal Decrease in U.S. Major Hurricane Landfall During the Last Four Decades

Official records indicate that over the last century (1900–2000) 218 major hurricanes developed in the Atlantic basin and that of these category 3-4-5 storms, about one-third (73) have come ashore along the U.S. coastline. In 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 longterm one-of-three ratio of major hurricane landfalling-to total events observed during the last six years had occurred, then we should have experienced 7-8 major hurricane landfall events versus just the three that 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 time during the last six hurricane seasons. The 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. But our good luck cannot be expected to continue forever. Very few residents of the southeastern U.S. coastline are likely aware of how fortunate they have been over the last 3-4 decades.

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. As 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.

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 southeast coastal populations, we must also prepare for levels of hurricane damage never before experienced.

11 Forecast Theory and Cautionary Note

Our forecasts are based on the premise that those global environmental conditions which proceed comparatively active or inactive hurricane seasons in the past provide meaningful information about similar trends in future seasons as well. 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 storms will strike. Landfall probability estimates at 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.

12 The Active 1995–2000 Hurricane Seasons and Global Warming

There has been some speculation put forth in the media regarding the recent large upswing in Atlantic hurricane activity (since 1995) as being in some way related to increased human-induced greenhouse gases such as carbon dioxide (CO_2). Such an interpretation of the recent sharp upward Atlantic hurricane activity is not plausible. Globally, total tropical cyclone activity has shown a downward trend since 1995. See our 21 November 2000 verification on this Web site for more discussion.

13 Schedule for 2001 Forecast Updates

This 6 April 2001 forecast will be updated on Thursday 7 June 2001 and Friday 3 August 2001. The 3 August package will also include a separate forecast of August only hurricane activity. These updates will allow us to make adjustments as newer information becomes available. 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.

14 Acknowledgements

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 Sheaffer, John Knaff 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, David Masonis, Vern Kousky, 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 from Neil Frank, Robert Sheets, Robert Burpee, Jerry Jarrell, former directors of the National Hurricane Center (NHC), and from the current director, Max Mayfield.

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15 Additional Reading

Goldenberg, S. B. and L. J. Shapiro, 1996: Physical mechanisms for the association of El Niño and West African rainfall with Atlantic major hurricane activity. *J. Climate*, 1169-1187.

Gray, W. M., 1984a: Atlantic seasonal hurricane frequency: Part I: El Niño and 30 mb quasi-biennial oscillation influences. *Mon. Wea. Rev.*, 112, 1649-1668.

Gray, W. M., 1984b: Atlantic seasonal hurricane frequency: Part II: Forecasting its variability. *Mon. Wea. Rev.*, 112, 1669-1683.

Gray, W. M., 1990: Strong association between West African rainfall and US landfall of intense hurricanes. *Science*, 249, 1251–1256.

Gray, W. M., C. W. Landsea, P. W. Mielke, Jr., and K. J. Berry, 1992: Predicting Atlantic seasonal hurricane activity 6–11 months in advance. *Wea. Forecasting*, 7, 440-455.

Gray, W. M., C. W. Landsea, P. W. Mielke, Jr., and K. J. Berry, 1993: Predicting Atlantic basin seasonal tropical cyclone activity by 1 August. *Wea. Forecasting*, 8, 73-86.

Gray, W. M., C. W. Landsea, P. W. Mielke, Jr., and K. J. Berry, 1994a: Predicting Atlantic basin seasonal tropical cyclone activity by 1 June. *Wea. Forecasting*, 9, 103-115.

Gray, W. M., J. D. Sheaffer and C. W. Landsea, 1996: Climate trends associated with multi-decadal variability of intense Atlantic hurricane activity. Chapter 2 in "Hurricanes, Climatic Change and Socioeconomic Impacts: A Current Perspective", H. F. Diaz and R. S. Pulwarty, Eds., Westview Press, 49 pp.

Gray, W. M., 1998: Atlantic ocean influences on multi-decadal variations in El Niño frequency and intensity. Ninth Conference on Interaction of the Sea and Atmosphere, 78th AMS Annual Meeting, 11-16 January, Phoenix, AZ, 5 pp.

Henderson-Sellers, A., H. Zhang, G. Berz, K. Emanuel, W. Gray, C. Landsea, G. Holland, J. Lighthill, S-L. Shieh, P. Webster, K. McGuffie, 1998: Tropical cyclones and global climate change: A post-IPCC assessment. *Bull. Amer. Meteor. Soc.*, 79, 19-38.

