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

A year for which both overall hurricane activity and US hurricane landfall probability are anticipated to be above average

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

By

William M. Gray,* Christopher W. Landsea**, Paul W. Mielke, Jr. and Kenneth J. Berry***

`  * Professor of Atmospheric Science`
`** Meteorologist with NOAA/AOML HRD Lab., Miami, FL`
`*** Professors of Statistics`

[David Weymiller and Thomas Milligan, Colorado State University, Media Representatives (970-491-6432) are available to answer various questions about this forecast.]

Department of Atmospheric Science
Colorado State University
Fort Collins, CO 80523
Phone Number: 970-491-8681

4 June 1999

UPDATED 1999 ATLANTIC BASIN SEASONAL HURRICANE FORECAST AS OF 4 JUNE 1999

Tropical Cyclone Seasonal Forecast for 1999 (Climatological mean values are shown in parenthesis)

Named Storms (NS) (9.3)	**14**
Named Storm Days (NSD) (46.9)	**75**
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 and 7 April 1999)

SUMMARY OF PROBABILITIES FOR ONE OR MORE 1999 MAJOR HURRICANE LANDFALLS ON THE FOLLOWING COASTAL AREAS. (100-YEAR AVERAGE PROBABILITY VALUES SHOWN IN PARENTHESIS)

1. U.S. East Coast including Peninsula Florida £#54 percent (31%).
2. Gulf Coast from the Florida Panhandle westward to Brownsville £#40 percent (30%).
3. For the entire U.S. coastline £#72 percent (50%).
4. For the Caribbean and Bahamas land areas £#72 percent (51%).
5. Along the East Coast of Mexico £#28 percent (18%).

DEFINITIONS

ABSTRACT

Information obtained through May 1999 indicates that 1999 Atlantic hurricane activity is likely to be above the 1950-1990 average. Predictions for 1999 include 9 hurricanes (average is 5.8), 14 named storms (average 9.3), 75 named storm days (average is 47), 40 hurricane days (average is 24), 4 intense (category 3-4-5) hurricanes (average is 2.2), 10 intense hurricane days (average is 4.7) and a Hurricane Destruction Potential (HDP) of 130 (average is 71). Collectively, net tropical cyclone activity is expected to be about 160 percent of the long term average, comparable to the recent busy 1996 and 1998 hurricane seasons. Evidence suggests that we have entered an extended period of enhanced major hurricane activity.

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. This report presents the details of our forecast of 1999 Atlantic tropical cyclone activity as well as a

general estimate of the probability of US Caribbean Basin, and Mexican East Coast hurricane landfall during 1999. Landfall probabilities this year are appreciably above the last 100-year average. The 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 atmospheric and oceanic information which is not yet incorporated in our statistical models.

1 Introduction

Very 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 May (see Fig. 3). A brief summary of these predictor indices and their specific implications for 1999 are provided in the following.

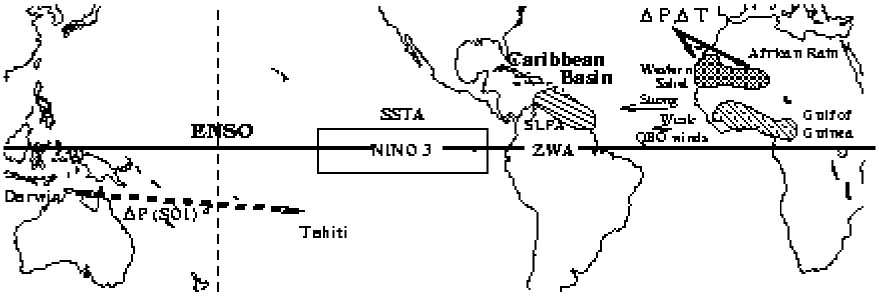

Figure 1: Meteorological parameters used in various versions of our older early August (Gray et al. 1994a) seasonal forecast.

