EARLY JUNE UPDATED FORECAST OF ATLANTIC BASIN SEASONAL HURRICANE ACTIVITY AND LANDFALL PROBABILITIES FOR 2000

(A year of expected continued above average hurricane activity and landfall probability)

This forecast is based on ongoing research by the authors and their colleagues, together with meteorological information available through May 2000

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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 (970-491-6432) who are available to answer various questions about this forecast.

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SYNOPSIS OF 2000 ATLANTIC BASIN SEASONAL HURRICANE FORECAST

Tropical Cyclone Seasonal	8 Dec 1999 Forecast	Updated 7 April Forecast	Updated 7 June Forecast
Named Storms (NS) (9.3)	11	11	12
Named Storm Days (NSD) (46.9)	55	55	65
Hurricanes (H)(5.8)	7	7	8
Hurricane Days (HD)(23.7)	25	25	35
Intense Hurricanes (IH) (2.2)	3	3	4
Intense Hurricane Days (IHD)(4.7)	6	6	8
Hurricane Destruction Potential (HDP) (70.6)	85	85	100
Maximum Potential Destruction (MPD) (61.7)	70	70	75
Net Tropical Cyclone Activity (NTC)(100%)	125	125	150

PROBABILITY OF ONE OR MORE MAJOR (CATEGORY 3-4-5) HURRICANE LANDFALL IN THE FOLLOWING COASTAL AREAS:

1) Entire U.S. coastline – 71% (average for last century is 52%)

2) U.S. East Coast Including Peninsula Florida – 52% (average for last century is 31%)

3) Gulf Coast from the Florida Panhandle westward to Brownsville – 40% (average for last century is 30%)

4) Caribbean basin (about 15% above the last century average).

(A full report on the methodology involved with these landfall probabilities being prepared and will be listed on this Web site).

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 6-22°N, 18-80°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 May 2000 indicates that the Atlantic hurricane season in 2000 is likely to be slightly less active than the four recent very busy years of 1995, 1996, 1998 and 1999. However, total activity is expected to exceed the long term average and should notably be more active than the mean for the recent period of 1970 through 1994. We estimate that 2000 will bring about 8 hurricanes (average is 5.7), 12 named storms (average is 9.3), 65 named storm days (average is 47), 35 hurricane days (average is 24), 4 intense (category 3-4-5) hurricanes (average is 2.2), 8 intense hurricane days (average is 4.7) and a Hurricane Destruction Potential (HDP) of 100 (average is 71). Collectively, net tropical cyclone activity in year 2000 is expected to be about 150 percent of the long term average. This early June forecast update is higher than our prior (8 December 1999) and 7 April forecasts.

Our evolving forecast techniques are based on a variety of global and regional predictors which have previously been shown to be related to forthcoming seasonal Atlantic tropical cyclone activity and landfall probability. These predictions are based on results of statistical forecast schemes and analog techniques plus qualitative adjustments which reflect additional effects associated with supplementary global atmosphere and ocean information.

1 Introduction

Useful long-range predictive signals exist for seasonal tropical cyclone activity in the Atlantic basin. Our research with prior data has shown that a sizeable portion of the season-to-season variability of nine indices of Atlantic tropical cyclone activity can be skillfully (i.e., with skill as defined as improvement on climatology) estimated many months prior to the active portion of the hurricane season. Forecast techniques are based on precursor atmosphere and ocean signals observed (in historical data) to contain predictive skill. Qualitative adjustments are added to accommodate additional processes which are not yet incorporated into our statistical models. Predictors include two measures of Western Sahel rainfall during the prior year (Figs. 1 and 2), the phase of the stratospheric Quasi-Biennial Oscillation (QBO) of zonal winds at 30 mb and 50 mb (which can be readily extrapolated many months into the future), extended range estimates of El Niño-Southern Oscillation (ENSO) variability (Fig. 2), the October-November and March strength of the Azores high surface pressure and the configuration of broad scale Atlantic sea surface temperature anomaly patterns (see Fig. 3). A brief summary of these predictor indices and their specific implications for the 2000 season is as follows:

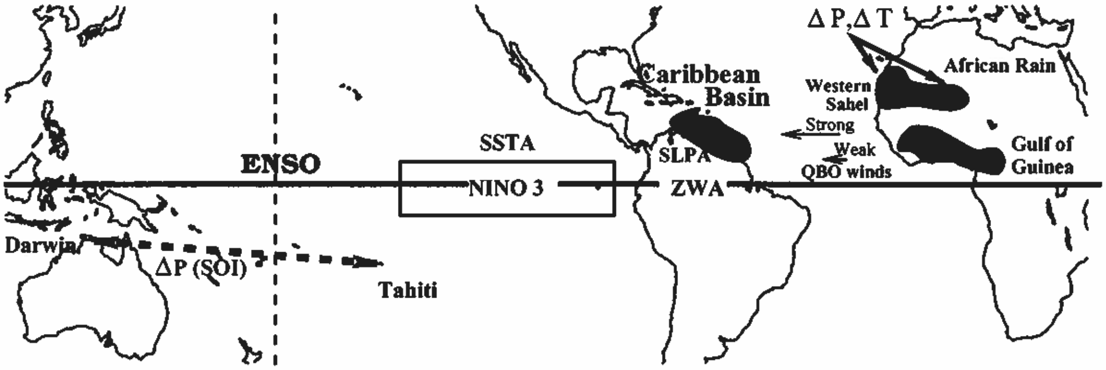

Figure 1: Meteorological parameters used in various versions of our older early August (Gray et al. 1994a) seasonal forecast.

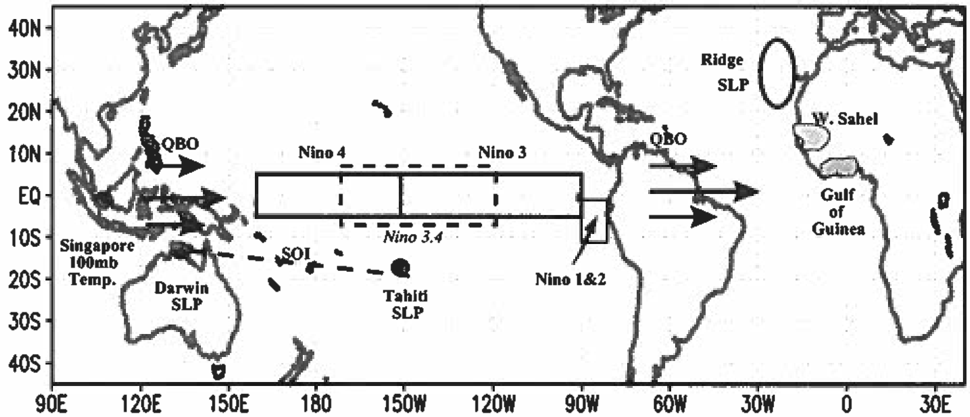

Figure 2: Additional parameters used or consulted in our extended-range forecasts.