Knaff, J. A., 1997: Implications of summertime sea level pressure anomalies. *J. Climate*, 10, 789-804.

Knaff, J. A., 1998: Predicting summertime Caribbean sea level pressure. *Weather and Forecasting*, 13, 740–752.

Landsea, C. W., 1991: West African monsoonal rainfall and intense hurricane associations. Dept. of Atmos. Sci. Paper, Colo. State Univ., Ft. Collins, CO, 272 pp.

Landsea, C. W., 1993: A climatology of intense (or major) Atlantic hurricanes. *Mon. Wea. Rev.*, 121, 1703-1713.

Landsea, C. W. and W. M. Gray, 1992: The strong association between Western Sahel monsoon rainfall and intense Atlantic hurricanes. *J. Climate*, 5, 435–453.

Landsea, C. W., W. M. Gray, P. W. Mielke, Jr., and K. J. Berry, 1992: Long-term variations of Western Sahelian monsoon rainfall and intense U.S. landfalling hurricanes. *J. Climate*, 5, 1528–1534.

Landsea, C. W., W. M. Gray, K. J. Berry and P. W. Mielke, Jr., 1997: Revised Atlantic basin seasonal tropical cyclone prediction methods for 1 June and 1 August forecast dates. To be submitted to *Wea. Forecasting.*

Landsea, C. W., W. M. Gray, K. J. Berry and P. W. Mielke, Jr., 1996: June to September rainfall in the African Sahel: A seasonal forecast for 1996. 4 pp.

Landsea, C. W., N. Nicholls, W.M. Gray, and L.A. Avila, 1996: Downward trends in the frequency of intense Atlantic hurricanes during the past five decades. *Geo. Res. Letters*, **23**, 1697-1700.

Landsea, C. W., R. A. Pielke, Jr., A. M. Mestas-Nunez, and J. A. Knaff, 1999: Atlantic basin hurricanes: Indices of climatic changes. *Climatic Changes*, 42, 89-129.

Mielke, P. W., K. J. Berry, C. W. Landsea and W. M. Gray, 1996: Artificial skill and validation in meteorological forecasting. *Wea. Forecasting*, 11, 153-169.

Mielke, P. W., K. J. Berry, C. W. Landsea and W. M. Gray, 1997: A single-sample estimate of shrinkage in meteorological forecasting. Submitted to *Wea. Forecasting.*

Pielke, Jr. R. A., and C. W. Landsea, 1998: Normalized Atlantic hurricane damage, 1925–1995. *Wea. Forecasting*, **13**, 621–631.

Rasmusson, E. M. and T. H. Carpenter, 1982: Variations in tropical sea-surface temperature and surface wind fields associated with the Southern Oscillation/El Niño. *Mon. Wea. Rev.*, **110**, 354-384.

Sheaffer, J. D., 1995: Associations between anomalous lower stratospheric thickness and upper ocean heat content in the West Pacific warm pool. Presentation at the 21st AMS Conference on Hurricanes and Tropical Meteorology, Miami, FL, April 22-28.

Sheaffer, J. D. and W. M. Gray, 1994: Associations between Singapore 100 mb temperatures and the intensity of subsequent El Niño events. Proceedings, 18th Climate Diagnostics Workshop, 1-5 November, 1993, Boulder, CO.

Verification of All Past Seasonal Forecasts Follows in Appendix A

APPENDIX A: Verification of Past Seasonal Forecasts

The first author has now issued seasonal hurricane forecasts for 16 consecutive years (1984–1999). In the majority of these forecasts, the predictions were superior to climatology (i.e., long-term averages), particularly for named storms. Figures 8 and 9 offer comparisons of our 1 August forecasts of named storms and hurricanes versus climatology and actual year-to-year variability. Overall, there is predictive skill greater than climatology.

We have issued forecasts for intense or major (category 3-4-5) hurricanes since 1990. The 1 August forecast correlation for these 11 years has been r = .73.

