EARLY APRIL FORECAST OF ATLANTIC SEASONAL HURRICANE ACTIVITY AND US LANDFALL STRIKE PROBABILITIES FOR 1999

A year for which above average hurricane activity and US hurricane landfall probability are anticipated

This forecast is based on ongoing research by the authors, along with meteorological information through March 1999

By

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UPDATED 1999 ATLANTIC BASIN SEASONAL HURRICANE FORECAST AS OF 7 APRIL 1999

Tropical Cyclone Seasonal Forecast for 1999 (Climatology in parenthesis)

Named Storms (NS) (9.3)	14
Named Storm Days (NSD) (46.9)	65
Hurricanes (H)(5.8)	9
Hurricane Days (HD)(23.7)	40
Intense Hurricanes (IH) (2.2)	4
Intense Hurricane Days (IHD)(4.7)	10
Hurricane Destruction Potential (HDP) (70.6)	130
Maximum Potential Destruction (MPD) (61.7)	130

Net Tropical Cyclone Activity (NTC)(100%) 160

(These values are the same as those in our initial seasonal forecast for 1999 which was issued on 4 December 1998)

PROBABILITY OF ONE OR MORE 1999 MAJOR HURRICANE LAND-FALLS ALONG THE U.S. COASTLINE

1. U.S. East Coast including Peninsula Florida ~ 54 percent.
2. Gulf Coast from the Florida Panhandle westward to Brownsville ~ 40 percent.
3. For the entire U.S. coastline ~ 72 percent.

DEFINITIONS

ABSTRACT

Information obtained through March 1999 indicates that 1999 Atlantic hurricane activity is likely to be above the average for the 1950-1990 period with 9 hurricanes (average 5.8), 14 named storms (average 9.3), 65 named storm days (average 47), 40 hurricane days (average 24), 4 intense (category 3-4-5) hurricanes (average 2.2), 10 intense hurricane days (average is 4.7) and a Hurricane Destruction Potential (HDP) of 130 (average 71). Collectively, net tropical cyclone activity is expected to be about 160 percent of the long term average. The 1999 season should have hurricane activity comparable to the recent busy hurricane seasons of 1996 and 1998. Evidence suggests that we have entered a new era of enhanced major hurricane activity.

This report presents details of our extended range seasonal forecast of tropical cyclone activity as well as a general estimate of the probability of US hurricane landfall during 1999. The forecasts are based on the results of statistical forecast schemes (developed by the authors) plus qualitative adjustments which reflect additional effects associated with supplementary global atmosphere and ocean information which is not yet incorporated in our statistical models. Our evolving forecast techniques are based on a variety of global and regional predictors previously shown to be related to forthcoming seasonal Atlantic tropical cyclone activity and landfall frequency.

1 Introduction

Surprisingly useful long-range predictive signals exist for Atlantic basin seasonal tropical cyclone activity. Our research on 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 estimated in hindcast tests (i.e., skill exceeding climatology) as early as December of the prior year. The forecast is based on experiments which yield prediction schemes for estimating hurricane activity in the following months plus qualitative adjustments for processes not yet incorporated into our statistical models. Forecasts have been developed from hindcast data for the 48-year period spanning 1950-1997. Our extended-range predictors include the phase of the stratospheric Quasi-Biennial Oscillation (QBO) of zonal winds at 30 mb and 50 mb (which can be readily extrapolated ten months into the future), two measures of Western Sahel rainfall during the prior year (Figs. 1 and 2), extended range estimates of El Niño-Southern Oscillation (ENSO) variability (Fig. 2), the October-November strength of the Azores high surface pressure and the configuration of broad scale Atlantic sea surface temperature anomaly patterns and strength of the Azores anticyclone through March (see Fig. 3). A brief summary of these predictor indices and their specific implications for 1999 are provided in the following.

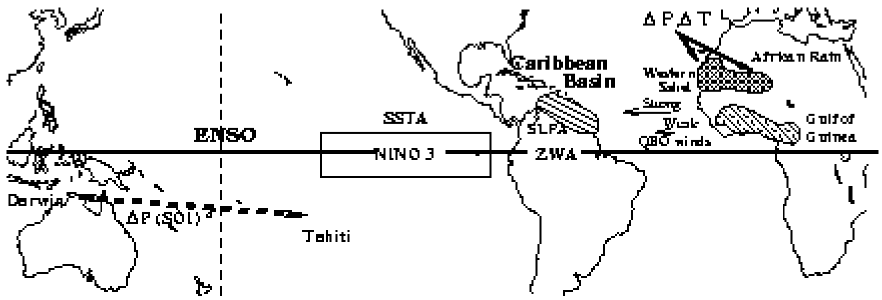

Figure 1: Meteorological parameters used in various versions of our older early August (Gray et al. 1994a) seasonal forecast.

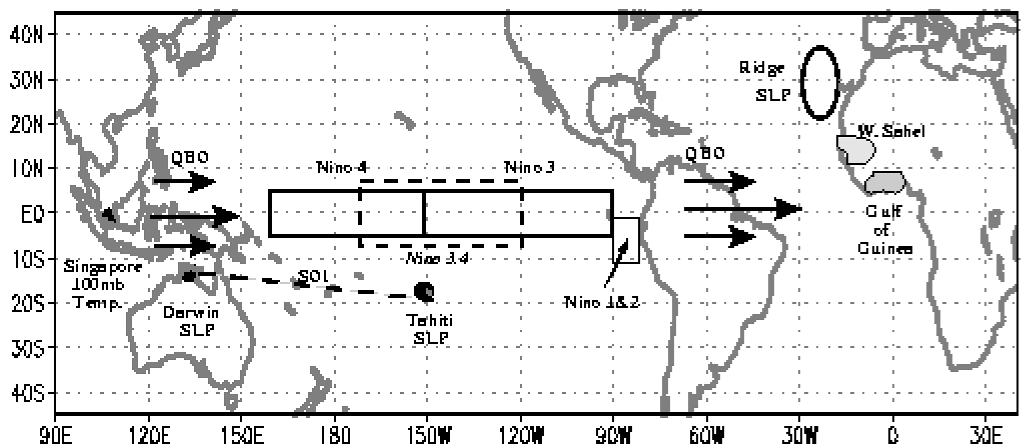

Figure 2: Additional parameters used or consulted in our extended-range forecasts.

