EXTENDED RANGE FORECAST OF ATLANTIC SEASONAL HURRICANE ACTIVITY AND US LANDFALL STRIKE PROBABILITY 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 November 1998

By

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4 December 1998

1999 ATLANTIC BASIN SEASONAL HURRICANE FORECAST

	4 December 1998
Tropical Cyclone Seasonal Forecast for 1999	
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

MAJOR HURRICANE LANDFALL PROBABILITY

1. Along the East Coast Including Peninsula Florida - 185% of normal
2. Along the Gulf Coast from the Florida Panhandle westward to Brownsville - 168% of normal
3. In the Caribbean a little less than twice the long period average. Caribbean landfall probability varies in a similar fashion to that of the US East Coast and Peninsula Florida average. (Sub-region breakdown are given in the text)

Update and Correction of 1998 Hurricane Season Statistics

Our 1998 forecast verification of last week (25 November 1998) did not fully account for Hurricane Nicole or give the final adjusted National Hurricane Center statistics for all of 1998. The following table contains updated information (as of 4 December 1998).

Comparison of the 1998 season with long-term average hurricane conditions.

Forecast Parameter	**1950-1990 Mean**	**1998**	**1998 in percent of 1950-1990 Ave.**
Named Storms (NS)	9.3	14	151
Named Storm Days (NSD)	46.6	84	172
Hurricanes (H)	5.8	10	172
Hurricane Days (HD)	23.9	49	197

Intense Hurricanes (IH)	2.2	3	136
Intense Hurricane Days (IHD)	4.7	9.2	197
Hurricane Destruction Potential (HDP)	71.2	145	199
Maximum Potential Destruction (MPD)	66.0	109	165
Net Tropical Cyclone Activity (NTC)	100	173	173

In terms of Net Tropical Cyclone (NTC) activity, 1998 was the sixth most active season since 1933. More active seasons include 1950, 1955, 1961, 1995 and 1996.

DEFINITIONS

ABSTRACT

Information obtained through November 1998 indicates that 1999 Atlantic hurricane activity is likely to be much above the average for the 1950-1990 period with 9 hurricanes (average 5.7), 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 very busy hurricane seasons of 1995, 1996 and 1998. Evidence strongly suggests that we have entered a new era of enhanced major hurricane activity.

This paper presents the details of our 6-11 month extended range seasonal forecast of tropical cyclone activity as well as of the probability of US hurricane landfall during 1999. This forecast is 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 not yet incorporated in our statistical models. These schemes allow estimates of seasonal Atlantic tropical cyclone activity to be made in early December of the prior year. 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) by early December of the prior year. The forecast is based on experiments which have now yielded two prediction schemes for estimating hurricane activity in the following year plus qualitative adjustments for processes not yet incorporated into our statistical models. Two separate 1 December forecasts are developed utilizing 41 years (1950-1990) and 46 years (1950-1995) of data respectively. Our extended-range 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 ten months into the future), extended range estimates of El Niño-Southern Oscillation (ENSO) variability (Fig. 2), and Western Sahel rainfall anomalies for the following summer, the October-November 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 1999 are as follows:

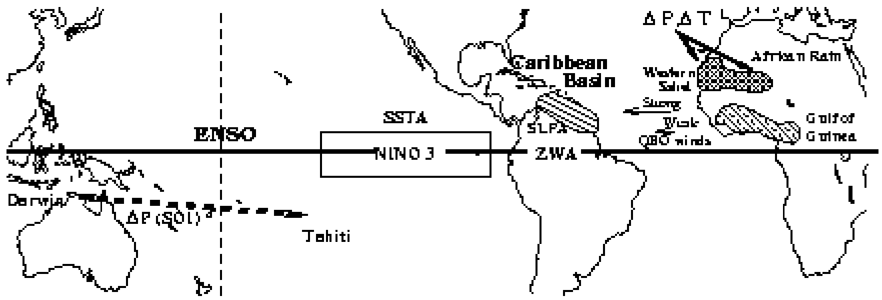

Figure 1: Meteorological parameters used in various versions of our older early August (Gray et al. 1994a) seasonal forecast.

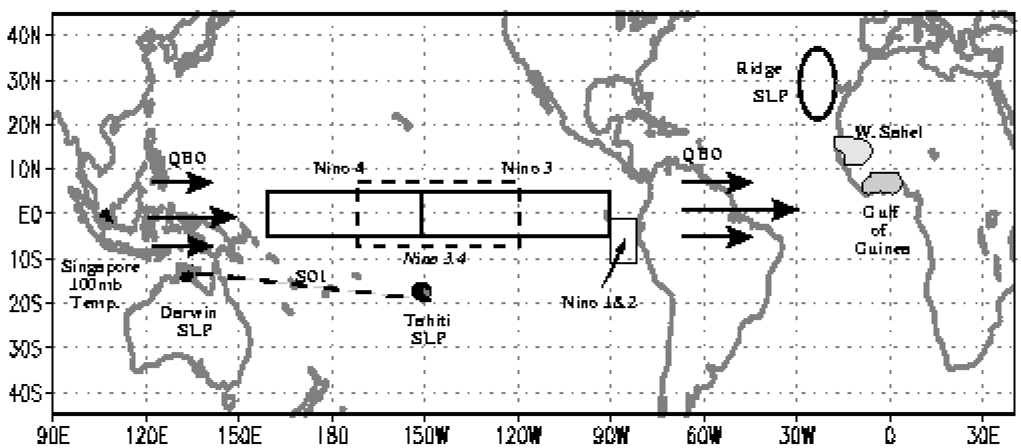

Figure 2: Additional parameters used or consulted in our extended-range forecasts.

