EARLY APRIL FORECAST OF ATLANTIC SEASONAL HURRICANE ACTIVITY AND US LANDFALL STRIKE PROBABILITIES FOR 2000

A year of expected continued above average hurricane activity and Florida-East Coast landfall probability

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

By

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2000 ATLANTIC BASIN SEASONAL HURRICANE FORECAST

Tropical Cyclone Seasonal	**8 December 1999** and 7 April Update **Forecast for 2000**
Named Storms (NS) (9.3)	11
Named Storm Days (NSD) (46.9)	55
Hurricanes (H)(5.8)	7
Hurricane Days (HD)(23.7)	25
Intense Hurricanes (IH) (2.2)	3
Intense Hurricane Days (IHD)(4.7)	6
Hurricane Destruction Potential (HDP) (70.6)	85
Maximum Potential Destruction (MPD) (61.7)	70
Net Tropical Cyclone Activity (NTC)(100%)	125

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

1) Entire U.S. coastline - 60% (average for last century is 52%)

2) U.S. East Coast Including Peninsula Florida - 39% (average for last century is 31%)

3) Gulf Coast from the Florida Panhandle westward to Brownsville - 34% (average for last century is 30%)

4) Caribbean basin (about 10% 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). Probabilities are somewhat lower from our 8 December 1999 forecast due to new research results.

DEFINITIONS

ABSTRACT

Information obtained through March 2000 indicates that the Atlantic hurricane season in 2000 is likely to be 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 7 hurricanes (average is 5.7), 11 named storms (average is 9.3), 55 named storm days (average is 47), 25 hurricane days (average is 24), 3 intense (category 3-4-5) hurricanes (average is 2.2), 6 intense hurricane days (average is 4.7) and a Hurricane Destruction Potential (HDP) of 85 (average is 71). Collectively, net tropical cyclone activity in year 2000 is expected to be about 125 percent of the long term average. This April forecast update is identical to our prior (8 December 1999) forecast for 2000 except where the U.S. landfall probability has been somewhat reduced.

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:

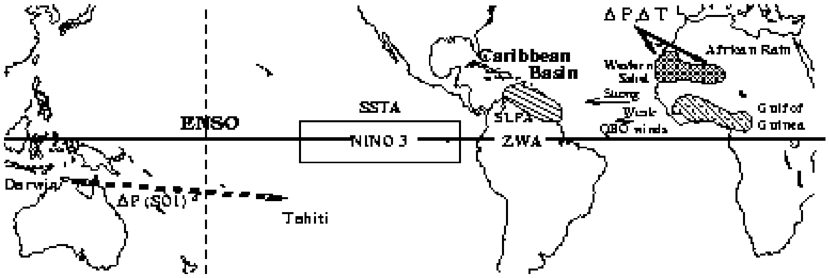

Figure 1: Meteorological parameters used in various versions of our older early August (Gray et al. 1994a) seasonal forecast.

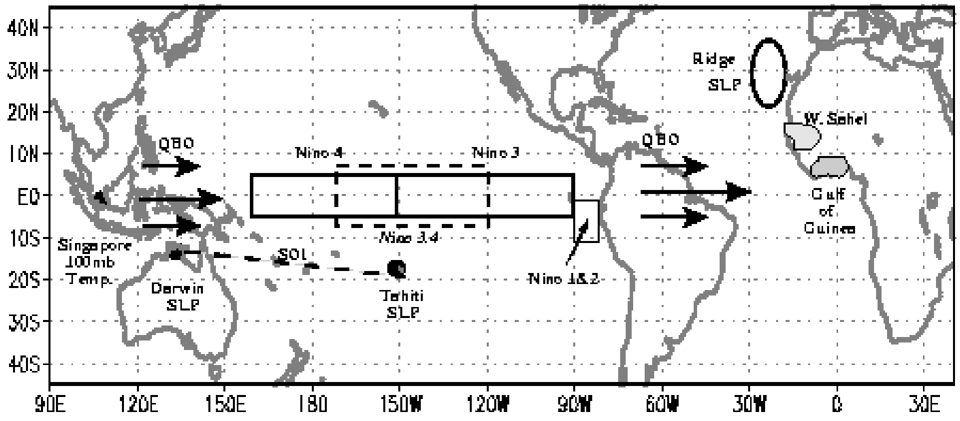

Figure 2: Additional parameters used or consulted in our extended-range forecasts.