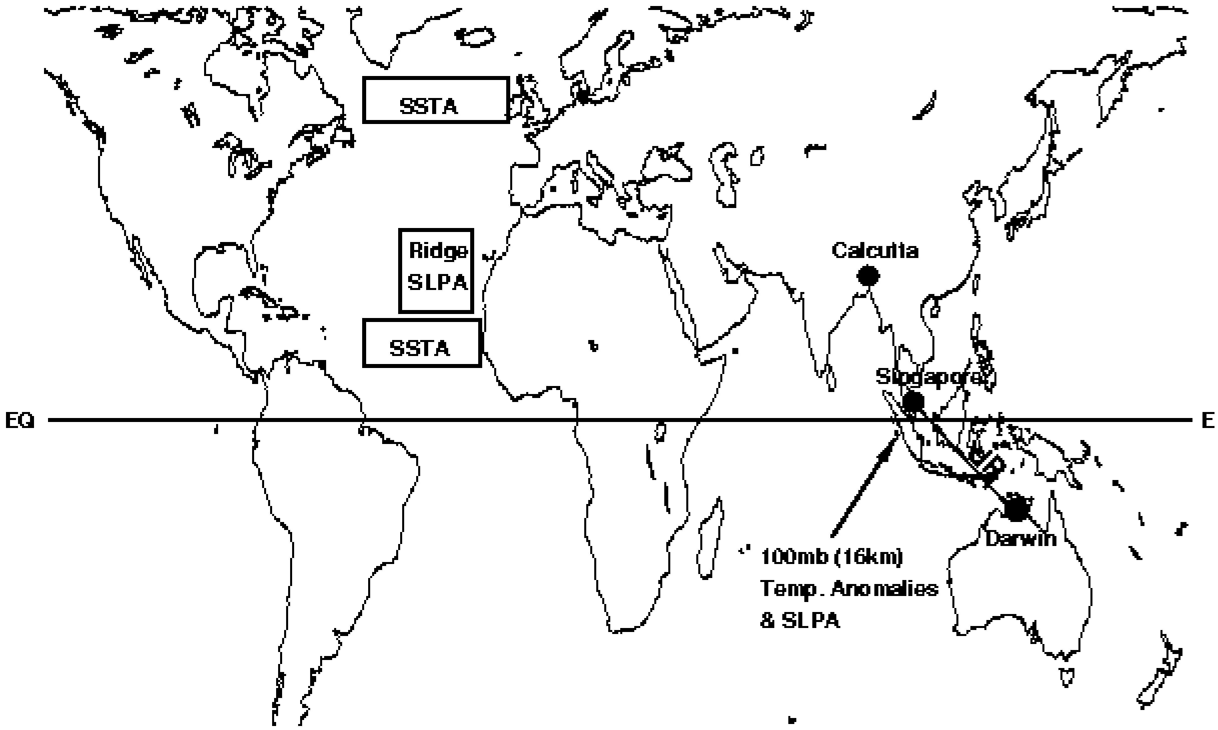

Figure 3: Additional (new) predictors which have recently been noted to be related to the upcoming Atlantic hurricane activity.

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, consequently, 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 an easterly phase and the wind shear between 30- and 50 mb is large. During 1999 QBO winds are projected to be from a relatively westerly direction with small wind shear between these two levels. We extrapolate the 30 and 50-mb actual zonal winds near 11-13˚N in September 1999 will be near zero at 50 mb (this equates to a +10 m/s zonal wind speed relative to the average September wind) and only -1 m/s at 30 mb (+15 m/s relative wind speed). These relatively westerly winds should be an enhancing influence on next year's hurricane activity, especially for major hurricane activity.

b) African Rainfall-Tropical Cyclone Lag Relationship

As discussed by Landsea (1991), Gray and Landsea (1992) and Gray et al. (1992), strong predictive signals for seasonal hurricane activity can be found in West African rainfall data for the mid-summer to fall periods of the prior year. These rainfall-linked signals include:

(1) August-September Western Sahel Rainfall. The Western Sahel area (see Fig. 2) has experienced large year-to-year persistence of rainfall trends. Wet years tend to be followed by wet years (e.g., in the 1950s and 1960s) and enhanced hurricane activity while dry years are typically followed by dry years (e.g., in the 1970s, 1980s and first half 1990s) and suppressed hurricane activity. Since the rainfall in this region is positively related to Atlantic hurricane activity, persistence alone tends to provide a moderate amount of skill for forecasting next season's African rainfall as well as the associated Atlantic hurricane activity. This year's rainfall for the Western Sahel during August-September 1997 was -0.23 SD above average and thus is a weak positive factor for 1999 hurricane activity.

(2) August-November Rainfall in the Gulf of Guinea. Landsea (1991) and Gray and Landsea (1992) documented a strong African rainfall - intense hurricane lag relationship using August through November rainfall along the Gulf of Guinea (see Fig. 2). Intense hurricane activity during seasons following the ten wettest August-November Gulf of Guinea years is many times greater than occurs during hurricane seasons following the ten driest August-November periods in the Gulf of Guinea.