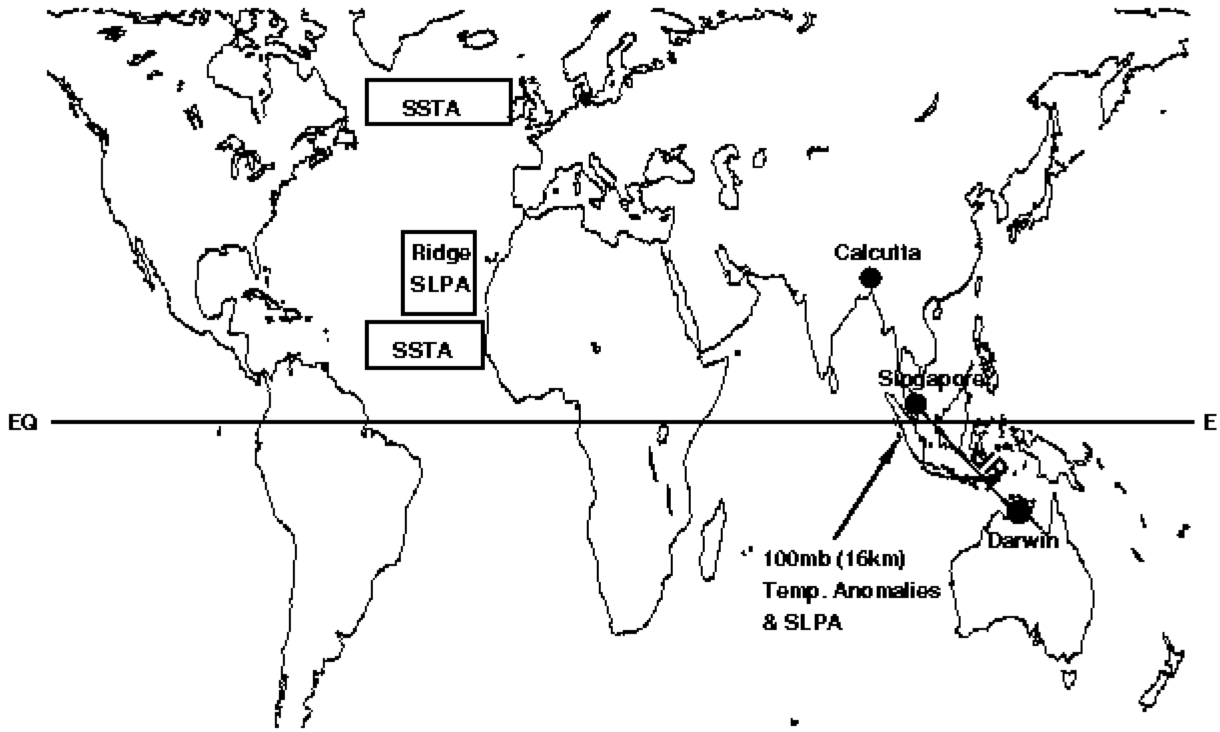

Figure 3: Additional (new) predictors which have recently been noted to be related to the upcoming Atlantic hurricane activity.

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, 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 (+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. As these rainfall relationships have not worked very well during the last few years (1995-98) we are qualitatively given them less weight with this 1999 forecast. The 1998 August-November Gulf of Guinea rainfall was slightly below average (-0.32 SD), suggesting this to be a slightly negative influence for 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 (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 to persist through the key months of August through October 1999 and thus be an enhancing influence on 1999 hurricane activity.

d) Strength of the October-November 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). Consequently, this factor is presently judged to be a slightly negative influence on 1999 hurricane activity.

e) Other Potential Long Range Predictors

Our analyses have revealed additional global scale parameters which are of value in assessing and adjusting the output of our statistical scheme. These include:

- The configuration of SST anomaly patterns over much of the high and low latitude Atlantic: warm SST anomalies in these regions during the summer and fall are usually associated with an enhancement of next summer's hurricane activity and similarly, cold SST anomaly patterns with a reduction of next year's hurricane activity. Summer and fall 1998 SST anomaly patterns have been anomalously warm in the Atlantic and are (barring a warm ENSO event next year which we presently consider unlikely) an enhancing influence for our prediction of next summer's hurricane activity.
- Middle latitude circulation patterns during the September through November period: When middle latitude westerly oceanic wind patterns are more zonal, and both the Aleutian low and the Icelandic low are stronger (eg., blocking action in Atlantic is reduced), then hurricane activity during the following summer is typically reduced. When the opposite conditions exist (i.e., when the westerly circulation and Aleutian low pressure are weaker and more blocking action is present), the following year's hurricane activity is typically enhanced. The recent flow patterns have been more typical of the latter (enhancing) condition.

2 Extended Range 8-11 Month Prediction Schemes

2.1 Outline of Earlier (Gray et al. 1992) Scheme

Our original extended range forecast scheme had the following form:

$$(\text{Seasonal Forecast}) = e_o \left(1 + a_1 U_{50} + a_2 U_{30} + a_3 |U_{50} - U_{30}| + a_4 R_s + a_5 R_G \right) \quad (1)$$

where

1. U_{50} = 10 month extrapolated 50 mb QBO zonal wind near 10°N for September 1999
2. U_{30} = 10 month extrapolated 30 mb QBO zonal wind near 10°N for September 1999
3. $|U_{50} - U_{30}|$ = 10 month extrapolated 50 mb minus 30 mb QBO absolute value of zonal wind for September 1999 shear
4. R_s = Measured standard deviation of previous year August-September 1998 Western Sahel rainfall
5. R_G = Measured standard deviation of previous year August-November 1998 Gulf of Guinea rainfall

The e_o and ``a" coefficients are determined to maximize the hindcast predictive signals. Different $e_o$ and ``a" coefficients are determined for each predictor. These equations were developed on data from the 41 years of 1950-1990. They explain about 40-50 percent of the variance of each of the nine forecast parameters in non-independent hindcasts.