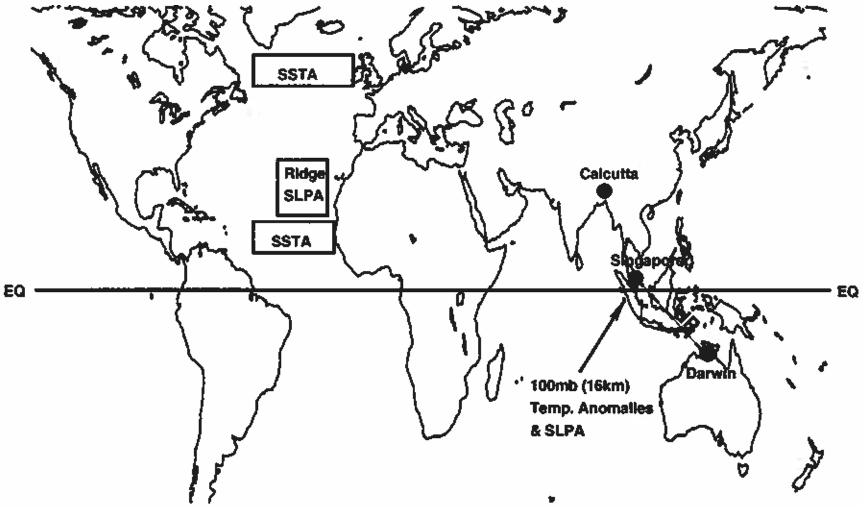

Figure 3: Additional (new) predictors which have recently been noted to be related to upcoming Atlantic hurricane activity.

a) 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 and, when the vertical wind shear (ie., the variation of wind speed with height) between these two levels is comparatively small. Conversely, seasonal hurricane activity is typically reduced when the stratospheric QBO is in the easterly phase and the wind shear between 30- and 50 mb is large. During September 2000, QBO winds are projected to be from an easterly direction with rather large vertical wind shear between these two levels. This should be a suppressing influence on next year's hurricane activity, especially for major low latitude hurricane activity.

b) 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. These rainfall-linked signals include the following:

(1) June–September Western Sahel Rainfall: The Western Sahel area (see Fig. 2) experiences large year-to-year persistence in rainfall. 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. Since the rainfall in this region is positively related to concurrent Atlantic hurricane activity, year-to-year persistence (associated with long-term trends) provides a moderate amount of skill for forecasting the following season's African rainfall as well as the associated Atlantic hurricane activity. Last year's (1999) rainfall over the Western Sahel during August-September was +0.15 SD above average and thus is a modest positive factor for 2000 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). In historical data, intense hurricane activity during seasons in the years following the wettest August–November Gulf of Guinea seasons is typically much greater than the hurricane activity that occurs during hurricane seasons following the driest August-November periods in the Gulf of Guinea. As this rainfall relationship has not held during the last few years (1995–1999), it is being given less qualitative weight in the 2000 forecast. The 1999 August-November Gulf of Guinea rainfall was below average (-0.60 SD), implying a slight negative influence on next year's hurricane activity.

c) The El Niño-Southern Oscillation (ENSO) relationship

ENSO is one of the principal global-scale environmental factors affecting Atlantic seasonal hurricane activity. Hurricane activity is usually suppressed during El Niño seasons (e.g., 1997) when anomalously warm surface water is present 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 and 1999. We expect the current strong cool ENSO conditions to relax somewhat through the key months of August through October 2000 but to remain an enhancing influence for 2000 hurricane activity. (We do not project an El Niño to develop for the coming season).

d) Strength of the October–November (1999) and March (2000) Atlantic Subtropical Ridge (Azores High) Between 20-30°W

Higher than normal surface pressure associated with this atmospheric ridge feature is positively related to stronger east Atlantic trade winds which, in turn, enhance upwelling of cold water off the northwest African coast. Colder sea surface temperatures created by enhanced ocean upwelling can cause higher surface pressures during spring which can then create a self-enhancing (positive feedback) response resulting in higher Caribbean pressures during the summer (Knaff 1999). The long-term memory and the feedbacks in this association make it a useful parameter for predicting seasonal hurricane activity. Higher-than-normal surface pressure during the prior fall and spring periods portends reduced hurricane activity and vice versa. Negative ridge index values are associated with a reduced Azores high, weaker trade winds and, thereby, generally enhanced hurricane activity. Ridge strength during October-November 1999 and March 2000 was somewhat below (−0.14 SD and −0.10 SD respectively) the long-term mean. Consequently, this factor is presently judged to be a slight positive influence for 2000 hurricane activity.

e) Other Global Predictors

Our more recent work has identified additional global scale parameters which are of value in assessing and adjusting the output of our statistical scheme. These include:

- The broadscale configuration of SST anomaly patterns over much of the high (50-60°N, 10-50°W) and low latitude (10-22°N, 18-50°W) Atlantic: Warm SST anomalies in these regions during the fall and winter tend to be associated with an enhancement of this coming summer's hurricane activity and similarly, cold SST anomaly patterns indicate a reduction of hurricane activity. Fall and winter 2000 SST anomaly patterns have been warm in both of these Atlantic regions and are expected to become warm and to be an enhancing influence on this summer's hurricane activity.

- The arrangement of SST anomaly patterns in the Pacific and the Indian Oceans. During the last few years these SST anomalies have taken on configurations which historically have been associated with an enhancement of Atlantic hurricane activity. This configuration of global SSTs includes the recently delineated Pacific Decadal Oscillation (PDO) and the development of cooler ocean temperature patterns in tropical portions of the Indian and western Pacific Oceans. The west Pacific warm pool has recently been recharging at a slow rate. These Pacific and Indian Ocean SST anomaly patterns, along with the new Atlantic Ocean SST anomaly changes (since late 1995) indicate that there is a global scale reconfiguration of ocean SSTAs to patterns which are more typical of a stronger global conveyor belt (or thermohaline) circulation as suggested by Gray (1998), Gray et al. (1997), and others. Similar global SSTA patterns existed during the 1930s to the 1960s.

2 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), the Hurricane Destruction Potential (HDP), Net Tropical Cyclone activity (NTC), and the Maximum Potential Destruction (MPD). (Definitions for these indices are given on page 3). For each of these measures, 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 June forecast is shown in Table 1. The specific values of these parameters for 2000 used are shown in the right hand column.

A number of statistical forecasts are made for each activity parameter. Table 2 lists the seasonal hurricane indices that we predict, the number of forecast parameters we use in each forecast and which forecast parameters these are. Our hindcast skill (between 50-60 percent) for the 48-year period of 1950-97 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

Table 1: Pool of predictive parameters and their estimated values for the early June 2000 prediction. This is based on meteorological data through May 2000. See Figs. 1 and 2 for the locations of these predictors.