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 (eg., 1997) during El Niño seasons when anomalously warm water temperatures are present in the equatorial eastern and central Pacific. Conversely, activity tends to be enhanced during seasons with cold (or La Niña) water conditions. We expect the current cool ENSO conditions (March Nino 3.4 = -1.27°C) to persist through the key months of August through October 1999 and thus be an enhancing influence for 1999 hurricane activity. Most ENSO prediction, both statistical and numerical, foresee cool ENSO conditions remaining through the fall of this year.

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

High 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 when surface pressure associated with the Azores high is anomalously high. Colder sea surface temperatures created by this enhanced ocean upwelling can cause higher surface pressures to develop in the spring which then create a self-enhancing (positive feedback) response resulting in higher Caribbean pressures during the summer (Knaff 1998). The long-term memory and feedbacks in this association make it a useful parameter for predicting next year's seasonal hurricane activity. Higher than normal surface pressure the prior fall goes with reduced hurricane activity the subsequent year and vice versa. Ridge strength during this October-November (1998) was slightly above the long-term mean (+0.45 SD) but fell sharply to a value of -1.49 SD during March of this year. Consequently, this effect should be a strong enhancing influence for this year's hurricane activity.

e) Sea Surface Temperature Anomalies (SSTA) in the North (50-60°N, 10-50°W) and the Tropical Atlantic (6-22°N, 18-80°W) in January through March provide a predictive signal for the following hurricane season. Warmer January through March SSTAs are associated with enhanced hurricane activity and colder SSTAs are associated with reduced seasonal hurricane activity. These North and

Tropical Atlantic SSTAs for January through March were near average (-0.09˙C in the North and -0.07˙C in the tropics). We expect these slightly negative SSTAs to become positive anomalies by the active part of the hurricane season. The current slightly cool Atlantic SSTAs are a result of the strong December through February NAO and gyre wind circulation. This enhanced ocean evaporation cooling. This gyre circulation weakened in March. We expect a continuation of the long period warming of the Atlantic which has occurred since 1995.

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 best three to six predictors (i.e., those resulting in optimum prediction skill) from a group of 13 possible forecast parameters 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 used in this year's April forecast are shown in the right hand column of this table.

Our statistical forecast is summarized in Table 2 with the number of forecast parameters shown in parenthesis. We make every attempt to minimize the skill degradation of these equations when making independent forecasts (i.e., reduce statistical ``overfitting'') by choosing the least number of predictors for the highest amount of hindcast variance. We stop adding predictors when the hindcast improvement of the next best predictor adds less than a 0.025 improvement to the total variance explained.

We have also studied a scheme which uses various fixed number of predictors. This procedure investigates how hindcast variance (not necessarily true skill) increases as a fixed number of predictors are 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 interpolation and possible influence to our final ``adjusted'' forecast.

Table 1: Pool of predictors (and their values as of 1 April) are used to develop the 1999 prediction based on meteorological data available through March 1999. 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)	0 m/s
2) U30 (Mar extrapolated to Sep)	-1 m/s
3) AbsShe - absolute shear (Mar extrapolated to Sep)	+1 m/s
4) Balboa - U50 (June-Aug, 1998)	-20 m/s
5) Rain GG- Aug-Nov Guinea Coast Rain	-0.28 SD

6) Rain WS- Jun-Sep West Sahel Rain	-0.23 SD
7) R-ON - Ridge SLPA (Oct to Nov)	+0.45 SD
8) R-M - Ridge SLPA (Mar)	-1.49 SD
9) NATL (Jan to Mar) SSTA	-0.09˙C
10) TATL (Jan to Mar) SSTA	-0.07˙C
11) Nino 3.4 Mar SSTA	-1.49˙C
12) Nino 3.4 (Mar minus Feb) SSTA	-0.19˙C
13) Nino 4 (Jan, Feb, Mar minus Oct, Nov, Dec) SSTA	-0.5˙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 minimum number of predictors shown in parentheses. Columns (b) and (c) give our hindcast skill with the best 4 and 6 predictors, respectively.

		Fixed Number of predictors	
	Variable Predictors (a)	**4 (b)**	**6 (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

Table 2 lists hindcast prediction skill for our various statistical models. Probability dictates that, on average, a net degradation of this hindcast skill of between 5-15 percent of total in variance 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 while in other years, a given forecast can perform quite poorly. This is because our 48-year (1950-1997) base of predictors likely does not explain the full range of independent possibilities. Our 1997 forecast is a good example. No year in our 1950 through 1996 developmental data sets had ever experienced an El Niño event anywhere nearly as intense (by a factor of 2) as the 1997-98 El Niño - the most intense event ever measured. Our forecast failed.

3(1) Early April Forecast

Table 3a lists our April statistical forecast prediction for the 1999 hurricane season along with what we consider our current best qualitatively adjusted forecast. Table 3b shows the 25 and 75 percent expected spread of our variable predictor scheme.