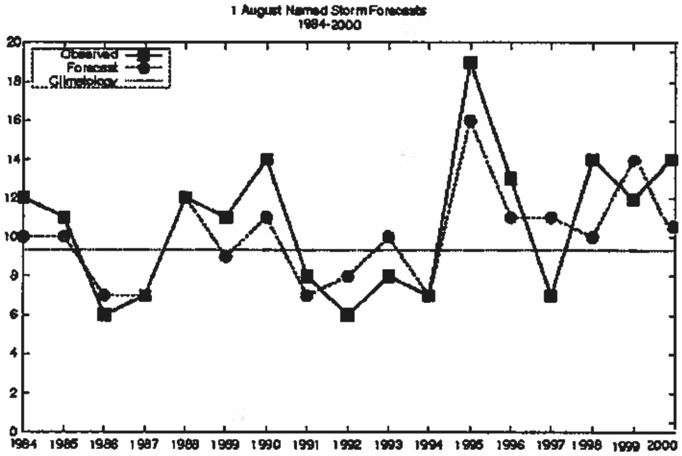

Figure 7: 1 August prediction of total named storms versus the number of actually observed versus long-term climatological mean (r = 0.80) for period 1984–2000.

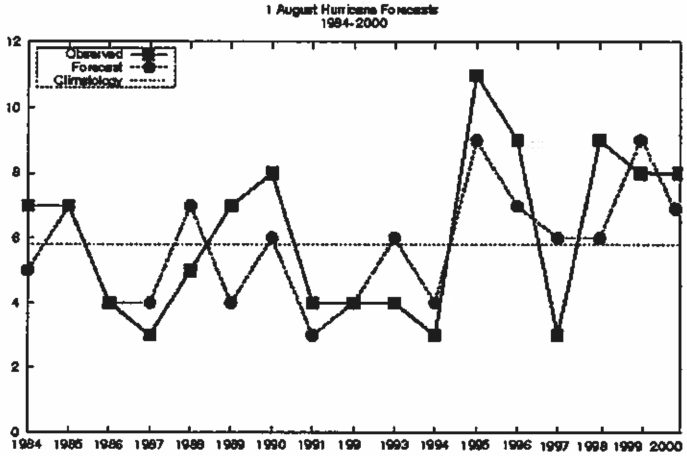

Figure 8: 1 August prediction of total hurricanes versus the number of actually observed versus climatological long-term mean (r = 0.64) for period 1984–2000.

Table 13: Summary verifications of the author's prior seasonal forecasts of Atlantic TC activity between 1984-2000.

	Prediction Dates		
1984	24 May and 30 July Update		Observed
No. of Hurricanes	7		5
No. of Named Storms	10		12
No. of Hurricane Days	30		18
No. of Named Storm Days	45		51
1985	of 28 May	Update 27 July	Observed
No. of Hurricanes	8	7	7
No. of Named Storms	11	10	11
No. of Hurricane Days	35	30	21
No. of Named Storm Days	55	50	51
1986	29 May	Update 28 July	Observed
No. of Hurricanes	4	4	4
No. of Named Storms	8	7	6
No. of Hurricane Days	15	10	11
No. of Named Storm Days	35	25	23
1987	26 May	Update 28 July	Observed
No. of Hurricanes	5	4	3
No. of Named Storms	8	7	7
No. of Hurricane Days	20	15	5
No. of Named Storm Days	40	35	37
1988	26 May and 28 July Update		Observed
No. of Hurricanes	7		5
No. of Named Storms	11		12
No. of Hurricane Days	30		21
No. of Named Storm Days	50		47
Hurr. Destruction Potential(HDP)	75		81
1989	26 May	Update 27 July	Observed
No. of Hurricanes	4	4	7
No. of Named Storms	7	9	11
No. of Hurricane Days	15	15	32
No. of Named Storm Days	30	35	66
Hurr. Destruction Potential(HDP)	40	40	108
1990	5 June	Update 3 August	Observed
No. of Hurricanes	7	6	8
No. of Named Storms	11	11	14
No. of Hurricane Days	30	25	27
No. of Named Storm Days	55	50	66
Hurr. Destruction Potential(HDP)	90	75	57
Major Hurricanes (Cat. 3-4-5)	3	2	1
Major Hurr. Days	Not Fcst.	5	1.00
1991	5 June	Update 2 August	Observed
No. of Hurricanes	4	3	4
No. of Named Storms	8	7	8
No. of Hurricane Days	15	10	8
No. of Named Storm Days	35	30	22
Hurr. Destruction Potential(HDP)	40	25	22
Major Hurricanes (Cat. 3-4-5)	1	0	2
Major Hurr. Days	2	0	1.25