Predictive Parameter	
1 = QBO 50 mb 4-month extrapolation of zonal wind at 12°N to Sept. 2000	$-5\ ms^{-1}$
2 = QBO 30 mb 4-month extrapolation of zonal wind at 12°N to Sept. 2000	$-30\ ms^{-1}$
3 = QBO absolute value of shear between 50 and 30 mb at 12°N to Sept. 2000	$25\ ms^{-1}$
4 = Rgc AN Gulf of Guinea rainfall anomaly (Aug-Nov of 1999)	-0.6 SD
5 = Rws West Sahel rainfall anomaly (June-Sept 1999)	0.15 SD
6 = Temp East-West Sahel temperature gradient(Feb-May 2000)	0.50 SD
7 = SLPA April-May Caribbean basin sea level pressure anomaly	+1.1 mb
8 = ZWA April-May Caribbean basin zonal wind anomaly	-2.8 m/s
9 = R-ON: Azores surface pressure ridge strength in Oct-Nov 1999	-0.14 SD
10 = R-M: Mar Azores surface pressure ridge strength in Mar 2000	-0.10 SD
11 = SST3.4 Nino 3.4 SSTA in April-May 2000	-0.54°C
12 = D-SST3.4: Nino 3.4 SSTA for April-May minus Feb-Mar 2000	+0.70°C
13 = TATL Tropical Atlantic SSTA anomaly (10-22°N,18-50°W) (Apr-May)	+0.00°C
14 = NATL North Atlantic SSTA anomaly (50-60°N,10-50°W) (Apr-May)	+0.5°C
15 = SATL Mid Atlantic SSTA anomaly (5-18°S,50°W-10°E) (Apr-May)	+0.30°C

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.

We have also studied a scheme which uses various fixed (maximum) numbers of predictors. Table 3 lists these predictors. 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 and 2) are also consulted for further qualitative inter-relations and possible influences on our final "adjusted" forecast.

Table 4 lists hindcast prediction skills for our various statistical models including the variable (number) predictor schemes along with the fixed (4, 6 and 8) predictor schemes. 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 48-year (1950-1997) predictor data base 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 1996 developmental data sets had never experienced an El Niño event anywhere nearly as intense (by a factor of 2) as the 1997-98 El Niño event.

Table 2: Listing of predictors chosen for each parameter that is forecast and the total hindcast variance explained by these predictors for the enclosed updated 1 June forecast.

Forecast Parameter	No. of Predictors	Predictors Chosen from Table 1	Variability Explained by Hindcast (1950-1997)	Likely Independent Forecast Skill
NS	3	1, 3, 9	.498	.322
NSD	6	3, 4, 5, 7, 9, 10	.562	.405
H	6	3, 4, 5, 7, 10, 11	.532	.361
HD	6	2, 4, 5, 6, 9, 14	.544	.379
IH	5	1, 4, 6, 9, 10	.557	.402
IHD	3	4, 6, 11	.443	.230
HDP	5	1, 4, 5, 6, 10	.532	.366
NTC	5	1, 4, 5, 6, 10	.554	.398
MPD	4	3, 4, 9, 14	.591	.453

Table 3: Hindcast (i.e., regression testing on data for past years) statistical predictor skill (measure of agreement or variance explained) of our separate hindcasts for the period of 1950-1997 for 4, 6 and 8 predictor numbers.

	Best Four Predictors	Hindcast Skill
NS	U50, AbsShe, R-ON, SATL	.538
NSD	AbsShe, Rgc, R-ON, NATL	.502
H	AbsShe, Rgc, R-ON, R-M	.480
HD	AbsShe, Rgc, R-ON, NATL	.482
IH	U50, Rgc, Del-T, R-M	.519
IHD	Rgc, Del-T, SST3.4, SATL	.466
HDP	U50, Rgc, Rws, Del-T	.481
NTC	AbsShe, Rgc, SST3.4, NATL	.516
MPD	AbsShe, Rgc, R-ON, NATL	.591
	Best Six Predictors	Hindcast Skill
NS	U50, AbsShe, Rgc, Del-T, R-ON, SATL	.586
NSD	AbsShe, Rgc, Rws, SLPA, R-ON, R-M	.562
H	AbsShe, Rgc, Rws, SLPA,R-ON, SST3.4	.532
HD	U30, Rgc, Rws, Del-T, R-ON, NATL	.544
IH	U50, U30, Rgc, Del-T, R-ON, R-M	.571
IHD	Rgc, Del-T, R-ON, SST3.4, NATL, SATL	.487
HDP	U30, Rgc, Del-T, R-ON, TATL, NATL	.549
NTC	U30, Rgc, Del-T, R-ON, TATL, NATL	.577
MPD	U50, U30, Rgc, Rws, R-ON, R-M	.635
	Best Eight Predictors	Hindcast Skill
NS	U50, AbsShe, Rgc, Del-T, R-ON, TATL, NATL, SATL	.606
NSD	AbsShe, Rgc, Rws, Del-T, SLPA, R-ON, R-M, SST3.4	.591
H	U50, AbsShe, Rgc, Rws, Del-T, SLPA, R-ON, SST3.4	.553
HD	U30, AbsShe, Rgc, Del-T, ZWA, R-ON, SST3.4, NATL	.568
IH	U50, U30, Rgc, Del-T, R-ON, R-M, TATL, SATL	.602
IHD	U50, AbsShe, Rgc, Rws, Del-T, R-ON, Del-SST3.4, SATL	.516
HDP	U50, U30, Rgc, Rws, Del-T, R-ON, R-M, Del-SST3.4	.584
NTC	U50, U30, Rgc, Del-T, R-ON, SST3.4, Del-SST3.4, NATL	.606
MPD	U50, U30, Rgc, Rws, Del-T, R-ON, R-M, Del-SST3.4	.652

Table 4: 1 June statistical forecasts which have a variable number of predictors with variable predictors (column 1) along with 4, 6 and 8 fixed predictors forecast (columns 2, 3). Column 4 is our final adjusted early June forecast of 2000 hurricane activity. Column 5 gives climatology.

Full Forecast Parameter	(1) Variable Predictor	(2) Fixed predictors 4 Predictors	(3) Fixed predictors 6 Predictors	(4) Adjusted Actual Fcst	(5) 1950-1990 Climatology
Named Storms (NS)	7.6	9.6	9.0	12	9.3
Named Storm Days (NSD)	22.7	33.9	22.7	65	46.9
Hurricanes (H)	1.8	3.1	1.8	8	5.8
Hurricane Days (HD)	25.0	18.9	25.0	35	23.7
Intense Hurricanes (IH)	2.3	2.2	1.9	4	2.2
Intense Hurricane Days (IHD)	5.0	5.5	7.2	8	4.7
Hurricane Destruction Potential (HDP)	83.0	77.3	76.7	100	70.6
Maximum Potential Destruction (MPD)	42.4	42.4	49.2	75	61.7
Net Tropical Cyclone Activity (NTC)	109%	96.1%	99.0%	150%	100%

In Table 4, columns 1-3 lists each of our statistical forecasts, column 4 contains our best qualitatively adjusted "final" forecasts and column 5 provides the climatological mean for each parameter for 1950-1990. Note in column 4 that we have made a large upward adjustment to our statistical forecasts to reflect the expectation of a more active hurricane season.