Table 3: a: April statistical forecasts which have a variable number of predictors with variable predictors (column 1) along with 4 and 6 fixed predictors forecast (column 2). Column 4 is our final adjusted early April forecast of 1998 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)	11.6 (4)	11.6	11.2	14	9.3
Named Storm Days (NSD)	71.7 (5)	69.8	72.3	65	46.6
Hurricanes (H)	7.3 (4)	7.3	7.5	9	5.8
Hurricane Days (HD)	28.6 (5)	23.8	35.2	40	23.9
Intense Hurricanes (IH)	3.8 (4)	3.9	4.8	4	2.3
Intense Hurricane Days (IHD)	4.1 (3)	4.3	11.7	10	4.7
Hurricane Destruction					
Potential (HDP)	85.4 (5)	67.0	86.8	130	71.2
Net Tropical Cyclone					
Activity (NTC)	129.8 (6)	104.0	164.1	160	100
Maximum Potential					
Destruction (MPD)	71.1 (5)	70.6	78.5	110	66

Table 3: b: Statistical spread of hindcasts from the variable prediction model for various tropical cyclone parameters. (Thus, from hindcasts on the year 1950-1997, 50% should fall within the numbers given in the first and third columns.)

Fcst Parameter	No. of Prediction	Lowest 25% Below	Variable Model Forecast	Highest 25% Above
Named Storms (NS)	(4)	11.1	11.6	13.1
Named Storm Days (NSD)	(5)	66.0	71.7	76.4
Hurricanes (H)	(4)	6.1	7.3	8.0
Hurricane Days (HD)	(5)	21.9	28.6	32.7
Intense Hurricanes (IH)	(4)	3.2	3.8	4.3
Intense Hurricane Days (IHD)	(3)	2.6	4.1	6.4
Hurricane Destruction				
Potential (HDP)	(5)	56.7	85.4	96.3
Net Tropical Cyclone				
Activity (NTC)	(6)	113.3	129.8	135.8
Maximum Potential				
Destruction (MPD)	(5)	63.9	71.1	78.5

Discussion

Forecast signals for 1999 contain a mix of positive and negative influences. Of the 13 potential predictors listed in Table 1, eight (those four predictors associated with the QBO, the March NE Atlantic ridge, and all three of the ENSO predictors) indicate above average hurricane activity, whereas the other five predictors of African rain, Atlantic SSTA and R-ON indicate slight negative influences.

Another 1 April predictor available to us but not yet quantitatively incorporated into our statistical forecast scheme is a June through September prediction of Caribbean basin Sea Level Pressure Anomaly (SLPA). This has recently been developed by J. Knaff (1998) a former project member. We find that August-September SLPA has a very strong association with seasonal hurricane activity. Knaff's 1 April forecast for a June through September SLPA of -0.39 mb adds further evidence that the 1999 hurricane season should be an active one. Table 4 provides details of these 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), the tropical Atlantic (6-22°N, 18-80°W) and January through March Niño 3.4 (5°N-5°S, 120°W-170°W) SST anomalies. Using these 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. Lower SLPA forecasts enhance hurricane activity, higher SLPA reduce it.

Table 4: April 1, 1999 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	+0.11	-0.29	-0.39

We anticipate an abundance of low latitude hurricane formations from African waves this year. This results in long tracked tropical cyclones. We anticipate that subtropical cyclone formation will somewhat suppressed.

In summary, data through the end of March indicate that 1998 will experience hurricane activity significantly above that of the average hurricane season and particularly much more active than the typical hurricane seasons between 1970-1994 when major hurricane activity was suppressed. Our forecast of an NTC of 160 and a value of SSTA* of 36 makes the combination of NTC+SSTA* to be 196. This NTC+SSTA* value of 196 is the tenth highest value of this parameter for the past 100 years. SSTA* is an index of recent year North Atlantic SSTA* and is related to the multi-decadal variability of North Atlantic SSTA. Space limitation prevents a full description in this paper.

3(2) Analog Years

The closest analog years since 1950 when QBO and reliable African rainfall data were available with similar 1 April precursor data signals to 1999 are the busy hurricane years of 1950, 1995, and 1961. These prior years, like 1999, occurred in an active multi-decadal era and had (by the end of March) and maintained through the hurricane season, cold ENSO conditions, near ideal stratospheric QBO westerly phase conditions, low March ridge conditions, below average 1 April prediction of western Caribbean SLPA, and very similar SSTA configurations in the Atlantic. Table 5 shows that there was very little variations between individual 1 April climate predictors for 1950, 1955, and 1961 and those of 1999. The average of these 1 April predictors during these three analog years and the 1 April 1999 predictors as shown in Table 6. This table gives the seasonal hurricane activity in each of these three very active analog years. Except for the number of named storms, our 1999 forecast, despite suggesting a very active coming hurricane season, is below that of the average of these three analog years. In this sense, our forecast of a very active 1999 season may, given the special climate signals now present be considered a rather conservative estimate.

Table 5: Comparison of 1 April predictors of 1999 with 1 April predictors of the three analog years of 1950, 1955, and 1961.

Years	**Active Multi-decadal Era**	**Ob. (Jan-Mar) and Aug-Sep Fcst ENSO**	**QBO**	**March Ridge**	**N.Atl SSTA J-F-M**	**T. Atl. SSTA J-F-M**
Ave. 1950,1955,1961	Yes	Cold	Ideal Westerly	-.96 SD	-.09˙C	+.07˙C
1999	Yes	Cold	Ideal Westerly	-1.49 SD	-.09˙C	-.07˙C

Table 6: Analog year seasonal hurricane activity and comparison with 1999 forecast.

	NS	**NSD**	**H**	**HD**	**IH**	**IHD**	**NTC**
1950	13	98	11	60	7	15.5	240
1955	12	83	9	47	5	13.75	196
1961	11	71	8	48	6	20.75	220
Average	12	84	9.3	51.7	6	16.7	219
1999 Fcst	14,	65	9	40	4	10	160

Predicted named storm totals for 1999 have been raised to reflect our belief that there may have been a low bias in the number of weaker tropical cyclones in the earlier years. Had the current satellite information been available during the 1950s and early 1960s it is likely that a few additional tropical storms would have been detected and named in these earlier active years.