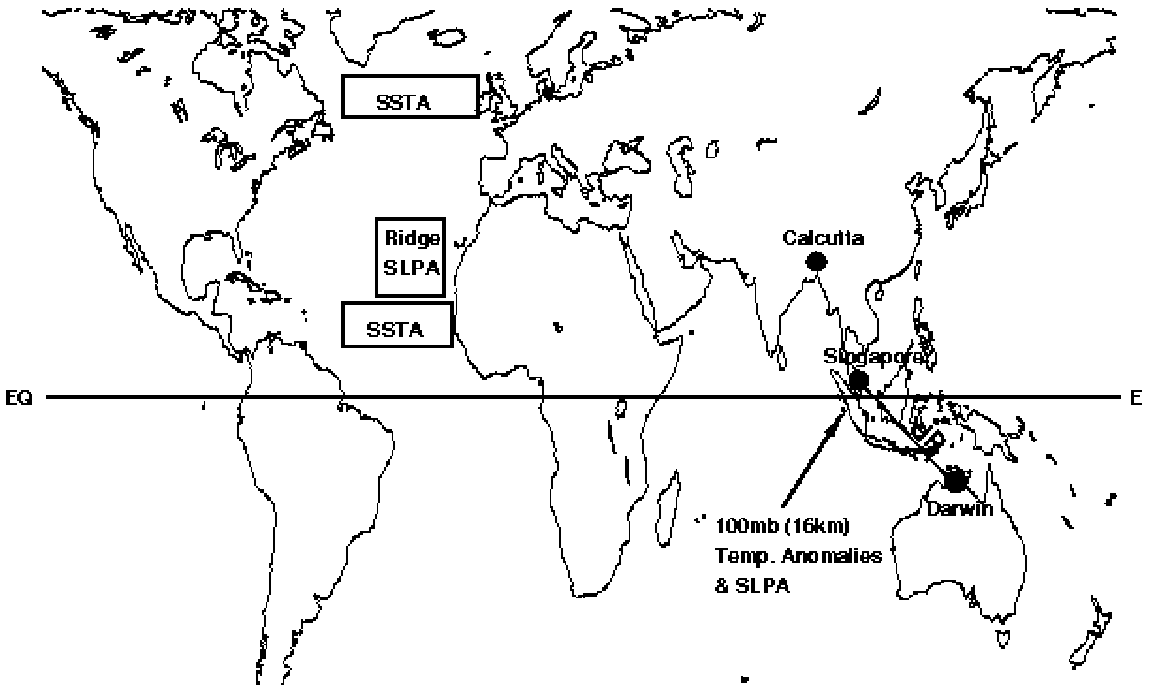

Figure 3: Additional (new) predictors which have recently been noted to be related to the upcoming Atlantic hurricane activity.

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 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 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 cold 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 around this Azores high 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 (8-22°N, 10-50°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 likely to remain 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. In the last few years these SST anomalies have begun to arrange themselves in ways that historically have been associated

with an enhancement of Atlantic hurricane activity. This involves the recently delineated Pacific Decadal Oscillation (PDO) and the development of cooler ocean temperature patterns in the 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 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 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 1. 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 2. The number of forecast parameters is given in parenthesis. 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 is increased 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 and 2) are also consulted for further qualitative perspective and may influence to our final ``adjusted" forecast.

Table 1: Pool of predictors (and their values as of 1 April) used to develop the 2000 prediction based on meteorological data available through March 2000. See Figs. 1 and 2 for the locations of these predictors.

For 1 April Prediction (see Figs. 1 and 2 for location)	**Specific 1 April Fcst Parameters**
1) U50 (Mar extrapolated to Sep)	-18 m/s
2) U30 (Mar extrapolated to Sep)	-30 m/s
3) AbsShe - absolute shear (Mar extrapolated to Sep)	+12 m/s
4) Balboa - U50 (June-Aug, 1998)	-3.0 m/s
5) Rain GG- Aug-Nov Guinea Coast Rain	-0.6 SD
6) Rain WS- Aug-Sep West Sahel Rain	+0.15 SD
7) R-ON - Ridge SLPA (Oct to Nov)	-0.14 SD
8) R-M - Ridge SLPA (Mar)	-0.10 SD
9) NATL (Jan to Mar) SSTA (50-60°N, 10-50°W)	+0.30°C