Values of the forecast parameters used for prediction of the next year's 1999 Atlantic hurricane activity are given in Table 1. Substitution of the values in Table 1 into Eq. 1 yields the forecast of next year's Atlantic basin seasonal hurricane activity shown in Table 2. Again, this forecast indicates much below average hurricane activity during 1999. Table 2 also gives the hindcast and expected forecast skill associated with each prediction. This older and simpler forecast scheme does not incorporate many of the positive physical associations discussed previously and thus gives a forecast for next year's hurricane activity which we believe to be too low.

Table 1: Values of the five (input) parameters for the 1999 forecast are as follows:

1. U_{50} = 0 m/s
2. U_{30} = -1 m/s
3. $|U_{50} - U_{30}|$ = 1 m/s
4. Sahel (R_s) (Aug-Sep, 1998) = +0.23 S.D.
5. Gulf of Guinea (R_G) (Aug-Nov, 1998) = -0.32 S.D.

Table 2: Statistical prediction for the 1999 season as obtained with Eq. 1 and the final amount of non-degraded variance explained in the 41-year hindcast developmental data set (1950-1990). The third column gives the expected forecast skill when this forecast scheme is applied to future observations which may not be fully representative of the hindcast data set.

Forecast Parameter	Gray et al. (1992) Statistical Forecast for 1999	Amount of Hindcast Variance Explained	Expected Independent Forecast Skill
Named Storms (NS)	11.2	.44	.17
Named Storm Days (NSD)	59.5	.51	.30
Hurricanes (H)	7.0	.45	.18
Hurricane Days (HD)	29.6	.49	.26
Intense Hurricanes (IH)	2.4	.47	.22
Intense Hurricane Days (IHD)	5.1	.45	.19
Hurricane Destruction Potential (HDP)	76.7	.44	.18
Net Tropical Cyclone Activity (NTC)	109.5	.53	.33

2.2 More Recent Modifications of Our Extended Range Forecast Scheme

A new version of our extended range forecasting scheme differs from the original scheme in that it involves an updated pool of predictors to which we apply a ``leaps-and-bounds" regression method. This procedure iteratively chooses the best two predictors, the best three predictors, etc. to as many as ten predictors. Total variability accommodated by the resulting forecast equations typically increases as we add predictors, but at an ever-decreasing rate of improvement of true skill. Given the limited pool of hindcast years (46) from which to develop our scheme (1950-1995), degrading of true skill occurs when the scheme is applied to independent data if too many predictors are used (i.e., overfitting). Consequently, it is prudent to limit the number of predictors, typically to between three and seven.

Table 3 shows the pool of ten potential predictors and their numerical values for this year's forecast; Table 4 shows the predictors chosen for each of our nine forecast hurricane activity parameters. Table 5 shows the predictions for the 1999 hurricane season with this newer forecast scheme, along with the amount of non-degraded variance explained within the 46-year developmental data sets. We judge the newer scheme to provide better estimates of next year's activity. But this newer (methodology) forecast may also underestimate 1999 activity as it does not incorporate our consensus belief that the current cold La Niña conditions will persist through the heart of the 1999 hurricane season and out expectation of continuing warm North Atlantic SST anomalies. And, we also find that our statistical forecast schemes typically underforecasts very active seasons.

Table 3: Predictor values for 1999 forecast.

Pool of 10 Potential Predictors

Predictor No.	**Predictor**	**Predictor Values for 1999 Fcst**
1 =	U_{50}	0 m/s
2 =	U_{30}	-1 m/s
3 =	$\lvert U_{50} - U_{30} \rvert$	1 m/s
4 =	Guinea Rain (Aug-Nov)	-0.32 SD
5 =	West Sahel rain (Jun-Sep)	-0.17 SD
6 =	Atlantic Ridge (Oct-Nov)	+0.45 SD
7 =	Darwin (May-Jul)	-0.1 mb
8 =	Nino-4 Trend (Aug-Oct)-(May-Jul)	-0.6°C
9 =	SOI (Aug-Oct)	+1.1 SD
10 =	SOI Trend (Aug-Oct)-(May-Jul)	+0.4 SD

Table 4: Most skillful predictor values for 1999 forecast.

Top predictors chosen for each forecast variable

Number

Predictors	1	2	3	4	5	6	7	8	9	10
NS (3)		2		4		6				
NSD (6)	1	2		4	5	6				10
H (5)	1		3	4	5	6				
HD (5)	1	2		4	5	6				
IH (4)	1		3	4		6				
IHD (3)			3	4	5					
HDP (5)	1	2		4	5	6				
NTC (4)			3	4	5	6				
MPD (4)	1		3	4	5	6		8	9	

Table 5: Our second extended range forecast scheme for 1999 hurricane activity with the amount of non-degraded forecast variance explained. Developmental data is for the years of 1950-1995. The third column gives the expected forecast skill when this forecast scheme is applied to future observations which may not be fully representative of the hindcast data set.

Forecast Parameter	Best Forecast Forecast	Amount of non-degraded Variance Explained	Expected Independent Forecast Skill
NS	10.4	.519	.332
NSD	52.0	.547	.374
H	6.5	.494	.297
HD	25.6	.536	.358
IH	2.3	.436	.196
IHD	4.6	.417	.160
HDP	67.3	.492	.294
NTC	62.1	.528	.350
MPD	93.6	.660	.523

Real Forecast Skill. Application of both forecast schemes to independent data (i.e., the future) usually entails forecast skill degradation such that the amount of real forecast skill is less than that encountered in our experimental hindcast examples. [Our hurricane forecast for 1997 is a classic example. In our developmental data set, there was no El Niño event nearly so strong as the one that occurred.] Nevertheless, on average this degradation should be on the order of 15-25 percent from the hindcast skill shown.

Table 6 provides a comparison of the forecasts from both hurricane prediction schemes and our qualitative (upward) adjustment of the actual 1999 seasonal forecast. The third column shows our 1999 forecast, column four gives 1950-1990 climatology and column five gives the 1999 forecast activity expressed as percent of the 1950-1990 average season. Net tropical cyclone activity is expected to be about 160 percent of the average of the 1950-1990 hurricane seasons.