Three other strong predictors that have not yet been quantitatively incorporated into our statistical forecast scheme and which indicate 2000 seasonal activity above that indicated by our current statistical schemes include the following:

1. June through September prediction of Caribbean basin Sea Level Pressure Anomaly (SLPA). This has recently been developed by J. Knaff (1998). Lower SLPA forecasts indicate enhanced hurricane activity, while higher SLPA indicates a reduction. August-September SLPA has a very strong association with seasonal hurricane activity. Knaff's 1 April 2000 forecast of June through September SLPA gave a value of –0.30 mb. This adds additional evidence for an active 2000 hurricane season. Table 5 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. Using 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, and June through September, respectively. Hindcasts of this predictive signal since 1903 show good skill and a significant association with variations of seasonal hurricane activity. Knaff finds that additional April-May information does not improve on this forecast.

2. A realization that both Atlantic and now, global climate have shifted to a new mode favorable to increased Atlantic major hurricane activity, as experienced from the 1930s through the mid-1960s. This recent climate shift occurred in the Atlantic in 1995 and appears to have now (2000) extended over most of the globe.

3. New information on the configuration of mid-latitude East Pacific SSTAs shows cold values. These SSTAs have not yet been incorporated into our statistical forecast model. Separate analysis of such anomaly patterns in prior data indicate that they are associated with active hurricane seasons.

Table 5: April 1, 2000 multi-month independent statistical prediction of Caribbean basin and Western tropical Atlantic Sea Level Pressure Anomaly (SLPA) for this summer (Knaff 1998). Separate regression analyses are made for each monthly category. SLPA predictions are given in terms of mb.

	June-July	August-September	June through September
SLPA	+0.30	–0.25	–0.30

These three 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 what our analog (discussed next) analysis indicates. Consequently, data through the end of May indicate that 2000 will experience above average hurricane activity and notably more than the average for seasons between 1970–1994, when major hurricane activity was greatly suppressed.

3 Persistence of La Niña Conditions Through October 2000

From recent data we infer that no new El Niño will develop this summer and fall. Rather, the current La Niña (cool surface temperatures in the eastern equatorial Pacific) will continue through this hurricane season, though likely diminished somewhat from the very cold conditions observed in 1999. Our reasoning in this regard includes the following:

1. Less than two years will have passed since the end of the strongest (by a factor of two) 1997–1998 El Niño on record (in terms of August through October anomalies). El Niño's tend to be irregularly spaced at 3-5 year intervals; at least three intervening years occur between the end of the prior and the start of successive El Niño events, especially during multi-decade long periods of warm North Atlantic SST anomalies. We are in a period of enhanced Atlantic Ocean thermohaline conditions and El Niño activity tends to be less during strong versus weak thermohaline periods. For example, there were 10 El Niños (or 0.208 events per year) during the aggregate 48-year period of 1926–1968 and 1995–1999 when the thermohaline circulation was strong versus 26 El Niños (0.464 events per year) during the 56 year period (1896–1925 and 1969–1994) when the Atlantic thermohaline circulation was weak; a greater than two-to-one difference. The likely physics for this association have been described in a conference paper by the first author (Gray 1998). In particular, records indicate that a strong thermohaline circulation is associated with longer periods between El Niños. Examples include the El Niño hiatus between 1931–1939 (nine years), 1942–1950 (nine years) or 1889–1894 (6 years). We judge that the thermohaline circulation and North Atlantic temperatures during these periods were similar (strong) to the current condition. On this basis, it is unlikely that an El Niño will occur during the 2000 hurricane season.

2. The May Nino 3.4 SSTA has remained cool and strong MJO disturbances have not progressed eastward into the central Pacific. We attribute part of this MJO frequency decrease due to the maintenance of 50 mb QBO westerly winds.

3. The majority of the coupled ocean and dynamic model simulations for the period of August through October 2000 do not anticipate an El Niño event during 2000.

Thus, our best estimate is that the probability of an El Niño event for this summer is remote. We anticipate a continuation of the cool ENSO conditions that have been in place during the 1998 and 1999 seasons. A modest sea-level warming in the eastern tropical Pacific during April and May has now largely dissipated and will not intensify into an El Niño event before the hurricane season is over.

4 2000 Hurricane Activity Inferred from Analog Years

We find that certain years in the historical records have similar global oceanic and atmospheric conditions which provide useful clues to the amount of hurricane activity likely to occur in a given year. Although the physical associations involved with these analog relationships are not completely understood, they are useful for additional guidance in extended range prediction. We look for atmospheric and oceanic conditions resembling current May 2000 conditions starting from 1950 (when direct stratospheric QBO wind data were available).

There are four May analogs since 1950 which are fairly similar to March of this year wherein

- the North Atlantic (50-60°N, 10-50°W) tropical Atlantic (10-22°N, 18-50°W) had persistent warm SST anomalies during the prior fall and winter months,
- La Niña conditions were present and persisted (as we expect this year),
- easterly QBO winds were present at 30 and 50 mb during the following September,
- Pacific SST anomalies include broadscale cold water off the North American Coast and warm anomalies southeast of Japan and cool conditions in the eastern tropical Pacific.

The closest analog years for 2000 when many or all of the above conditions are present include 1949, 1956, 1989, and 1996. Table 5 lists the hurricane activity which occurred in the four seasons. The 1956 season was suppressed while the years of 1949, 1989 and 1996 had above average activity despite easterly stratospheric QBO winds.

Table 6: Atlantic basin tropical cyclone activity (during analog seasons for the year 2000).

	NS	NSD	H	HD	IH	IHD	HDP	NTC
1949	13	62	7	22	3	3	64	115
1956	8	30	4	13	2	2.25	39	69
1989	11	66	7	32	2	9.75	108	135
1996	13	78	9	45	6	6.00	135	204
Average	11.3	59	6.8	28	3.3	5.3	87	131
2000 Forecast	12	65	8	35	4	8	100	150

Our actual forecast represents a compromise closer to our analog analysis than our statistical forecast models.

Observations through the end of May indicate that the season of 2000 will experience above average Atlantic basin hurricane activity and much more activity than that which occurred during the generally suppressed hurricane seasons of 1970–1994.