10) TATL (Jan to Mar) SSTA (8-22°N, 10-50°W)	+0.10°C
11) Nino 3.4 Mar SSTA	-1.05°C
12) Nino 3.4 (Mar minus Feb) SSTA	+0.30°C
13) Nino 4 (Jan, Feb, Mar minus Oct, Nov, Dec) SSTA	-0.50°C

Table 2: Hindcast (i.e., regression testing on data for past years) statistical predictor skill (measure of agreement or r^2) of our separate 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

On average, a net degradation of this hindcast skill of between 5-15 percent of 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 contains 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 Continuation of La Niña Conditions Through October 2000

From recent data, we infer that there will be no El Niño 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 presently observed. 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 of this association has 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 March Nino 3.4 SSTA has remained cold and MJO events have not been progressing eastward from the Indian Ocean. 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 next summer is fairly remote. We anticipate a continuation of the cool to neutral ENSO conditions that have been in place during the 1998 and 1999 seasons. We anticipate the next El Niño event not coming before 2001 or 2002.

4 Early April Forecast

Forecast signals for 2000 indicate a mix of positive and negative influences. Of the 13 potential predictors listed in Table 1, eight (those associated with the ENSO, the Atlantic ridge, the two Atlantic SSTA indices and that of August-September 1999 West African rainfall) indicate above average hurricane activity, whereas the other five predictors including Guinea rain, Balboa 50 mb wind and the three QBO predictors indicate negative influences.

Table 3 lists our April statistical prediction for the 2000 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 2000 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). And, we believe that the 2000 hurricane season will again 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 data base. 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 eastern North Pacific (La Niña) SST conditions through October 2000.

Part of this underprediction problem may also be due to an apparent weakening of the strong West African rainfall - hurricane relationship which was an important component of our statistical forecast scheme. For this reason, we have recently expanded study of past years which had pre-season climate conditions similar to 2000; the analog method.

Another 1 April predictor available to us but not yet quantitatively incorporated into our statistical forecast scheme is a prediction of June through September Caribbean basin Sea Level Pressure Anomaly (SLPA). Lower SLPA forecasts typically enhance hurricane activity, while higher SLPA reduce it. This predictor has recently been developed by J. Knaff (1998) a former project member. This SLPA forecast is based on information concerning the anomalous March Atlantic subtropical ridge, January through March SSTs in the North Atlantic (50-60°N, 10-50°W), the tropical Atlantic (8-22°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 years 1 April prediction of the Caribbean and western Atlantic SLPA for June through September 2000 and for the critical months of August-September indicate below average SLPA (Table 4). This should be an enhancing influence for hurricane activity and further evidence that the 2000 hurricane season should be a reasonably active one.

Table 3: April statistical forecasts for 2000. This includes a variable number of predictors and two other forecasts with 4 and 6 fixed predictors (column 2 and 3). Column 4 is our final adjusted early April forecast of 2000 hurricane activity. Column 5 gives climatology.

	(1)	**(2)**	**(3)**	**(4)**	**(5)**
		Fixed predictors			
Full Forecast Parameter	**Variable Predictor**	**4 Predictors**	**6 Predictors**	**Adjusted Actual Fcst**	**1950-1990 Climatology**
Named Storms (NS)	7.5 (4)	7.5	8.1	11	9.3
Named Storm Days (NSD)	54.2 (5)	58.6	58.9	55	46.9
Hurricanes (H)	5.2 (4)	5.2	5.2	7	5.8
Hurricane Days (HD)	16.2 (5)	16.0	21.0	25	23.7
Intense Hurricanes (IH)	1.5 (4)	1.2	2.2	3	2.2
Intense Hurricane Days (IHD)	3.6 (3)	3.9	5.4	6	4.7
Hurricane Destruction Potential (HDP)	46.1 (5)	38.6	44.6	85	70.6
Net Tropical Cyclone Activity (NTC)	62.1 (6)	57.7	95.2	125	100
Maximum Potential Destruction (MPD)	47.8 (5)	51.5	45.4	70	62

Table 4: April 1, 2000 multi-month independent statistical prediction of 2000 summertime Caribbean basin and Western tropical Atlantic Sea Level Pressure Anomaly (SLPA) from 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

5 2000 Hurricane Activity Inferred from Analog Years

We find that certain years in the historical records have similar (to the current year) global oceanic and atmospheric conditions that provide useful clues to the amount of hurricane activity likely to occur. 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 March 2000 conditions starting from 1950 (when direct stratospheric QBO winds were available).