Table 6: Comparison of our two objective forecast schemes with our qualitative upward adjustment due to changing atmosphere-ocean conditions not explicitly in our forecasts.

	(1)	(2)	(3)	(4)	(5)
Forecast Parameter	**Older 1 Dec Fcst Scheme**	**Newer 1 Dec Fcst Scheme**	**Qualitatively Adjusted 1998 Fcst**	**1950-1990 Average**	**Forecast Percent of 1950-1990 Period**
NS	11.2	10.6	14	9.3	151
NSD	59.5	53.9	65	46.6	139
H	7.0	6.6	9	5.8	155
HD	29.6	27.1	40	23.9	167
IH	2.4	2.4	4	2.2	182
IHD	5.1	5.2	10	4.7	213
HDP	76.7	71.7	130	71.2	181
MPD	-	64.9	130	66.0	200
NTC	109.5	98.7	160	100	160

Reasons for Upward Modification of 1999 Statistical Forecasts. We believe that the 1999 hurricane season will be more active than indicated by our statistical schemes because a number of new and likely hurricane enhancing features are known not to be fully incorporated in our statistical forecasts. This includes:

1. North and tropical Atlantic SSTA patterns associated with the Atlantic thermohaline circulation and
2. next summer's ENSO characteristics.

Both of these basic climate signals are expected to cause an enhancement of 1999 hurricane activity. In addition, our statistic schemes are known to underestimate during very active seasons.

3 Landfall Probabilities

Our forecast of seasonal hurricane and tropical storm landfall probability centers on the U.S. Gulf Coast and Eastern seaboard. Probabilities have been calculated from landfall statistics, yearly variations in Atlantic basin total hurricane activity and global circulation-climate information for the 98-year period spanning 1900-1997. Landfall probabilities are presented for 11 distinct Gulf Coast and U.S. East Coast regions extending from Brownsville, TX to Eastport, ME (Fig. 4). Specific landfall probabilities are given for all cyclone intensity classes including tropical storms (TS), category 1-2 hurricanes, and intense (i.e., major category 3-4-5) hurricanes for each of these 11 U.S. coastal regions. South Florida has the highest probabilities of landfalling intense hurricanes. 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.

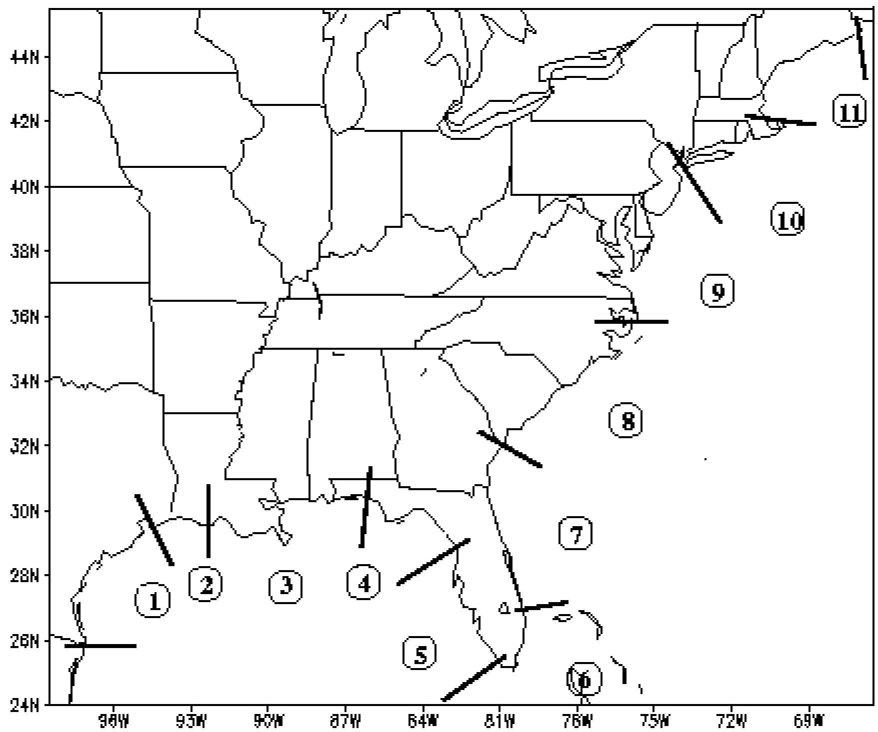

Figure 4: Location of the 11 coastal regions for which separate probability estimates are made.

Forecasts of the probability of U.S. hurricane landfall can be developed from our forecast Atlantic basin NTC activity and estimates of the strength of the Atlantic Ocean thermohaline circulation. 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. The Atlantic thermohaline circulation provides a longer-term (multi-decadal) component of forecast variability. Whereas many very 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) greatly reduced occurrence of landfall. For example, landfall observations during the last 98 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 a strong Atlantic Ocean thermohaline circulation is in place. The 33 years (during the last 98) with the combination of greatest 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 ratio of 8 to 1. Tables 8 and 9 summarize the links between intense hurricane landfall and combined NTC and thermohaline circulation effects for Florida and the East coast and upon only NTC for the Gulf. Atlantic basin NTC already 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 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)	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 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

When the Atlantic Ocean thermohaline circulation is judged to be strong (as during the 47-year period of 1926-1969, and 1995-1997) 26 category 3-4-5 hurricane landfalls occurred along the Florida and East Coast versus only 11 landfalls during 51 years (1900-1925, 1970-1994) when it was weak. However, there are some years of high NTC and weak thermohaline circulation and the reverse. This Atlantic thermohaline influence on intense hurricane landfall shows a weak inverse influence along the Gulf Coast (regions 1-4), however.

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 4 shows the locations of these 11 coastal zones. Distinctive landfall characteristics also occur for the Gulf Coast or (regions 1-4) extending just north of Spring Hill, FL and westwards to Brownsville, TX (34 total category 3-4-5 landfalls of this century) and the rest of the U.S. coast from Spring Hill, FL to Eastport, ME (37 landfalls in regions 5-11). Figure 5 shows that most intense hurricane landfall events occur on less than one-half of the U.S. coast area, however.