5 Reasons for Increasing Our 7 June forecast Over Our 8 December 1999 and 7 April 2000 Forecasts

1. North Atlantic SSTA: Recent analyses of SSTA across the Atlantic reveal a slight cooling over subtropical and tropical waters across the eastern and central Atlantic. Endfield and Mayer, however, show that this is a typical response of SSTs in the Atlantic during a La Niña event at this time of the year. We expect, however, that this is a temporary fluctuation and that SSTA will rebound to above normal levels by the peak of the season.

2. The state of ENSO: Although the current La Niña episode has been gradually dissipating since the late winter/early Spring, there is evidence that suggests that the currently weakening trend has halted with the result being that cool conditions are likely to persist into the summer and fall months.
3. 200mb wind anomalies: These anomalies are very suggestive of an active season with the typical La Nina cyclonic anomalies present over the central Pacific and anomalous ridging (easterlies at 200mb) from the Caribbean Sea to west Africa. Such a pattern is conducive to the formation of easterly waves at low latitudes over the tropical Atlantic.
4. Global monsoon activity: Observations and recent reports indicate that both the Asian and Mexican monsoons began ahead of schedule and have been characterized as strong. This pattern of convection (also seen in OLR anomalies) is consistent with the global pattern of precipitation during very active hurricane seasons. Increased monsoonal flow from Central America to Africa is already in evidence and portends another component to an active hurricane season.
5. Likewise, the east-west positive temperature gradient across northwest Africa suggests an enhancement in this summer's monsoon trough over the region. Thus there will likely be stronger and more organized easterly wave activity across the tropical Atlantic.

6 Landfall Probabilities for 2000

A new aspect of our research involves efforts to develop forecasts of the probability of hurricane landfall along the U.S. coastline. Whereas individual hurricane landfall events can not be accurately forecast for an individual year, the net yearly probability of landfall can be forecast with statistical skill. With the premise that andfall is a function of varying climate signals, a probability specification has been accomplished through a statistical analysis of all U.S. hurricane landfalls of named storms 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 statistically related to the overall Atlantic basin Net Tropical Cyclone Activity (NTC) 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*). The current value of SSTA* is 37. With a new prediction of NTC of 150, this yields a combination of NTC+SSTA* of (150 + 37) = 187. SSTA* is 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, particularly major hurricane activity.

As shown in Table 7, NTC is a combined measure of the year-to-year mean of six indices of hurricane activity, each expressed as a percentage differences from the long-term average. Whereas many active Atlantic hurricane seasons feature no landfalling hurricanes, a number of inactive years have experienced one or more landfalling hurricanes. Long period 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 highest NTC and when above average North Atlantic SSTA* conditions are in place. The 33 years (during the last 100) with the combined highest NTC and strongest thermohaline circulation experienced 24 category 3-4-5 hurricane strikes along the Florida and East Coast whereas the 33 years with the lowest NTC and the weakest thermohaline circulation saw only 3 such intense hurricane hits, a difference ratio of 8 to 1. Tables 8 and 9 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 and the U.S. East coast and also for NTC only for the Gulf Coast. Atlantic basin NTC can be skillfully predicted and the strength of the Atlantic Ocean thermohaline circulation can be inferred from North Atlantic Sea Surface Temperature (SST) anomalies from the prior year. These predictive relationships can therefore be utilized to make probability estimates of U.S. landfall .

Table 7: NTC activity in any year consists of the seasonal average 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 one-sixth of the percentage of 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, or 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

Table 8: Number of Florida Peninsula and U.S. East Coast (regions 5 through 11) hurricane landfall events by intensity class during the 33 highest versus the 33 lowest values of NTC plus Atlantic thermohaline circulation (SSTA) of 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 9: 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

Landfall characteristics occur for the Gulf Coast or (regions 1-4) extending from north of Tampa, FL and 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).

These differences are due primarily to the varying incidence of category 3-4-5 hurricanes in each of these areas. Figure 4 shows 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 in these 11 regions. Figure 5 gives a flow diagram outlining the procedures by which these forecasts are made.

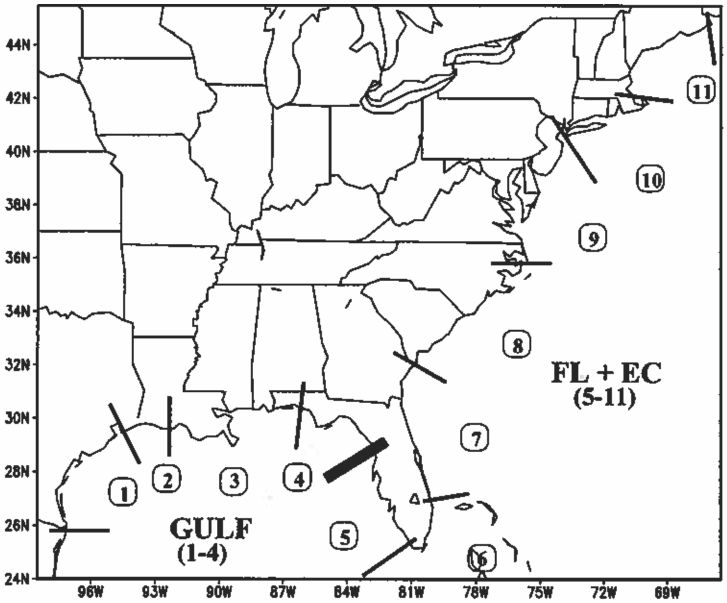

Figure 4: Location of the 11 coastal regions for which separate hurricane landfall probability estimates are made.

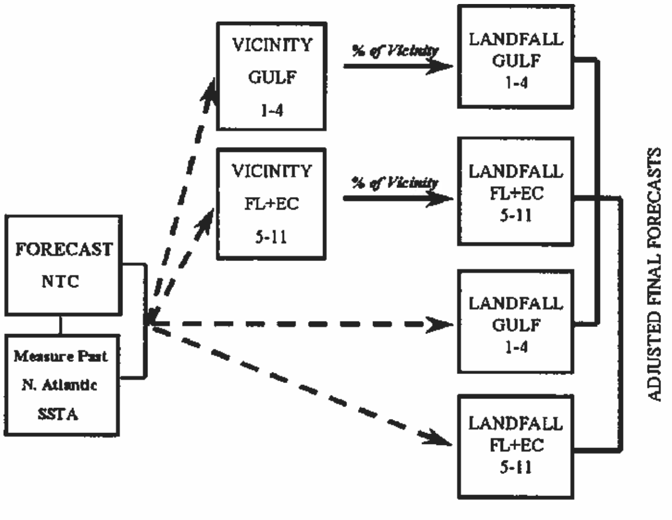

Figure 5: General flow diagram illustrating how forecasts of U.S. hurricane landfall probabilities are made. We forecast NTC and use an observed measure of the last few years of North Atlantic (50-60°N, 10-50°W) SSTA*. Regression equations are then developed from the combinations of forecast NTC and measured SSTA* values. A regression is then developed from U.S. hurricane landfall measurements of the last 100 years and separate equations are derived for the Gulf and for Florida and the East Coast (FL+EC).