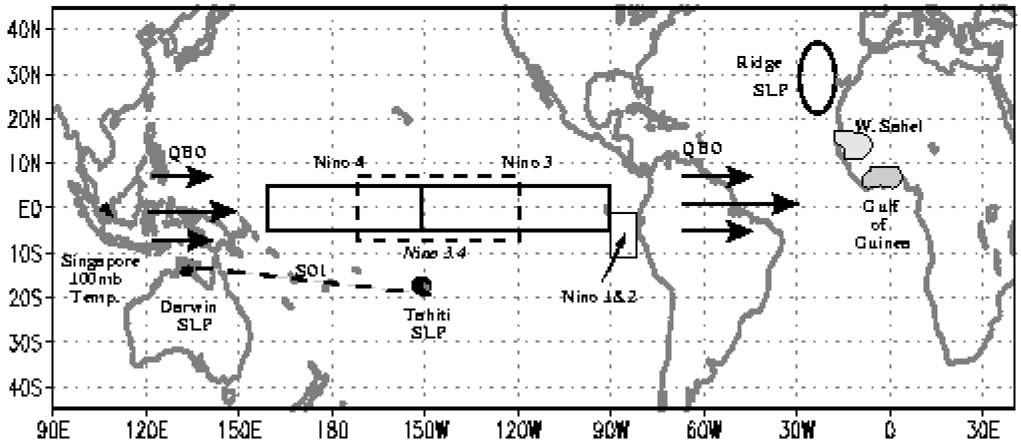

Figure 2: Additional parameters used or consulted in our extended-range forecasts.

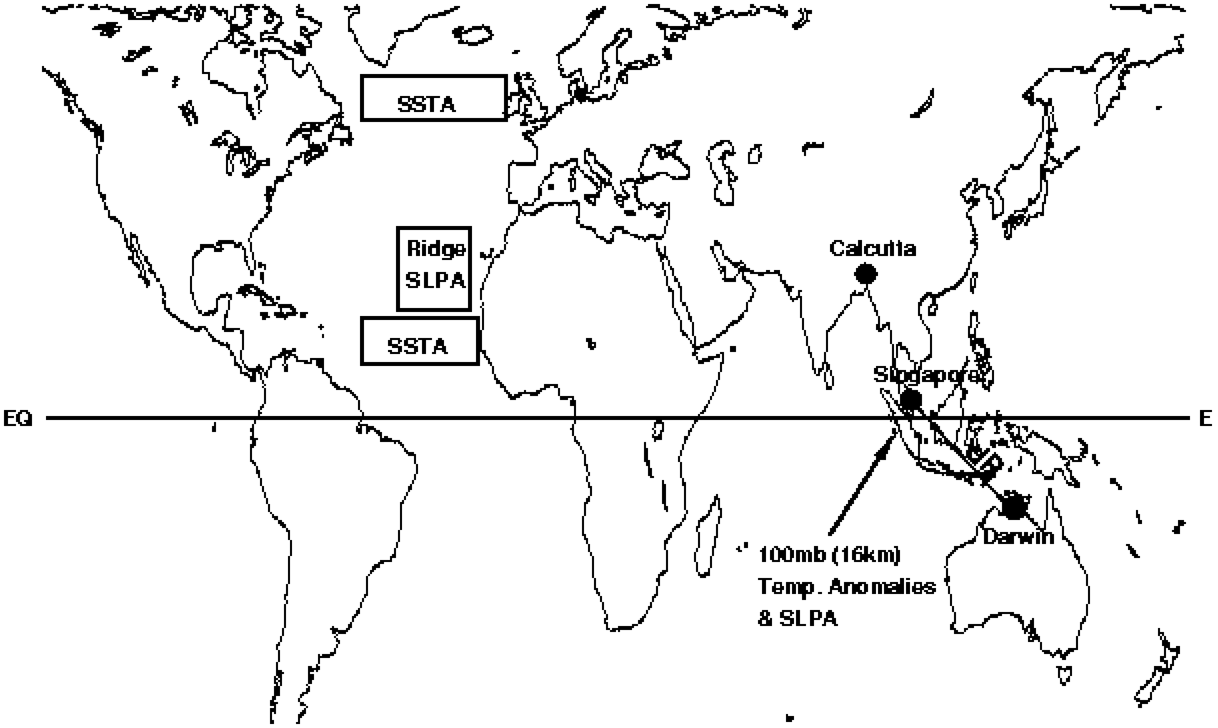

Figure 3: Additional (new) predictors which have recently been noted to be related to the upcoming Atlantic hurricane activity.

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 westerly anomalies 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 anomalously 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 June-September 1998 was -0.23 SD below average and thus is a neutral 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. Rainfall in the Gulf of Guinea region in August to November 1998 was near average, -0.28 SD.