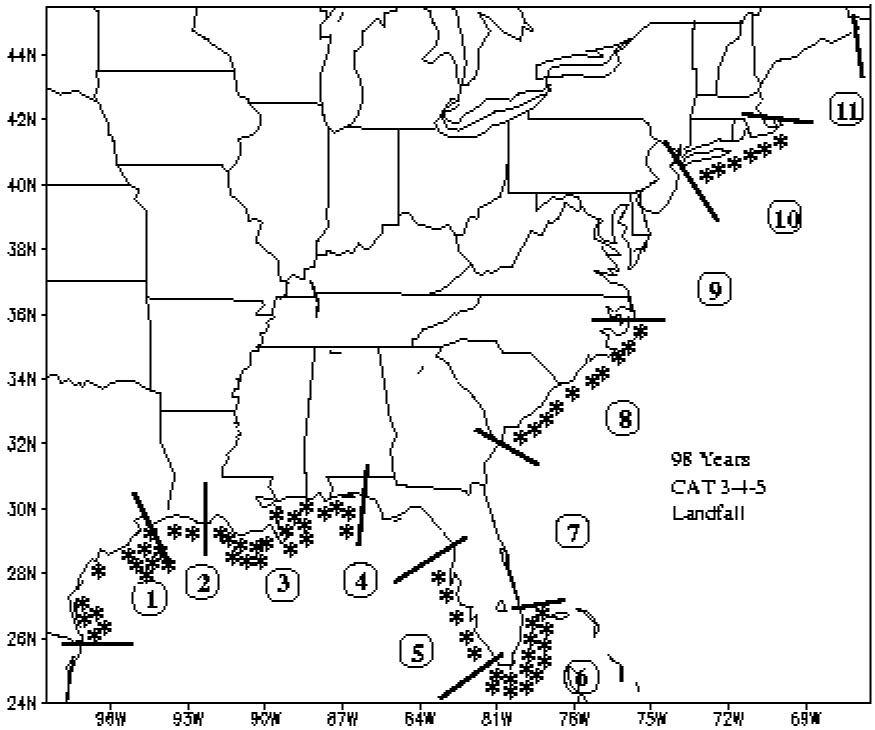

Figure 5: Locations of 72 intense (category 3-4-5) hurricane landfall events during 1900-1997.

There are distinctive coastal locations such as the Florida east coast north of Fort Pierce to the Georgia-South Carolina border and the coastline from north of Cape Hatteras to just west of New York City which have never experienced a landfalling category 3-4-5 hurricane during the last century. In contrast, U.S. coastal locations such as southern Florida and the Texas and Louisiana coasts have had many major landfalling hurricanes during the last century. As category 3-4-5 hurricanes do most of the coastal destruction [estimated to be 80-90 percent, Pielke and Landsea (1998)], it is expected that the large variability of coastal destruction would occur. Similar maps for the landfall frequency of category 1-2 hurricanes and tropical storms show less coastal variability.

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.