A similar set of regression relationships has been developed for the landfall probabilities of category 1-2 hurricanes and TSs with NTC separately along the Gulf Coast (regions 1-4) and along the Peninsula Florida and East Coastlines (regions 5-11). Research is now directed to make landfall probabilities available for 11 distinct Gulf Coast and U.S. East Coast regions extending from Brownsville, TX to Eastport, ME. Table 10 lists landfall probabilities for a range of TS, Cat 1-2, and Cat 3-4-5 hurricanes impacting the whole U.S. coastline, the Gulf Coast and Florida and the East Coast for 2000. The mean annual number of landfalling systems is given in parentheses.

Table 10: Estimated poisson probability (percent) of one or more U.S. landfalling Tropical Storms (TS), category 1-2 hurricanes, and 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 2000. The mean annual number 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)	87% (80)	80% (68)	71% (52)	94% (84)	98% (97)
Gulf Coast (Regions 1-4)	68% (59)	53% (42)	40% (30)	72% (61)	92% (83)
Florida plus East Coast (5-11)	58% (51)	59% (45)	52% (31)	80% (62)	91% (81)

Although not explicitly determined for this report, intense hurricane (category 3-4-5) frequency in the Caribbean area during 2000 should approximate that for Florida and the U.S. East Coast; the latter being somewhat greater than the long-term average and distinctly higher than during the recent downturn period between 1970–1994.

7 Forthcoming Technique for the Prediction of U.S. Hurricane Landfall Probability

Full documentation of the methodology for estimating hurricane landfall probability study is being prepared and will, hopefully, be available before our early August updated forecast. Landfall probabilities include specific forecast of the probability for tropical storms (TS) and hurricanes of category 1, 2, 3, 4-5 striking the following areas during 2000:

- anywhere along the entire U.S. coastline,
- the Florida and East Coast and along the Gulf Coast,
- each of 11 units of the U.S. coastline which are further subdivided by coastal population in 96 regions,
- each 100 km (65 mile) segment of U.S. coastline.

These forecast landfall probabilities will be supplemented with the probability for each 100 km coastal segment receiving gale force winds ($\geq$ 40 mph), sustained hurricane force winds ($\geq$ 75 mph), and major hurricane (category 3-4-5) winds ($\geq$ 115 mph).

There will also be a discussion of potential tropical cyclone spawned hurricane destruction within 96 different U.S. coastal locations based on population.

8 Evidence of Persistent Multi-Decade Enhancement of Atlantic Hurricane Activity Associated With a Major Reconfiguration of Global Ocean Surface Temperature Patterns

Recent observations indicate increased salinity in upper layers of the North Atlantic Ocean. Higher salinity increases the density of water in the upper ocean layers which is then more able to sink to great depth, thereby increasing compensating northward flow of Atlantic warm (and salty) replacement water in upper ocean levels. The resulting net northward transport of warm upper-layer water into the far North Atlantic (and compensating equatorward transport of deep cold water) is the principal manifestation of the Atlantic Ocean thermohaline (or "Conveyor Belt") circulation. A strong conveyor circulation increases ocean surface temperatures in the high latitude Atlantic areas by transporting more heat to high latitudes. Hence, slowly rising salinity values in the far North Atlantic during recent years suggest the development of conditions favorable for a stronger Atlantic thermohaline circulation. The effects of a stronger thermohaline circulation have been evident in the Atlantic since the spring of 1995. The best proxy signal for this enhanced circulation condition is the North Atlantic SST anomalies.

Three decades have passed since the SST anomaly patterns of the Atlantic Ocean have been so warm. Figure 6 shows the change of the mean SST anomalies for 1990 through 1999 versus the mean for 1995 to 1999. SSTA values in the North Atlantic (50-60°N, 10-50°W) for June through September 1999 were nearly 1°C warmer than the earlier five-year (1990–1994) period. These warmer SSTAs are a direct result of a stronger Atlantic Ocean thermohaline circulation. And this stronger thermohaline circulation has also led to a warming of the tropical Atlantic (8-22°N, 10-50°W) ocean SSTAs. Figures 7 and 8 show time changes of SST changes during two recent five-year periods and the time series of SSTA in the North Atlantic (50-60°N, 10-50°W) since 1900. It is assumed that these warm conditions will persist through 2000. Note that the general warming of the North Atlantic that has taken place during the last five years when the incidence of major hurricanes also increased is similar to that which occurred during active hurricane seasons in the period from the 1930s to the 1960s. This trend is hypothesized to manifest itself through alterations of many global climate parameters as seen in Fig. 9. This includes more hurricanes forming at low latitudes, more intense hurricanes, and more major hurricanes landfalling along the US East Coast, Florida, and in the Caribbean Sea. The Gulf Coast seems less affected by these changes. This trend may continue for several decades.

For years now, we have been suggesting (eg., Gray 1990, Gray et al. 1996) that the recent era of reduced Atlantic intense (category 3-4-5) hurricane activity (which occurred between 1970-1994) was likely ending and that Atlantic coastal residents 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.

Despite El Niño-linked reductions of hurricane activity during 1997, the last five years (1995–1999) are together the most active five (consecutive) year period on record. This activity includes the total number of named storms (65), hurricanes (41), major hurricanes (category 3-4-5) (20), major hurricane days (51) and Net Tropical Cyclone activity (842) which occurred during the last five years. Even with the inclusion of the weak 1997 hurricane season, the annual average of NS, H, IH, IHD and NTC during the last five years are 155, 178, 400, 816 and 311 percent (respectively) of the average hurricane activity for 1990–1994. And, the annual average NS, H, IH, IHD and NTC during the last five years has been 151, 165, 257, 263, 405 and 224 percent of the average for the previous 25-year period (1970-1994). The largest increases have come in IH and IHD activity.