3(3) Landfall Probabilities for 1999

A new aspect of our research involves efforts to develop forecasts of the probability of hurricane landfall along the U.S. coastline. Hurricane landfalls can never be accurately forecast in an individual year, but the yearly probability of landfall can be forecast with statistical skill. Landfall is a function of the varying climate signals and can be specified. Probability specification can be accomplished by a statistical study of all U.S. hurricane landfalls named storms for the last 100 years (1899-1998). Specific landfall probabilities can be given for all cyclone intensity classes for each U.S. coastal region. Landfall probability has been found to be (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. NTC gives an overall measure of Atlantic basin seasonal hurricane activity in any year. Distinctive landfall characteristics occur for the Gulf Coast or (regions 1-4) extending just north of Spring Hill, FL and westwards to Brownsville, TX (35 total category 3-4-5 landfalls of this century) and the rest of the U.S. coast from Spring Hill, FL to Eastport, ME (38 landfalls in regions 5-11) (Fig. 4).

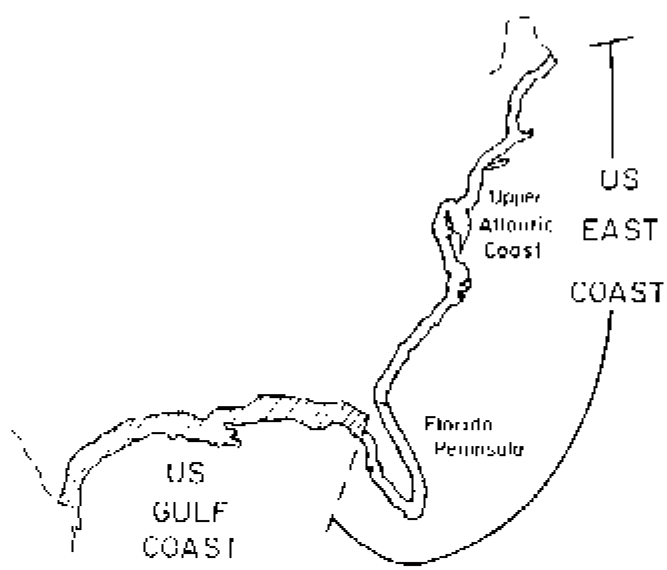

Figure 4: Portrayal of the separation of the two basic U.S. coastal areas which have different climate associations with their landfalling major hurricanes.

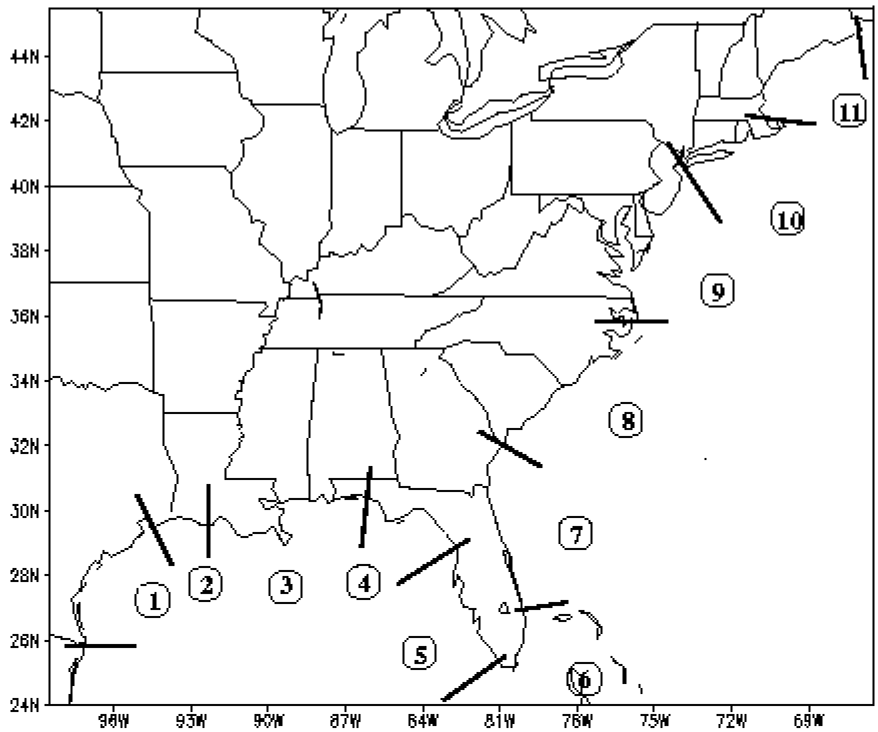

Figure 5: Location of the 11 coastal regions for which separate probability estimates are made.

As shown in Table 7, NTC is a combined measure of the year-to-year mean of six indices of hurricane activity expressed in percentage differences from the long-term average. Whereas many active Atlantic hurricane seasons may bring no landfalling hurricanes, some inactive seasons experience one or more landfalling intense hurricanes; however, the latter is not typical. Long period statistics show that, on average, the more active the overall Atlantic basin hurricane season is, the greater the probability of landfall. Less active Atlantic basin seasons have (on average) a greatly reduced occurrence of landfall. For example, landfall observations during the last 100 years show that more 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 were in place. The 33 years (of the last 100) with the combination of highest NTC and strongest thermohaline circulation experienced 24 category 3-4-5 hurricane strikes along the Florida and East Coast (Fig. 4) whereas the 33 years with the lowest NTC and the weakest thermohaline circulation saw only 3 such intense hurricane hits, a ratio of 8 to 1. Tables 8 and 9 summarize the links between hurricane and tropical storm landfall, with the combined influences of NTC and thermohaline circulation or North Atlantic temperature effects for Florida and the U.S. East coast and upon only NTC for the Gulf Coast. Atlantic basin NTC can be skillfully predicted and the strength of the Atlantic Ocean thermohaline circulation can be inferred from prior year North Atlantic Sea Surface Temperature (SST) anomalies. These predictive relationships can, thereby, 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 in comparison to 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 Catagory	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 33 highest and 33 lowest values of NTC of this century.