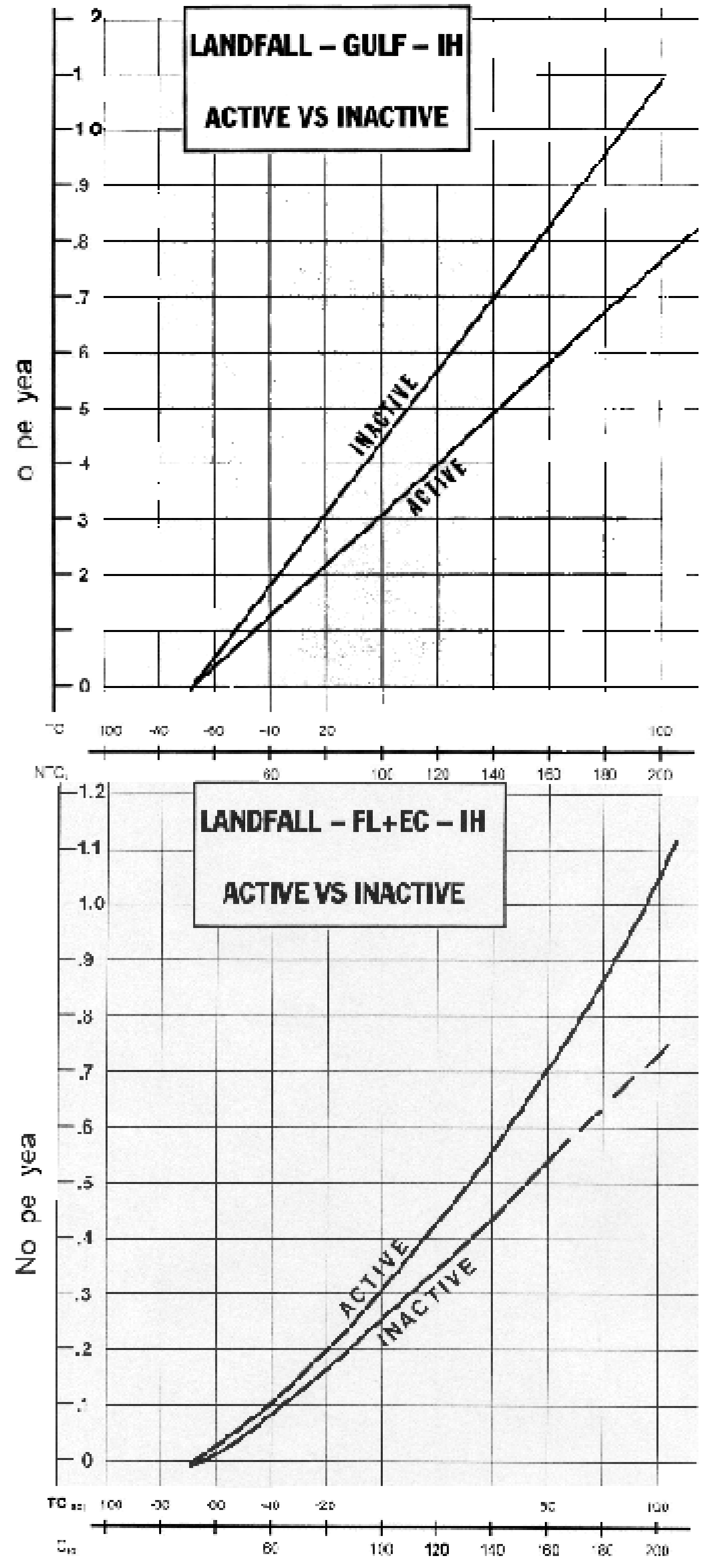

Figure 6: Empirical curves showing the relationship between NTC (bottom horizontal numbers) and the number of category 3-4-5 hurricanes making landfall along the US Gulf Coast (regions 1-4) during active thermohaline circulation conditions versus inactive or weaker thermohaline circulations (left diagram). 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 b 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). Forecast equations for each of the 11 US coastal areas take the form:

$$\text{No. per year} = a\,(NTC - 30)^b$$

for Category 3-4-5 hurricanes and

$$\text{No. per year} = a\,(NTC)^b$$

for Category 1-2 hurricanes and for TS, where a and b are empirically determined coefficients - listed in Table 10.

Table 10: Landfall equation coefficients for TS, category 1-2 and category 3-4-5 for the US Gulf Coast (regions 1-4) and for Florida Peninsula (regions 5-11). No./year = $a(NTC)^b$ for category 1-2, TS; No./year = $a(NTC-30)^b$ for category 3-4-5. Active and inactive periods refer to the strength of the thermohaline circulation, strong (active), weak (inactive).

Category 3-4-5	$a(10^{-2})$	b
Landfall - Gulf - Active	0.44	1.00
Landfall - Gulf - Inactive	0.63	1.00
Landfall - FL + EC - Active	0.12	1.30
Landfall - FL + EC - Inactive	0.08	1.34
Category 1-2	$a(10^{-2})$	b
Landfall - Gulf	2.09	0.71
Landfall - FL + EC	0.59	1.00
TS	$a(10^{-2})$	b
Landfall - Gulf	19.35	0.33
Landfall - FL + EC	4.54	0.74

These calculations assume a 1999 NTC value of 160 and that the Atlantic thermohaline circulation in 1999 will be strong. The major hurricane landfall probabilities by this method for Florida and the East Coast for 1999 are 13.7 times larger than the average for 1991-1994 when the mean NTC was 53 with a weak thermohaline circulation was in place. This major hurricane landfall forecast for 1999 is 5.5 times higher than the average for the quarter century period 1970-1994 when the thermohaline circulation was weak and the average NTC was 75. For the Gulf Coast our estimated numbers of category 3-4-5 hurricane landfalls in 1999 to the periods of 1991-94 and 1970-1994 is 4 and 2 to one.

Table 11 lists probabilities for a range of TS, Cat 1-2, and Cat 3-4-5 hurricanes impacting each of the 11 coastal locations (Fig. 4) during 1999. Values in parentheses are percentage comparisons of these 1999 forecast landfall probabilities to 1900-1997 annual average values. Note that the expected major hurricane activity along the Florida Peninsula and US East Coast (regions 5-11) is 184 percent of the long-term mean and about 168 percent of the long term mean for the Gulf Coast (regions 1-4). For the weaker category 1-2 hurricanes, these landfall probabilities are about 172 and 145 percent of the long-term average. For tropical storms it is 153 and 113 percent of the long-term mean.

Table 11: Estimated percent probability of US landfalling Tropical Storms (TS), category 1-2 hurricanes, and category 3-4-5 hurricanes along each of 11 US coastal locations (Fig. 4) for 1999. These probabilities as a percentage of the 1900-1997 mean is given in parentheses.

Coastal Region	**TS**	**Category 1-2 HUR**	**Category 3-4-5 HUR**
Gulf			
1	22 (113)	30 (145)	23 (168)
2	13 (113)	10 (145)	4 (168)
3	46 (113)	29 (145)	31 (168)
4	20 (113)	10 (145)	?#2
Florida Plus East Coast			
5	19 (153)	7 (172)	10 (184)
6	15 (153)	27 (172)	29 (184)
7	19 (153)	8 (172)	?#2
8	28 (153)	30 (172)	20 (184)
9	7 (153)	10 (172)	?#2
10	5 (153)	7 (172)	11 (184)
11	7 (153)	6 (172)	?#2

Although not explicitly figured in this report, the intense hurricane (category 3-4-5) frequency in the Caribbean area in 1999 should be close to that of the US East Coast or somewhat less than twice the long period average.

4 Discussion

The three major climate influences affecting variations in the Atlantic hurricane activity are as follows:

1. The SST configuration in the North Atlantic Ocean which varies in relation to the strength of the Atlantic Ocean thermohaline (conveyor belt) circulation. We represent this SST anomaly

configuration using a proxy value taken from North Atlantic (50-60˙N, 10-50˙W) SST anomaly data (N. ATL).
2. The phase of ENSO: El Niño, La Niña, or neutral.
3. The phase of the stratosphere equatorial QBO: easterly or westerly.

Seasonal trends in summer atmospheric circulations in the tropical Atlantic associated with variations in these three basic, global-scale ocean and atmosphere features determined much of the year-to-year trends of hurricane activity. Atlantic hurricane activity is enhanced by warm North Atlantic (N. ATL) SST anomalies, cold La Niña conditions and a westerly QBO. Minimum hurricane activity occurs with cold North Atlantic SST anomalies, an El Niño and an easterly QBO. Most of the parameters used in our extended-range forecasts are related to these three basic factors.