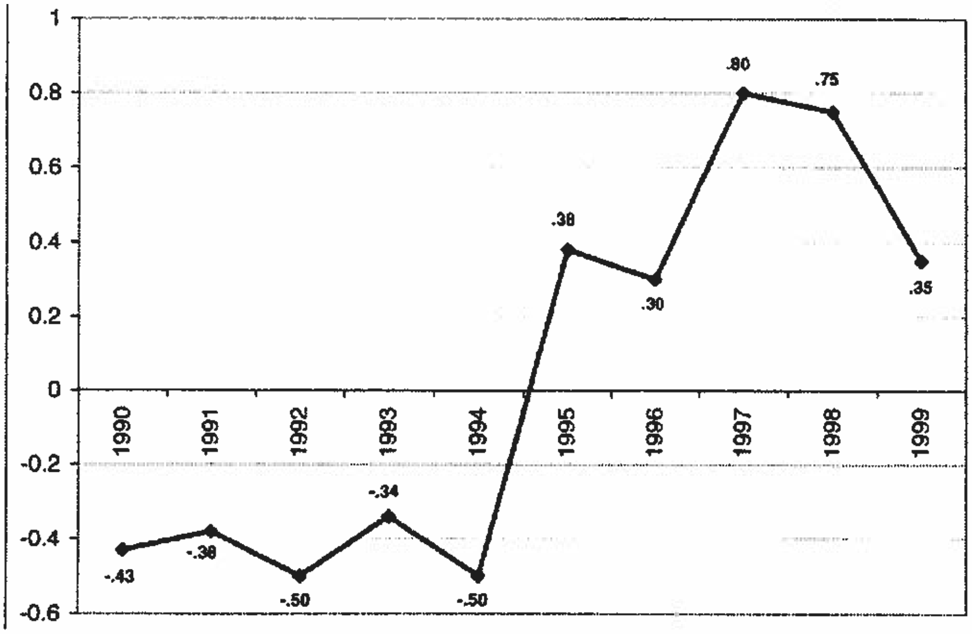

Figure 6: Time series of North Atlantic annual average SST (in °C) anomalies in the area between 50-60°N, 10-50°W for 1990 to 1999.

9 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 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 strike probability does not insure that a hurricane will not come ashore. Regardless of how active 2000 hurricane season should be, 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 1995–1999 Active Hurricane Period and Global Warming

Some readers may interpret the recent large upswing in Atlantic hurricane activity 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 since 1995 is not plausible. It should be noted that tropical cyclone activity in the other global basins has shown a downward trend since 1995. See our 24 November 1999 verification on this Web site for a more detailed discussion of this point.

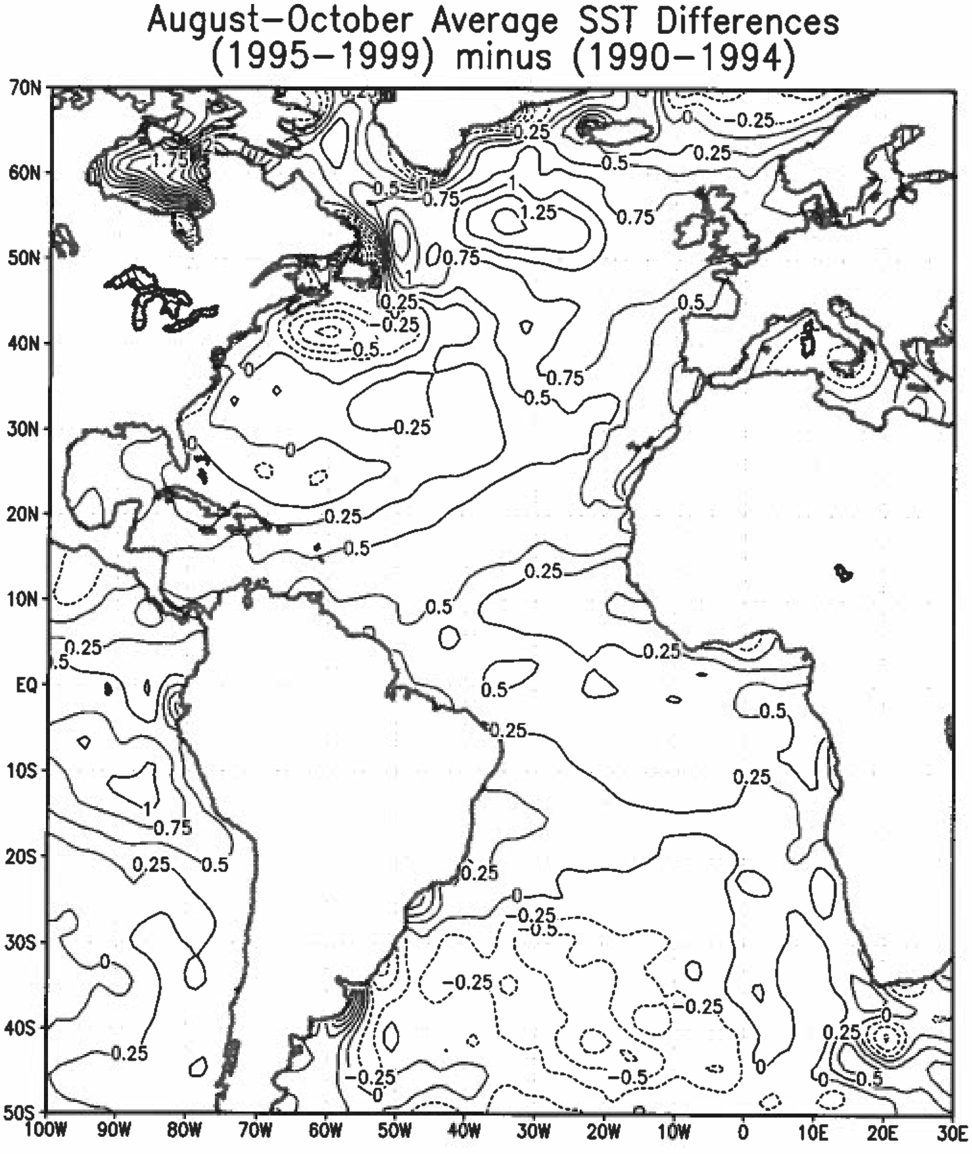

Figure 7: Average August through October SST differences (in °C) between two five-year periods: 1995 to 1999 minus 1990 to 1994.

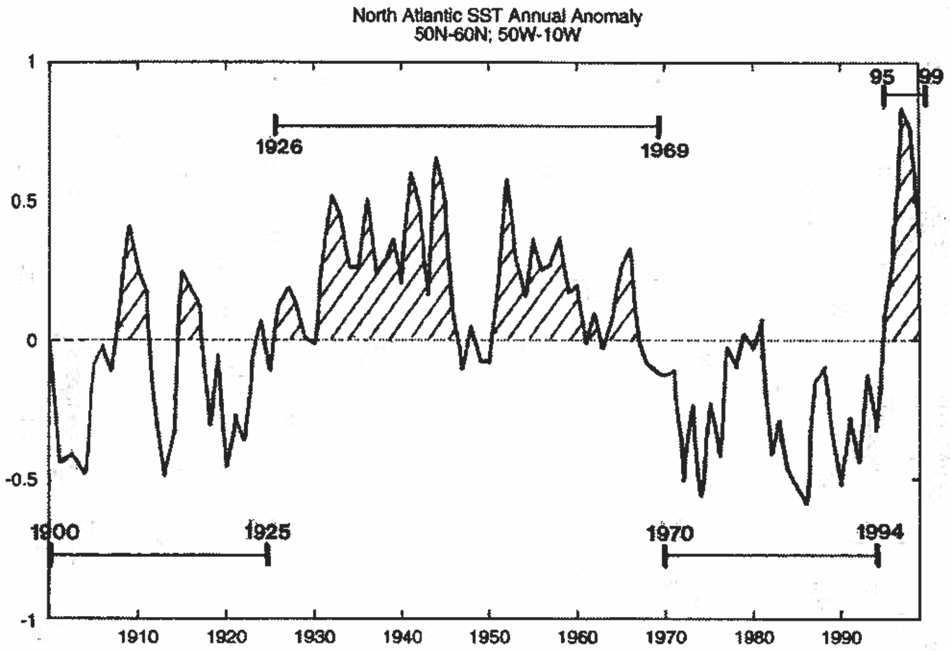

Figure 8: Time series of North Atlantic annual average SST anomalies (in °C) in the area between 50-60°N, 10-50°W for 1900 to 1999. The periods of positive SST anomalies are hatched.