Intensity Catagory	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

The analysis of a century of U.S. hurricane landfall data suggests that 11 different coastal regions be specified as having distinctive values of hurricane landfall activity during the last century. These differences are due primarily to the varying incidence of category 3-4-5 hurricanes. Figure 5 shows the locations of these 11 coastal zones.

An analysis of the general relationship between NTC data and category 3-4-5 landfall events is shown in Fig. 6 for both active (strong) and inactive (weak) Atlantic Ocean thermohaline circulations. Note how landfall probability increases as NTC increases. Major hurricanes do not occur with NTC values less than 30.

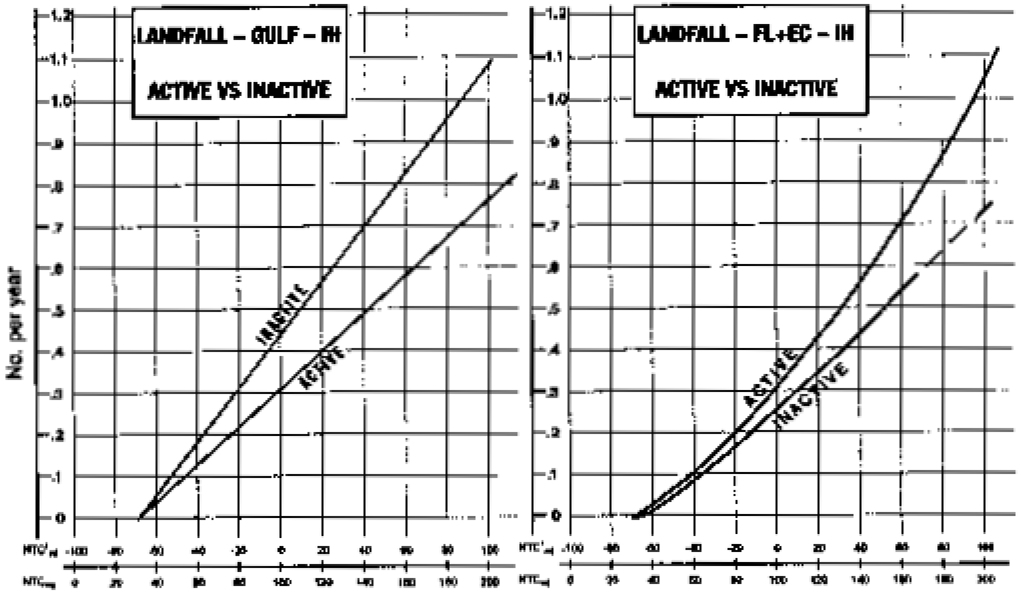

Figure 6: Empirical curves showing the relationship between NTC (bottom horizontal numbers) and the number of category 3-4-5 hurricanes making landfall along the US Gulf Coast (regions 1-4) during active or stronger thermohaline circulation conditions versus inactive or weaker thermohaline circulations (left diagram). An equivalent curve for the Florida Peninsula and the US East Coast (regions 5-11) during similar stronger (active) versus inactive (weaker) modes of the thermohaline circulation is given in the right diagram.

A similar set of curves have been constructed for variations of category 1-2 hurricanes and TS 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 (Fig. 5).

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 1999. The mean annual number of landfalling systems are given in parentheses.

Table 10: Estimated percent probability of one or more U.S. landfalling Tropical Storms (TS), category 1-2 hurricanes, and category 3-4-5 hurricanes 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 1999. The last 100 year mean annual number of landfalling systems is given in parenthesis).

Coastal Region	**TS**	**Category 1-2 HUR**	**Category 3-4-5 HUR**	**All HUR**	**Named Storms**
Entire U.S. coastline	87% (1.57)	67% (1.12)	72% (0.73)	94% (1.85)	97% (3.42)
Gulf Coast (Region 1-4)	69% (0.89)	54% (0.55)	40% (0.35)	72% (0.90)	92% (1.79)

Florida plus East Coast (Region 5 -11)	57% (0.68)	57% (0.57)	54% (0.38)	80% (0.95)	92% (1.63)

Although not explicitly figured in this report, the intense hurricane (category 3-4-5) frequency in the Caribbean area during 1999 should be close to that of Florida and the U.S. East Coast or somewhat less than twice the long period average, but about 4-5 times higher than during the large below average period of 1970-1994.

4 Comparison of 1999 Landfall Probabilities

These calculations forecast a 1999 NTC value of 160 and that the Atlantic thermohaline circulation in 1999 will be strong (SSTA* = 36). The major hurricane landfall expected number by this method for Florida and the East Coast for 1999 are 5.5 times larger than the average year during the quarter century period of 1970-1994 when the mean NTC was 75 (instead of the forecast value of 160 for this year) with a weak (rather than strong) thermohaline circulation was in place. For the Gulf Coast our forecast numbers of category 3-4-5 hurricane landfalls for 1999 in comparison with the periods of 1970-1994 is about twice as much.