For 1999 we project all three of these basic climate factors to be positive for hurricane activity. Specifically, for summer and early fall 1999 we expect the following:

- a) that the warm SSTAs which have been present in the North Atlantic since 1995 will persist through 1999,
- b) that this year's La Niña conditions will persist through next year, and
- c) that westerly QBO wind conditions will be well developed by summer 1999.

When, during past years of this century, these factors have been present, very active hurricane seasons have occurred. These conditions typically lead to enhanced low latitude and long-tracked hurricanes and a modest suppression of weaker and shorter storm track activity at high latitudes. We also anticipate continued above average hurricane activity in the Caribbean basin during 1999.

<u>Expected Persistence of La Niña through Aug-Oct 1999</u>. During the last two years, our early December forecasts have suffered from poor predictions of next year's ENSO conditions. In particular, we (and others) did not expect (in December 1996) the strong El Niño of 1997-98 and we were not at all sure (in early December 1997) that a strong La Niña would develop by summer 1998. The success of this early December forecast is very dependent on our assessment that cold water conditions will persist in the Eastern and Central Equatorial Pacific during the 1999 season.

<u>Analog Years</u>. El Niños events typically develop and/or intensify during stratospheric east-phase QBO conditions whereas La Niñas or cold water conditions tend to develop and/or become more prominent during QBO west-phase conditions. During the easterly QBO, deep convection tends to be enhanced along the Equator and suppressed at higher latitudes (10-20 degrees). The enhanced deep equatorial convection of QBO east phase years leads to the development of more frequent and stronger Madden-Julian Oscillations (MJOs) in the Indian and West Pacific warm pool region. These MJOs trigger ocean Kelvin waves which, when the west Pacific warm pool is well developed, can initiate El Niño events and maintain or strengthen existing El Niños. But this QBO-ENSO relationship is subtile and difficult to diagnose. Consequently, there appear to be occasional westerly QBO years when the West Pacific warm pool is well built-up and when MJOs and low latitude tropical cyclones become frequent and/or strong enough to trigger El Niños. The El Niño of 1997, the warmest on record, was of this type. It's effects appear to have contributed to rapidly depleting the West Pacific warm-pool, leading to a rapid rebound of La Niña (or cool) conditions by mid-1998, an easterly (beginning in June) QBO year.

There will be a westerly QBO in 1999 (presently at 30 mb and will likely reach 50 mb by late winter) which will favor the continuation of the current cold ENSO event. Our best judgement for 1999 is that cold La Niña conditions will continue. This view is shared by a number of other ENSO forecasts as discussed in the NOAA/CPC October Climate Bulletin.

We use historic measurements of SST to infer the sign and magnitude of the N. ATL and the ENSO anomalies back to 1870. For the QBO, we use direct measurements back to 1950. Before 1950 the QBO is inferred by (J. Sheaffer 1998 our project) using a technique for creating a provisional index extending the stratospheric QBO back in time to the 1870s. Presently, this is accomplished using hourly surface pressure observations taken at Batavia (Djakarta) on the Indonesia island of Java from 1856 to 1960. The timing and magnitude of the semi-diurnal pressure wave (¶1-1.5 mb) has characteristics which vary with the phase of the stratospheric QBO. We have been able to calibrate the main features of this association with data from tropical equatorial West Pacific stations for 1952-1990 when both actual (rawinsonde) QBO measurements and hourly surface pressure measurements were available. Studying the basic observational aspects of the association between the stratospheric QBO zonal winds and surface pressure tides allows us to infer the main QBO features prior to direct measures of these winds which were routinely begun in the early 1950s. Pending additional verification work this promises to be a very important accomplishment, allowing us to diagnose the interplay of the QBO with the other two fundamental (for our forecast) global processes (the global Ocean Conveyor Belt and the ENSO) for the last 130 years.

We have identified four three(consecutive)-year periods during the last 130 years when observed (or inferred) westerly stratospheric QBO zonal winds were associated with an El Niño warm event which was then followed the next year by the onset of both an easterly QBO and a La Niña cold event during the (Boreal) summer, as has now occurred during 1997 and 1998. In the year following each of these cases (eg., 1999), a second year of cold water or La Niña conditions persisted and a very active hurricane season ensued during the (second) year of the cold event. Table 12 lists each of these prior three-year analog cases. Note that in those years when the North Atlantic was warm and a westerly QBO was in place with La Niña following under easterly QBO conditions, that the following (or third year) continues with cold water conditions and an active hurricane season. We judge these four analog periods to be similar to the 1997 to 1999 period.

Table 12: Prior four consecutive 3-year periods when the North Atlantic in June-Sept was warm, the QBO went from west (year 1) to east (year 2) to west (year 3) and warm Nino-3 period was followed by two consecutive cold period. Nino-3 values in 10^{-2} ˙C are given in parentheses. Right column gives the calculated value of NTC in year three of each of these periods. Line 5 (bottom) lists measured (or projected) conditions during 1997-1999.

Analogs	**Year 1**	**Year 2**	**Year 3**	**Year 3**
N. ATL. SSTA	WARM	WARM	WARM	
QBO	WEST	EAST	WEST	CALCULATED
ENSO	WARM	COLD	COLD	NTC
1	1907 (+15)	1908 (-76)	1909 (-94)	129
2	1914 (+120)	1915 (-83)	1916 (-104)	225
3	1941 (+105)	1942 (-107)	1943 (-28)	136
4	1953 (+36)	1954 (-97)	1955 (-127)	216
Mean of				

4-prior periods	(+69) Warm	(-91) Cold	(-88) Cold	177
5	1997 (330)	1998 (-45)	1999 (Expected cold)	Expected high ~160

5 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 upper layers of the tropical Atlantic and North Atlantic. Higher salinity increases water density in these surface layers which is then more able to 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.