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 (April-May Nino 3.4 = -0.60°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 Atlantic Subtropical Ridge (Azores High) Between 20-30°W during the prior October-November and the Current March 1999

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 during the spring which then create a self-enhancing (positive feedback) response resulting in higher Caribbean pressures during the following 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 during the prior fall is correlated 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. The fall ridge values were a consequence of a stronger than normal NAO which has now completely reversed itself. 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) during January through March provide a predictive signal for the following hurricane season. Warmer April and May SSTAs are associated with enhanced hurricane activity and colder SSTAs are associated with reduced seasonal hurricane activity. These North and Tropical Atlantic SSTAs for April and May were near average (+0.20°C in the North and +0.20°C in the tropics). We expect these currently slightly positive SSTAs to become more positive by the active part of the hurricane season.

2 Prediction Methodology

We forecast nine measures of seasonal Atlantic basin tropical cyclone activity including seasonal numbers of the following: Named Storms (NS), Named Storm Days (NSD), Hurricanes (H), Hurricane Days (HD), Intense Hurricanes (IH), Intense Hurricane Days (IHD), the Hurricane Destruction Potential (HDP), Net Tropical Cyclone activity (NTC), and the Maximum Potential Destruction (MPD). (Definitions for these indices are given on page 3). For each of these measures, we choose the best three to six predictors (i.e., those resulting in optimum prediction skill) from a group of 15 potential forecast parameters known to be related to tropical cyclone activity. The current set of potential predictors used to develop our early June forecast is shown in Table 1. The specific values of these parameters used in the early June forecast are shown in the right hand column.

Table 1: Pool of predictive parameters and their estimated values for the early June 1998 prediction. This is based on meteorological data through May 1998. See Figs. 1 and 2 for the locations of these predictors.

Predictive Parameter	
1 = QBO 50 mb 4-month extrapolation of zonal wind at 12°N to Sept. 1999	0 m s^{-1}
2 = QBO 30 mb 4-month extrapolation of zonal wind at 12°N to Sept. 1999	-1 m s^{-1}
3 = QBO absolute value of shear between 50 and 30 mb at 12°N to Sept. 1999	1 m s^{-1}
4 = Rgc AN Gulf of Guinea rainfall anomaly (Aug-Nov of 1998)	-0.28 SD
5 = Rws West Sahel rainfall anomaly (June-Sept 1998)	-0.23 SD

6 = Temp East-West Sahel temperature gradient(Feb-May 1999)	-0.5 SD
7 = SLPA April-May Caribbean basin sea level pressure anomaly	+1.1 mb
8 = ZWA April-May Caribbean basin zonal wind anomaly	-2.8 m/s
9 = R-ON: Azores surface pressure ridge strength in Oct-Nov 1998	+0.45 SD
10 = R-M: Mar Azores surface pressure ridge strength in Mar 1999	-1.49 SD
11 = SST3.4 Nino 3.4 SSTA in April-May 1999	-0.60˙C
12 = D-SST3.4: Nino 3.4 SSTA for April-May minus Feb-Mar 1999	+0.40˙C
13 = TATL Tropical Atlantic SSTA anomaly (10-22˙N,18-50˙W) (Apr-May)	+0.20˙C
14 = NATL North Atlantic SSTA anomaly (50-60˙N,10-50˙W) (Apr-May)	+0.20˙C
15 = SATL Mid Atlantic SSTA anomaly (5-18˙S,50˙W-10˙E) (Apr-May)	+0.50˙C

A number of statistical forecasts are made for each activity parameter. Table 2 lists the seasonal hurricane indices that we predict, the number of forecast parameters we use in each forecast and which forecast parameters these are. Our hindcast skill (between 50-60 percent) for the 48-year period of 1950-97 is shown in the right column. These prediction equations are established for our variable parameter forecast model. This represents our best statistical forecast where, so as to minimize the skill degradation of these equations when making independent forecasts via statistical ``overfitting", we include the least number of predictors for the highest amount of hindcast variance. We stop adding predictors when the hindcast improvement of the next best predictor adds less than a 0.025 improvement to the total variance explained. These equations are also constrained to have regression coefficients whose sign match those when analyzed in isolation.

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

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

We have also studied a scheme which uses various fixed (maximum) numbers of predictors. Table 3 lists these predictors. This procedure considers how hindcast variance (not necessarily true skill) increases as the number of predictors increases from 4 to 6 to 8. Although independent forecast skill (i.e., ``true skill") typically degrades in approximate proportion to the increased number of predictors, it is of interest to assess the degree of hindcast improvement which occurs with added predictors.

Individual year forecast skill degradation from application of hindcast statistics can never be accurately specified. Consequently, as the latter are purely random effects, the hazards of overfitting become obvious.