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

- the North Atlantic (50-60°N, 10-50°W) tropical Atlantic (8-22°N, 10-50°W) had persistent warm SST anomalies during the prior fall and winter months,
- La Niña conditions were present and persisted (as we expect them to do 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 east 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 1956, 1989, 1996, and 1998. Table 5 lists the hurricane activity which occurred in the four seasons. The 1956 season was inexplicably suppressed while the 1989, 1996 and 1998 seasons all had above average activity despite easterly stratospheric QBO winds.

Table 5: Atlantic basin tropical cyclone activity during analog seasons for 2000

	NS	NSD	H	HD	IH	IHD	HDP	NTC
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
1998	14	80	10	49	3	9.25	145	168
Average	11.5	63.5	7.5	35	3.25	6.8	108.3	144
2000 Forecast	11	55	7	25	3	6	85	125

Note that the average hurricane activity during these four analog years is greater than our forecast while our statistical scheme indicates less activity than we forecast. Our actual forecast represents a compromise between our statistical forecast and our analog findings.

<u>Summary</u>: Observations through the end of March indicate that 2000 will experience Atlantic basin above average hurricane activity and notably much more activity than occurred during the generally suppressed hurricane seasons of 1970-1994.

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. Landfall is a function of varying climate signals and probability specification has been accomplished through 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*). Current values of SSTA* yields a combination of NTC+SSTA* of 132. This NTC+SSTA* value is about the 35th percentile range such that 65 of the last 100 years of hurricane seasons had a combined NTC + SSTA* smaller than the projected value for this year. 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 6, 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 may bring no landfalling hurricanes and some inactive seasons experience one or more landfalling intense hurricanes; however, neither is typical. 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 7 and 8 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 in the prior year. These predictive relationships can, thereby, be utilized to make probability estimates of U.S. landfall .

Table 6: 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 7: 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 8: 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 or regression equations have been developed relating forecasts of NTC ($\mathrm{NTC_f}$) and measured values of SSTA* to landfall probability in these 11 regions. Figure 5 gives a flow diagram of how these forecasts are made.

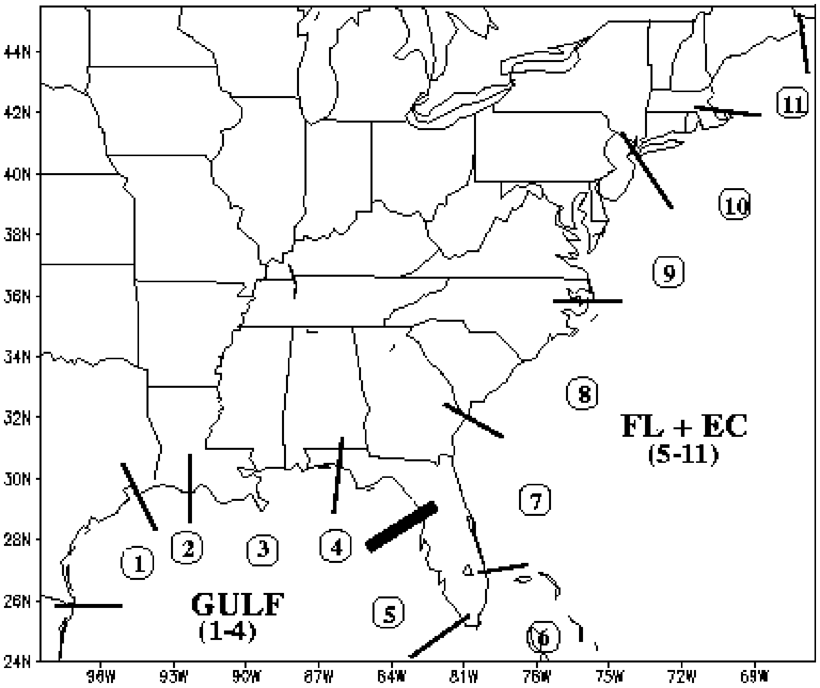

Figure 4: Location of the 11 coastal regions for which separate hurricane landfall probability estimates are made.