When the Atlantic Ocean thermohaline circulation is judged to be strong (as during the 48-year period of 1926-1969, and 1995-1997) 27 category 3-4-5 hurricane landfalls occurred along the Florida and East Coast versus only 11 landfalls during 52 years (1900-1925, 1970-1994) when it was weak. This Atlantic thermohaline influence on intense hurricane landfall shows a weak inverse influence along the Gulf Coast (regions 1-4), however.

5 Coming New Information on the Prediction of U.S. Hurricane Landfall Probabilities

A full documentation of the methodology of this hurricane landfall probability study is not ready at this time. The first author will try to finish this study by late May and make this information available on the internet. These landfall probabilities will include the forecast of the probability of tropical storms (TS) and hurricanes of category 1, 2, 3, 4-5 for the following areas:

- along the entire U.S. coastline,
- (separately) along the Florida and East Coast and along the Gulf Coast - Fig. 4,
- along each of 11 units of the U.S. coastline - Fig. 5,
- along each 100 km (65 mile) segment of U.S. coastline.

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

The general methodology of how these probability forecasts will be made is shown in Fig. 7.

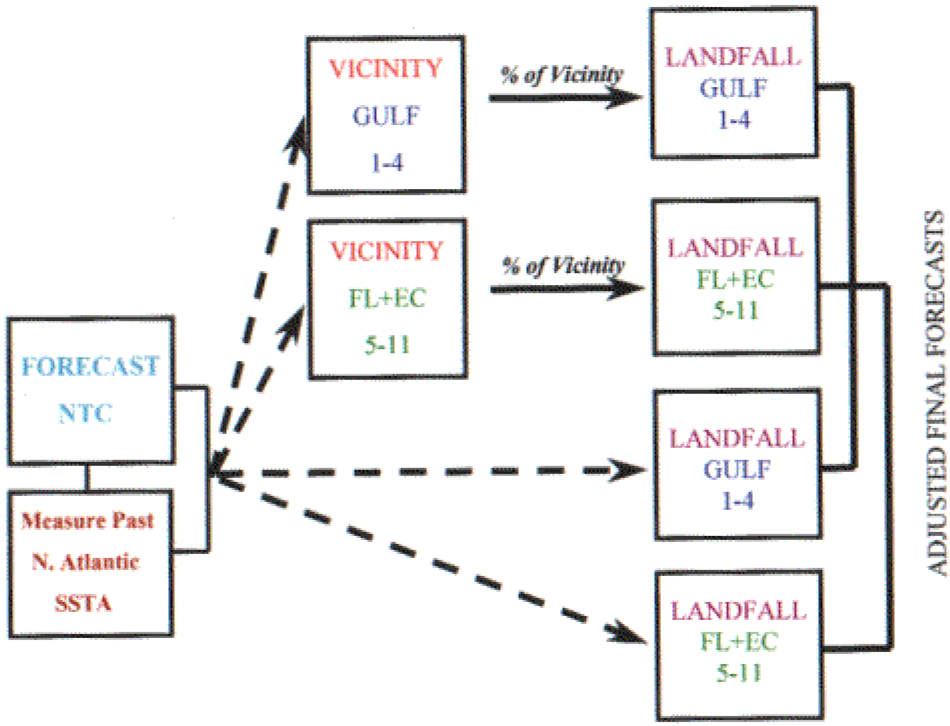

Figure 7: General flow diagram illustrating how forecasts of U.S. hurricane landfall probabilities are made. We forecast NTC and use an observed measure of the last few years of North Atlantic (50-60˚ N, 10-50˚W) SSTA*. Regression equations are then developed with the combination of forecast NTC and 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).

6 Evidence of Persistent Multi-Decade Enhancement of Atlantic Hurricane Activity Associated With a Major Reconfiguration of Atlantic Basin SSTs

Recent observations indicate increased salinity in the upper layers of the tropical Atlantic and North Atlantic. Higher salinity increases water density in these surface layers which can sink to great depth, thereby increasing equatorward flow of deep water and a compensating northward flow of warm (and salty) replacement water near the surface. The resulting net northward transport of upper-layer warm water into the high North Atlantic and equatorward transport of deep cold water is the principal manifestation of the Atlantic Ocean thermohaline (``Conveyor Belt") circulation. A strong conveyor circulation increases water temperatures in the high latitude areas and thus transports more heat to high latitudes. Hence, slowly rising salinity values in the far North Atlantic during the last 15 years suggest the development of conditions whereby the Atlantic Ocean has recently tended to a stronger thermohaline circulation.

Figure 8 shows changes of the mean SST anomalies for 1991 to 1994 versus 1995 to 1998. Note the general warming of the North Atlantic that has taken place during the last four years when the incidence of major hurricanes also increased to levels similar to the period of the 1930s to 1950s. This new SSTA pattern typically manifests itself in the form of more hurricanes forming at low latitudes and, especially, more intense low latitude hurricanes and more major hurricanes landfalling along the US East Coast, Florida, and in the middle Caribbean. We expect that this trend will continue for several decades.

For some 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 approximately between 1970-1994) would inevitably end and that Atlantic coastal residence should expect an eventual long-term increase in the probability 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 (1998) and Gray (1998)] major hurricanes are observed to cause 80 to 90 percent of all US tropical cyclone linked destruction.