Three decades have passed since the SST anomaly patterns of the Atlantic Ocean have had so strong a north/south SST gradient as is now observed. Figure 7 shows changes of the mean SST anomalies for 1991 to 1994 versus 1995 to 1998. June through September 1998 SSTA values in the North Atlantic (50-60°N, 10-50°W) were 0.81°C and 0.82°C anomaly was present in the tropical Atlantic. It is assumed that these warm conditions will continue through 1999. 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 more like the 1930s to 1960s. This trend manifests itself primarily 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.

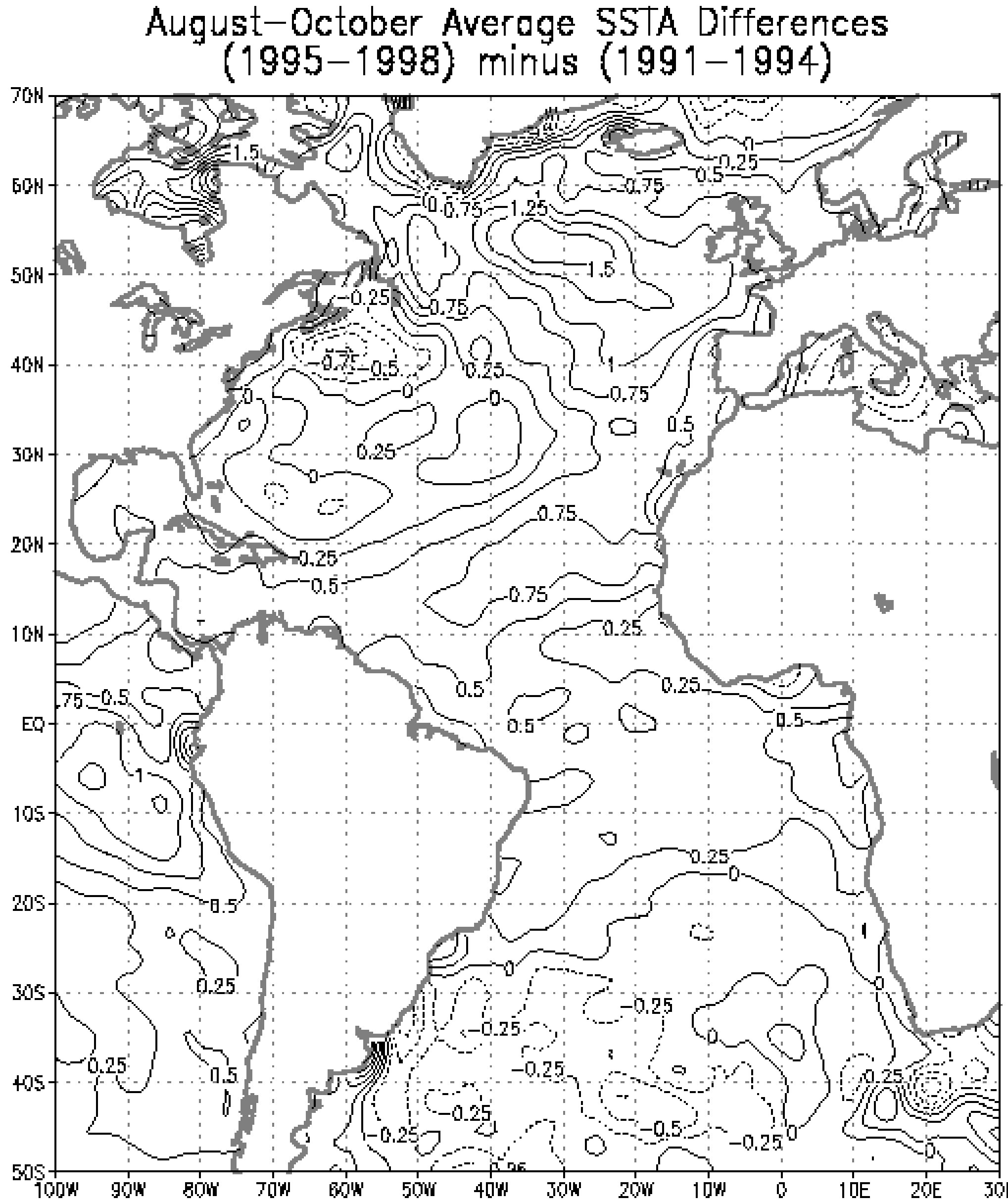

Figure 7: August through October SST difference between 1995 to 1998 minus 1991 to 1994. Values are in ˙C.

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 between 1970-1994 was likely ending 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.

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. Table 13 lists the 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. Note on line No. 4 of Table 13, that 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. And, as shown on line 6, 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 to increased hurricane activity support the notion that we have indeed entered a new era of increased major hurricane activity.

Table 13: Comparison of recent 1995-1998 hurricane activity annual activity in other recent periods.

Line No.	Year	Named Storms (NS)	Hurricanes (H)	Cat 3-4-5 Hurricanes (IH)	Cat 3-4-5 Hurricane Days (IHD)	Net Tropical Cyclone Activity (NTC)
	1995	19	11	5	11.50	229
	1996	13	9	6	13.00	198
	1997	7	3	1	2.25	54
	1998	14	10	3	9.25	172
1.	**TOTAL**	53	33	15	36.00	653
2.	**4-Year Ave 1995-1998**	13.2	8.25	3.75	9	163
3.	**1950-1990 Ave.**	9.3	5.8	2.2	4.7	100
4.	**1995-1998 Ave/1950-1990 in percent**	142	142	170	191	163
5.	**1970-1994/1950-1990 in percent**	92	86	68	46	75
6.	**1995-1998/1970-1994 in percent**	154	160	250	419	216
7.	**Years 1995, 96, 98/1970-97 Ave in percent**	174	194	311	524	248

6 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 an individual season is. But 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.

7 Schedule of Forecast Updates

This 4 December 1998 forecast will be updated on 7 April 1999, 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.

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9 Additional Reading

Verification of All Past Seasonal Forecasts