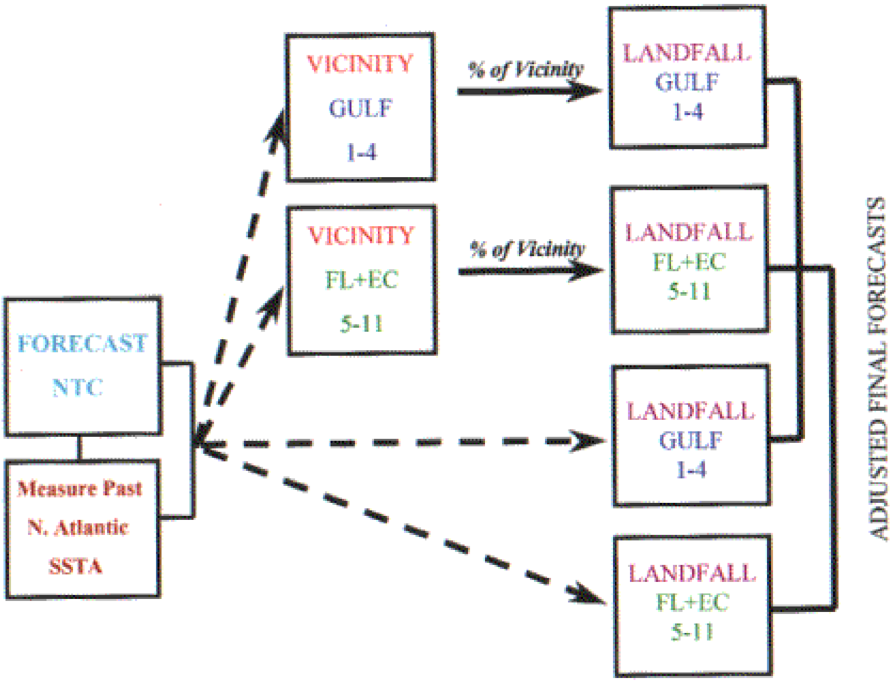

Figure 5: General flow diagram illustrating how forecasts of U.S. hurricane landfall probabilities are made. We forecast NTC and use an observed measure of the last few years of North Atlantic (50-60°N, 10-50°W) SSTA*. Regression equations are then developed with the combination of forecast NTC and measured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

A similar set of regression relationships have 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 proceeding to make landfall probabilities available for 11 distinct Gulf Coast and U.S. East Coast regions extending from Brownsville, TX to Eastport, ME.

Table 9 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 are given in parentheses.

Table 9: Estimated 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 parenthesis.

Coastal Region	TS	Category 1-2 HUR	Category 3-4-5 HUR	All HUR	Named Storms
Entire U.S. (Regions 1-11)	82% (80)	73% (68)	60% (52)	89% (84)	98% (97)
Gulf Coast (Regions 1-4)	67% (59)	46% (42)	34% (30)	62% (61)	87% (83)
		52% (45)	39% (31)		86% (81)

Florida plus East Coast (5-11)	47% (51)			72% (62)	

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

7 Coming 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 be available by early July on the internet. Landfall probabilities include a forecast of the conditional probability of tropical storms (TS) and hurricanes of category 1, 2, 3, 4-5 striking the following areas during 2000:

- anywhere on the entire U.S. coastline,
- the Florida and East Coast and along the Gulf Coast,
- each of 11 units of the U.S. coastline,
- each 100 km (65 mile) segment of U.S. coastline.

These forecasts of landfall probabilities will be expressed as the probability of each 100 km coastal segment receiving gale force winds (,40 mph), sustained hurricane force winds (,75 mph) and major hurricane (category 3-4-5) winds (,115 mph).

There will be a discussion of tropical cyclone spawned hurricane destruction within 56 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 at upper ocean levels. The resulting net northward transport of warm upper-layer water into the high 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 from the mean for 1990 to 1994 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 to levels similar to those 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 effected by these changes. This trend may continue for several decades.