1992		Update	Update	Observed
	26 Nov 1991	5 June	5 August	
No. of Hurricanes	4	4	4	4
No. of Named Storms	8	8	8	6
No. of Hurricane Days	15	15	15	16
No. of Named Storm Days	35	35	35	39
Hurr. Destruction Potential(HDP)	35	35	35	51
Major Hurricanes (Cat. 3-4-5)	1	1	1	1
Major Hurr. Days	2	2	2	3.25

1993		Update	Update	Observed
	24 Nov 1992	4 June	5 August	
No. of Hurricanes	6	7	6	4
No. of Named Storms	11	11	10	8
No. of Hurricane Days	25	25	25	10
No. of Named Storm Days	55	55	50	30
Hurr. Destruction Potential(HDP)	75	65	55	23
Major Hurricanes (Cat. 3-4-5)	3	2	2	1
Major Hurr. Days	7	3	2	0.75

1994		Update	Update	Observed
	19 Nov 1993	5 June	4 August	
No. of Hurricanes	6	5	4	3
No. of Named Storms	10	9	7	7
No. of Hurricane Days	25	15	12	7
No. of Named Storm Days	60	35	30	28
Hurr. Destruction Potential(HDP)	85	40	35	15
Major Hurricanes (Cat. 3-4-5)	2	1	1	0
Major Hurr. Days	7	1	1	0
Net Trop. Cyclone Activity	110	70	55	36

		Update	Update	Update	
1995	30 Nov 1994	14 April	7 June	4 August	Obs.
No. of Hurricanes	8	6	8	9	11
No. of Named Storms	12	10	12	16	19
No. of Hurricane Days	35	25	35	30	62
No. of Named Storm Days	65	50	65	65	121
Hurr. Destruction Potential(HDP)	100	75	110	90	173
Major Hurricanes (Cat. 3-4-5)	3	2	3	3	5
Major Hurr. Days	8	5	6	5	11.5
Net Trop. Cyclone Activity	140	100	140	130	229

		Update	Update	Update	
1996	30 Nov 1995	4 April	7 June	4 August	Obs.
No. of Hurricanes	5	7	6	7	9
No. of Named Storms	8	11	10	11	13
No. of Hurricane Days	20	25	20	25	45
No. of Named Storm Days	40	55	45	50	78
Hurr. Destruction Potential(HDP)	50	75	60	70	135
Major Hurricanes (Cat. 3-4-5)	2	2	2	3	6
Major Hurr. Days	5	5	5	4	13
Net Trop. Cyclone Activity	85	105	95	105	198

		Update	Update	Update	
1997	30 Nov 1996	4 April	6 June	5 August	Obs.
No. of Hurricanes	7	7	7	6	3
No. of Named Storms	11	11	11	11	7
No. of Hurricane Days	25	25	25	20	10
No. of Named Storm Days	55	55	55	45	28
Hurr. Destruction Potential(HDP)	75	75	75	60	26
Major Hurricanes (Cat. 3-4-5)	3	3	3	2	1
Major Hurr. Days	5	5	5	4	2.2
Net Trop. Cyclone Activity	110	110	110	100	54

1998	6 Dec 1997	Update 7 April	Update 5 June	Update 6 August	Obs.
No. of Hurricanes	5	6	6	6	10
No. of Named Storms	9	10	10	10	14
No. of Hurricane Days	20	20	25	25	49
No. of Named Storm Days	40	50	50	50	80
Hurr. Destruction Potential(HDP)	50	65	70	75	145
Major Hurricanes (Cat. 3-4-5)	2	2	2	2	3
Major Hurr. Days	4	4	5	5	9.2
Net Trop. Cyclone Activity	90	95	100	110	173

1999	5 Dec 1998	Update 7 April	Update 4 June	Update 6 August	Obs.
No. of Hurricanes	9	9	9	9	8
No. of Named Storms	14	14	14	14	12
No. of Hurricane Days	40	40	40	40	43
No. of Named Storm Days	65	65	75	75	77
Hurr. Destruction Potential(HDP)	130	130	130	130	145
Major Hurricanes (Cat. 3-4-5)	4	4	4	4	5
Major Hurr. Days	10	10	10	10	15
Net Trop. Cyclone Activity	160	160	160	160	193

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	65	65	75	75	77
Hurr. Destruction Potential(HDP)	85	85	100	90	85
Major Hurricanes (Cat. 3-4-5)	3	3	4	3	3
Major Hurr. Days	6	6	8	6	5.25
Net Trop. Cyclone Activity	125	125	160	130	134