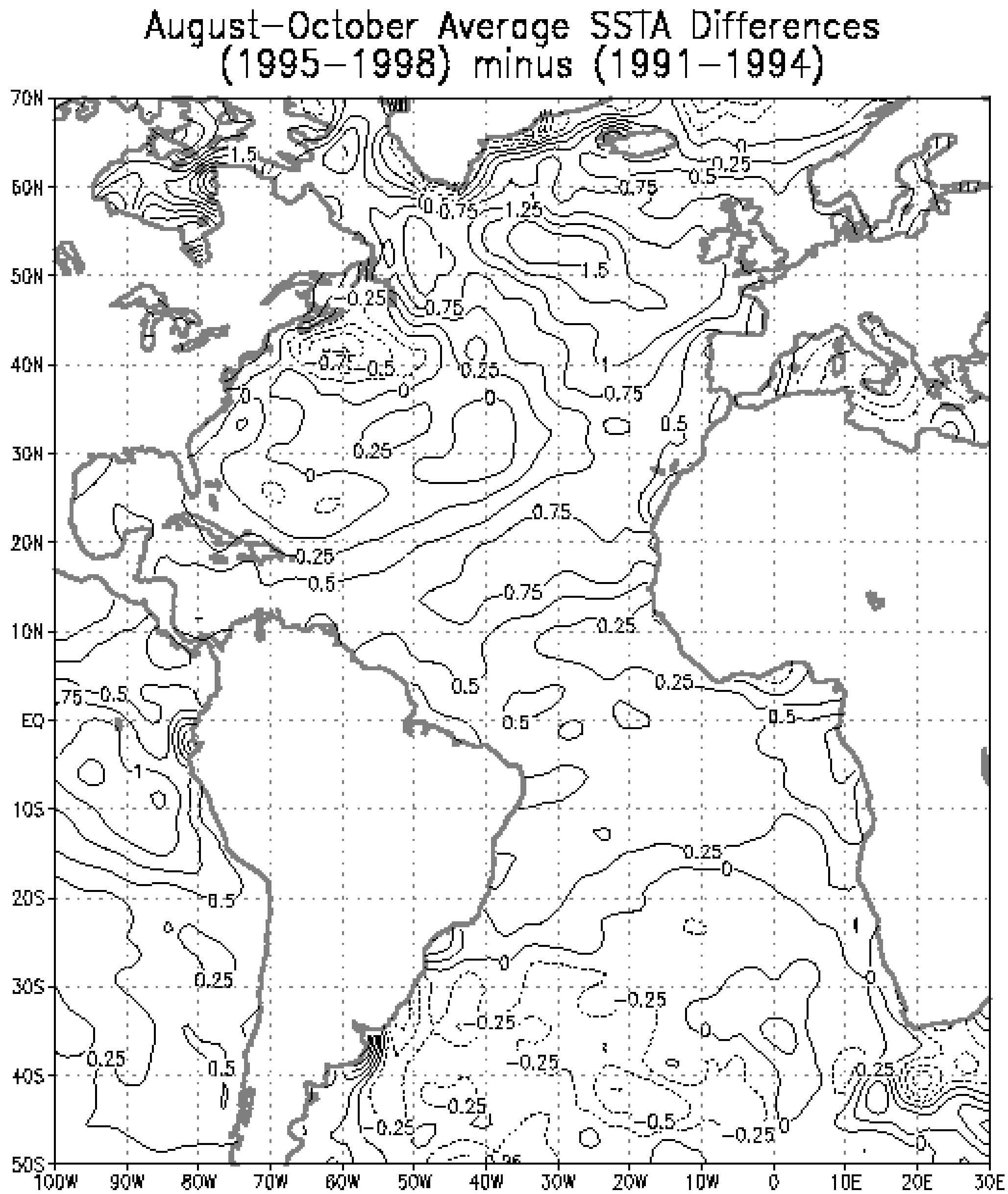

Figure 8: August through October SST differences in ˚C for 1995 to 1998 minus 1991 to 1994.

Despite El Niño-linked reductions of hurricane activity during 1997, the last four years (1995-1998) are together the most active four (consecutive) year period on record. There were a total number of named storms (53), hurricanes (33), major hurricanes (category 3-4-5) (15), major hurricane days (36) and Net Tropical Cyclone activity (653) which occurred during the last four years. Despite the weak 1997 hurricane season, the annual average NS, H, IH, IHD and NTC during the last four years are 142, 142, 170, 191 and 163 percent (respectively) of the average hurricane activity for 1950-1990. The annual average NS, H, IH, IHD and NTC during the last four years have been 154, 160, 250, 419 and 216 percent of the average for the previous 25-year period 1970-1994; the greatest increase occurring for IH and IHD activity. The three recent active hurricane seasons 1995, 1996 and 1998 had 311 (IH) and 524 (IHD) percent of the average intense hurricanes and intense hurricane days (respectively) of the means prior 25-year period 1970-1994. These trends towards increased hurricane activity support the notion that we have had an abrupt climate shift during 1995 and that we have entered a new era of increased major hurricane activity that was typical of the 1940s and 1950s.

7 Forecast Theory and Cautionary Note

Our forecasts are based on the premise that trends in global environmental conditions which preceded 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 for any one location along the coast are very low and reflect the fact that in any one season, most US coastal areas will not feel the effects of a hurricane no matter how active an individual season is. And, it must be emphasized that a low probability does not insure that a hurricane will not come ashore. Regardless of how active 1999 hurricane season should be, a finite probability also exists that one or more hurricanes may strike along the US or Caribbean Basin coastline and do much damage.

8 Schedule of Forecast Updates

This 7 April 1999 seasonal forecast will be updated on 4 June 1999 and 6 August 1999. These revisions will allow us to make adjustments as new information becomes available. A verification of this forecast will be issued in late November 1999 and a seasonal forecast for the 2000 hurricane season will, as in the past, be issued in early December, 1999.

9 Acknowledgements

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Additional Reading

Verification of All Past Seasonal Forecasts

See write-up of our verification of the 1998 season on this same Web site for verification tables and figures with discussion of our forecast verifications for the period 1984-1998.