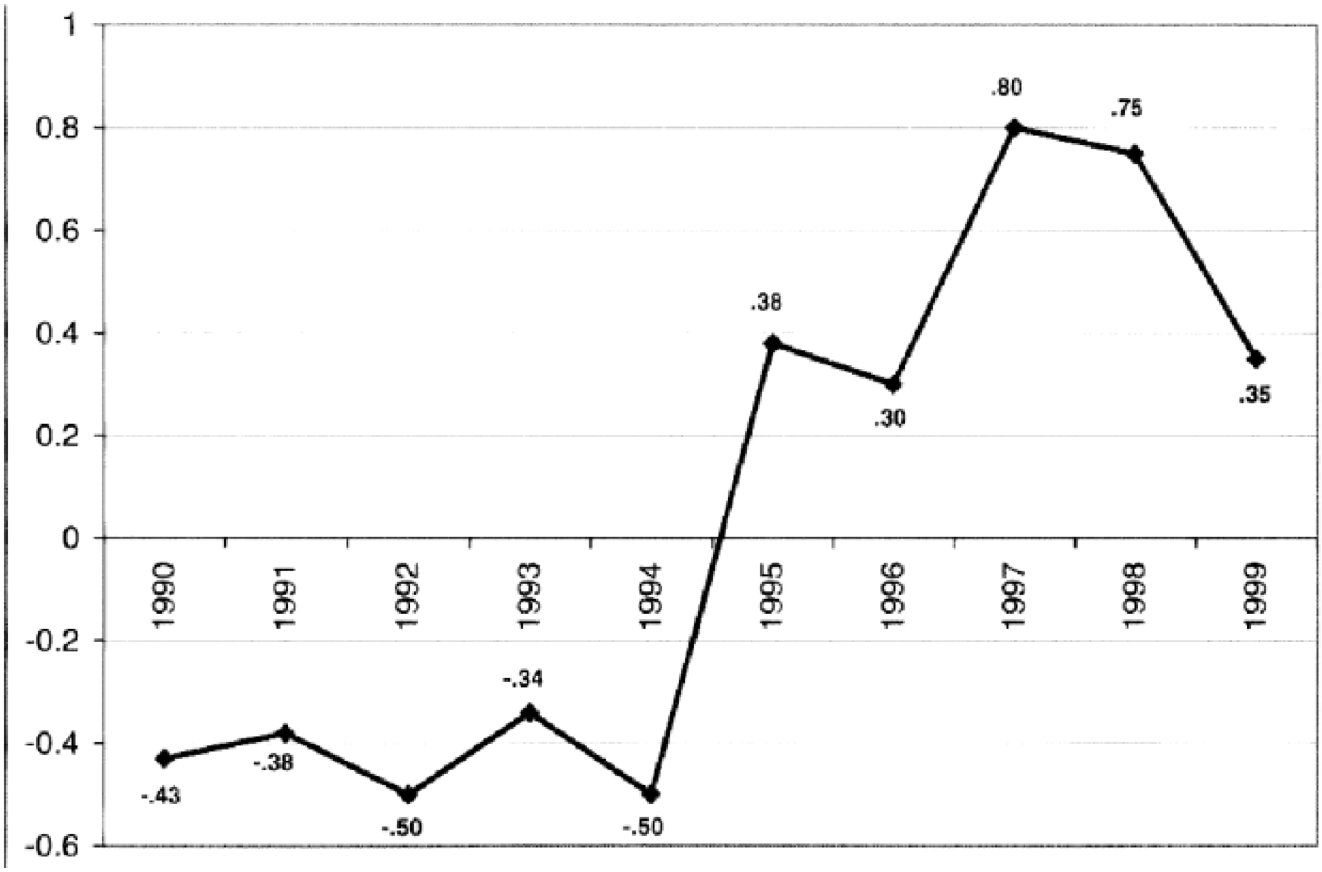

Figure 6: Time series of North Atlantic annual average SST (in °C) anomalies in the area between 50-60°N, 10-50°W for 1990 to 1999.