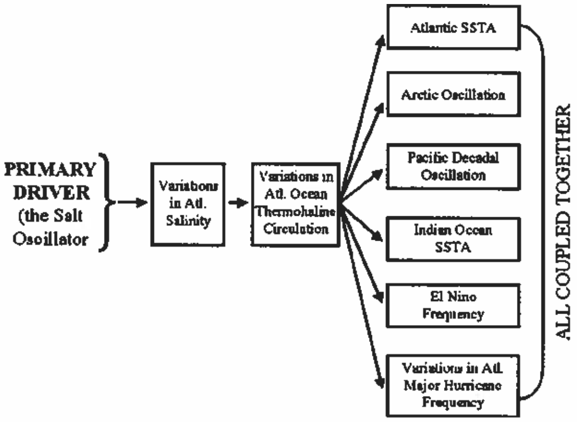

Figure 9: Conceptual outline of our theory on the primary cause of multi-decadal climate change. We look to long period ocean salinity changes (primarily in the Atlantic). These salinity changes cause Atlantic Ocean thermohaline changes which, with time lags of 4-6 years, manifest themselves in the other global oceans.

11 Schedule for 2000 Forecast Updates

This 7 June 2000 forecast will again be updated on 4 August 2000. This final update allows us the opportunity to make adjustments as newer information becomes available. A verification of this forecast will be issued in late November 2000 and a seasonal forecast for the 2001 hurricane season (likely an inactive season due to the potential for an El Niño) will be issued in early December 2000.

12 Acknowledgements

John Knaff, John Sheaffer, Todd Kimberlain, Eric Blake, and William Thorson have made many important contributions to the conceptual and scientific background for these forecasts. 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. We are particularly grateful to Arthur Douglas, Richard Larsen, David Masonis, Vern Kousky and Ray Zehr 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 indepth discussions with most of the current NHC hurricane forecasters. These include Lixion Avila, Miles Lawrence, Richard Pasch, Edward Rappaport, Jack Beven and James Franklin. The first author would further like to acknowledge the encouragement he has received for this type of forecasting research applications from Neil Frank, Robert Sheets, Robert Burpee, Jerry Jarrell, former directors of the National Hurricane Center (NHC) and from the current director, Max Mayfield.

The financial backing for the issuing and verification of these forecasts has, in part, been supported by the National Science Foundation. But this NSF support is insufficient. It is unfortunate that the other U.S. Federal agencies which are charged with supporting climate research have shown no interest in our seasonal hurricane forecast research. Recently, the Research Foundation of the United Services Automobile Association (USAA) and State Farm insurance companies have made contributions to the first author's project. It is this support which is allowing our seasonal predictions to continue.

13 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.

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.

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.

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.

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.

APPENDIX – Post-Season Reviews of All Prior Seasonal Forecasts

The first author has now issued seasonal hurricane forecasts for 16 consecutive years (1984–1999). In most of these prior forecasts, predictions have been superior to climatology (i.e., long-term averages), particularly for named storms. Whereas the forecasts for 1989 (underestimated), 1993 (overestimated), 1996 (underestimated), and 1997 (overestimated) were quite poor, they were also quite instructive in that each of these failures has led to important new insight and forecast model improvements. Figures 6 and 7 offer a comparison of our 1 June forecasts of named storms and hurricanes versus climatology and actual year-by-year variability.

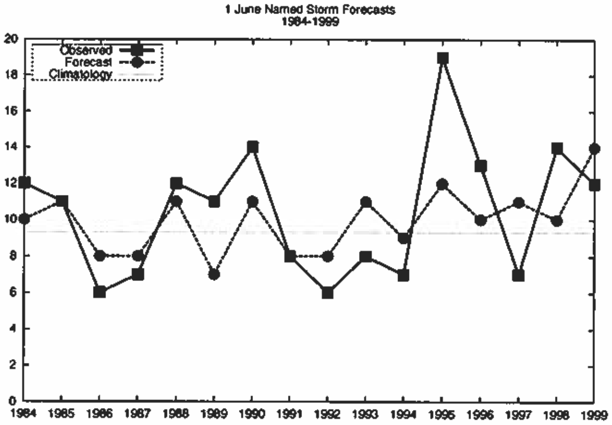

Figure 10: 1 June prediction of total named storms versus the number of actually observed versus long-term climatological mean for period 1984–1999.

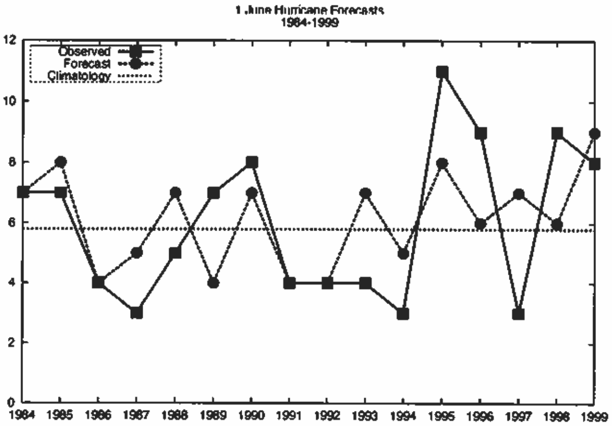

Figure 11: 1 August prediction of total hurricanes versus the number of actually observed versus climatological long-term mean .

Table 10: Summary verifications of the author's prior seasonal forecasts of Atlantic TC activity between 1984-1999.

		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	26 Nov 1991	Update 5 June	Update 5 August	Observed
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	24 Nov 1992	Update 4 June	Update 5 August	Observed
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	19 Nov 1993	Update 5 June	Update 4 August	Observed
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

1995	30 Nov 1994	Update 14 April	Update 7 June	Update 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

1996	30 Nov 1995	Update 4 April	Update 7 June	Update 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

1997	30 Nov 1996	Update 4 April	Update 6 June	Update 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