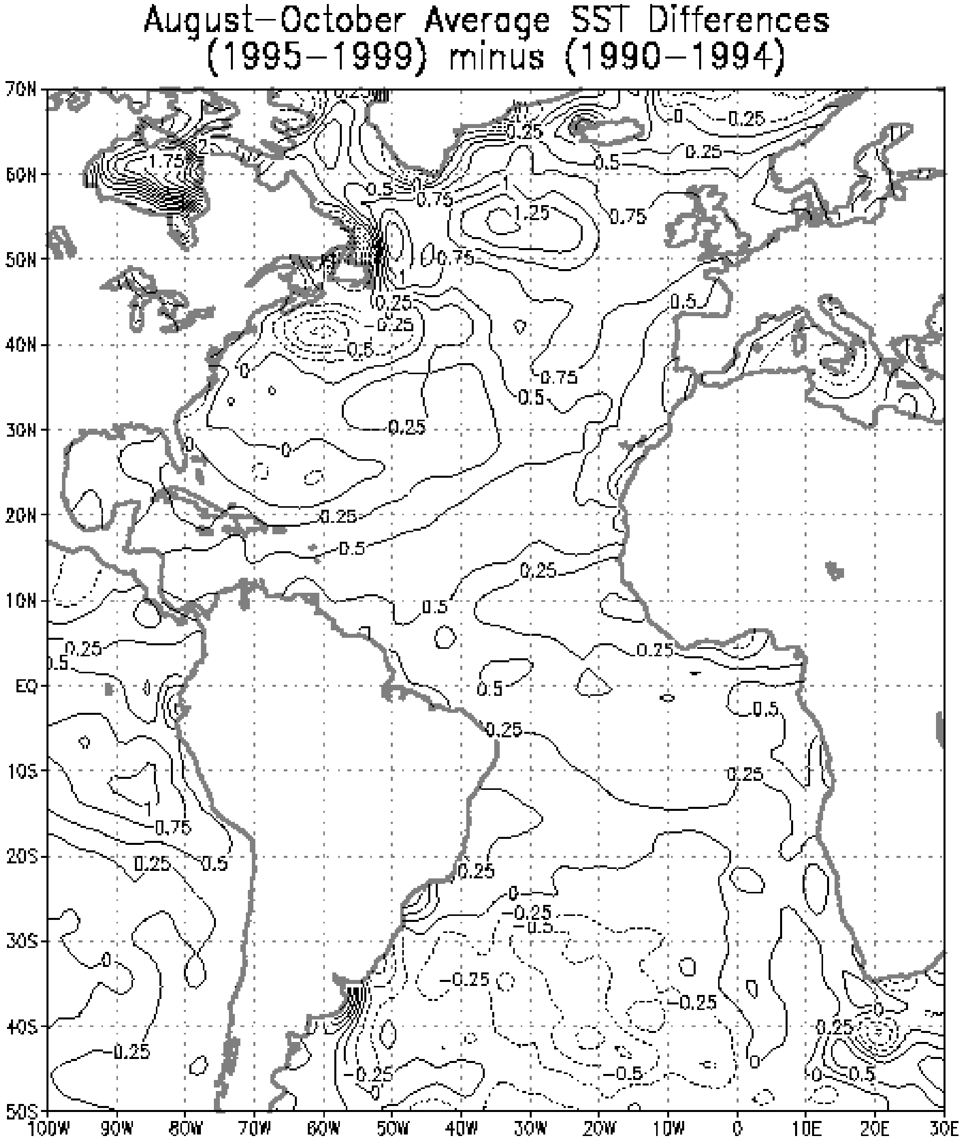

Figure 7: Average August through October SST differences (in ˙C) between two five-year periods: 1995 to 1999 minus 1990 to 1994.

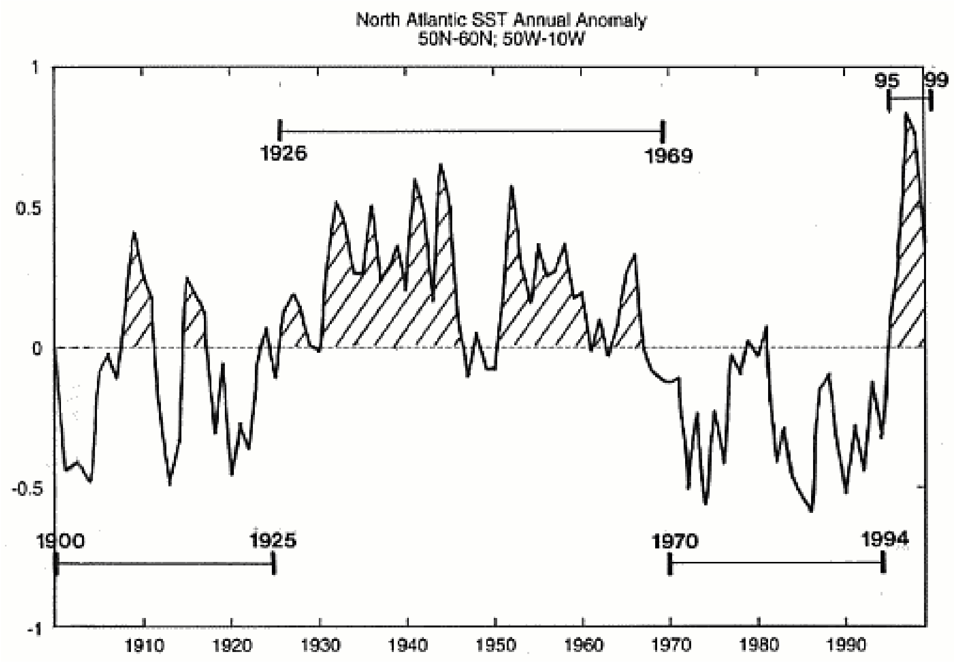

Figure 8: Time series of North Atlantic annual average SST anomalies (in °C) in the area between 50-60°N, 10-50°W for 1900 to 1999. The periods of positive SST anomalies are hatched.

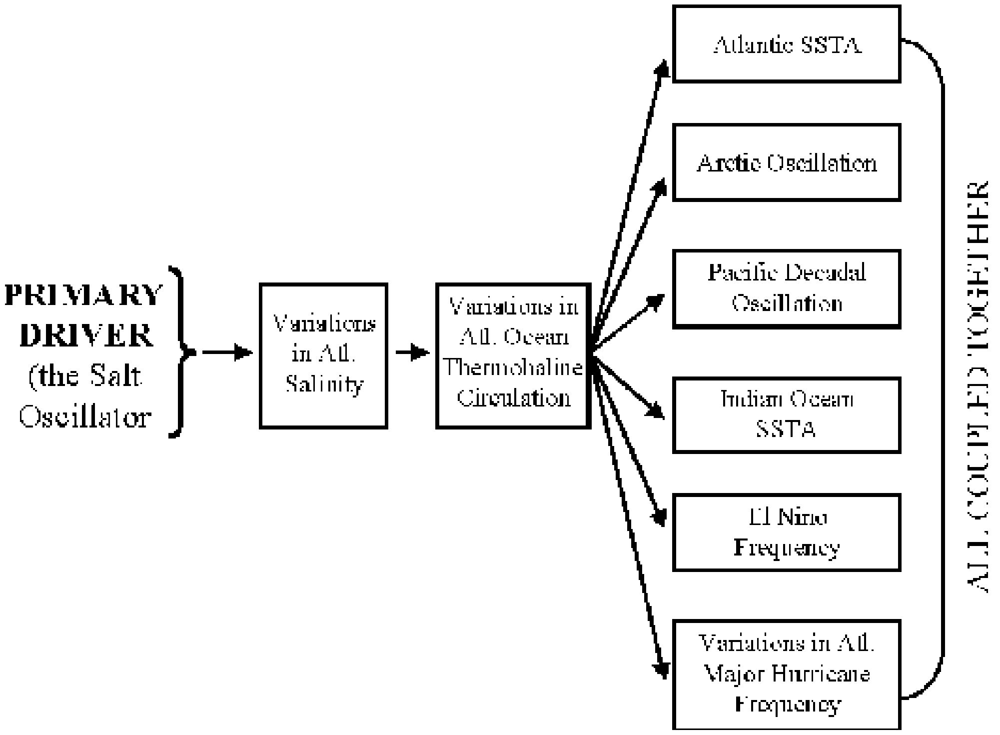

Figure 9: Conceptual outline of our theory on the primary cause of multi-decadal climate change. We look to long period ocean salinity changes (primarily in the Atlantic). These salinity changes cause Atlantic Ocean thermohaline changes which with time lags of 4-6 years manifest themselves in the other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

For years 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. Despite 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 with IH and IHD activity.

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. In view of the transitional condition of several key predictors, we are at this time less confident in this year's forecast than we were last year.) 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 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.

11 Schedule for 2000 Forecast Updates

This 7 April 2000 forecast will be updated on 7 June and 4 August 2000. These forthcoming updates allow 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) will be issued in early December 2000.

12 Acknowledgements

John Sheaffer and John Knaff 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, Ray Zehr and Vern Kousky 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, and Jerry Jarrell former directors of the National Hurricane Center (NHC) and from the current acting 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 climate research and seasonal predictions to continue.

13 Additional Reading

Summary verifications of prior seasonal forecasts