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

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

Additional forecast parameters representing conditions in the Atlantic and Pacific Ocean basins and in the Asia-Australia regions (refer to Figs. 1 and 2) are also consulted for further qualitative inter-relations and possible influences on our final ``adjusted" forecast.

Table 4 lists hindcast prediction skills for our various statistical models including the variable (number) predictor schemes along with the fixed (4, 6 and 8) predictor schemes. Probability dictates that, on average, a net degradation of this hindcast skill of between 10-20 percent of total variability will likely occur. The amount of degradation (if any) for an individual year forecast is a random process. In some years, when conditions include strong trends that are similar to past years, forecasts will do quite well, perhaps better than the skill of the hindcast scheme. In other years, a given forecast can perform quite poorly. This is because our 48-year (1950-1997) predictor data base likely does not contain realizations expressing the full range of independent possibilities. Our 1997 forecast is a good example. No year in our 1950 through 1996 developmental data sets had ever experienced an El Niño event anywhere nearly as intense (by a factor of 2) as the 1997-98 El Niño event.

Table 4: 1 June statistical forecasts which have a variable number of predictors with variable predictors (column 1) along with 4, 6 and 8 fixed predictors forecast (columns 2, 3). Column 4 is our final adjusted early June forecast of 1998 hurricane activity. Column 5 gives climatology.

Full Forecast Parameter	**(1) Variable Predictor**	**(2) Fixed predictors 4 Predictors**	**(3) 6 Predictors**	**(4) Adjusted Actual Fcst**	**(5) 1950-1990 Climatology**
Named Storms (NS)	11.9	12.3	12.2	14	9.3
Named Storm Days (NSD)	49.9	53.6	49.9	75	46.9
Hurricanes (H)	5.9	7.5	5.9	9	5.8
Hurricane Days (HD)	26.6	32.4	26.6	40	23.7
Intense Hurricanes (IH)	2.5	2.9	2.9	4	2.2
Intense Hurricane Days (IHD)	3.5	3.8	5.1	10	4.7
Hurricane Destruction Potential (HDP)	58.7	65.7	57.5	130	70.6
Net Tropical Cyclone Activity (NTC)	89.4%	132%	90.6%	160%	100%
Maximum Potential Destruction (MPD)	64.5	64.5	70.8	130	61.7

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

We consider the variable predictor scheme shown in column 1 of Table 4 to be our best forecast. Table 5 shows the statistical spread of our predictions. Table 2 also presents the hindcast skill and the expected likely skill with independent data.

Table 5: Statistical spread of variable parameter forecast. The lowest and highest 25 percent are obtained from the variable statistical scheme applied to our adjusted forecast.

Forecast Parameter	**Lowest 25%**	**Adjusted Forecast**	**Highest 25%**
NS	12.5	14	15.7
NSD	71.1	75	81.2

H	7.3	9	11.8
HD	33.9	40	44.5
IH	3.0	4	4.8
IHD	5.75	10	15.2
HDP	95.4	130	161
NTC	120.3%	160%	187%
MPD	104.3	130	143

Discussion

The forecast signals for 1999 contain a mix of generally positive and a few negative influences. Of the 13 potential predictors listed in Table 1, seven (those three predictors associated with the QBO, the March NE Atlantic ridge, and two of the three ENSO predictors and ZWA) indicate above average hurricane activity, whereas the only clearly negative predictor factors are the October-November NE Atlantic Ridge and the April-May SLPA. We perceive the latter as less important factors. April-May pressure in La Niña years tends to be high in springtime. The high ON ridge was due to a seasonal increase in the NAO that has now weakened.

Three other strong predictors that have not yet been quantitatively incorporated into our statistical forecast scheme and which indicate 1999 seasonal activity above that indicated by our current statistical schemes include the following:

1. June through September prediction of Caribbean basin Sea Level Pressure Anomaly (SLPA). This has recently been developed by J. Knaff (1998). Lower SLPA forecasts enhance hurricane activity, higher SLPA reduce it. August-September SLPA has a very strong association with seasonal hurricane activity. Knaff's 1 April 1999 forecast of June through September SLPA gave a value of -0.39 mb. This adds additional evidence for an active 1999 hurricane season. Table 6 provides details of these Caribbean-West Atlantic SLPA forecasts which are based on anomaly information concerning the March Atlantic subtropical ridge, January through March SSTs in the North Atlantic (50-60°N, 10-50°W), 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. Knaff finds that additional April-May information does not improve on this forecast.
2. Realization that the Atlantic regional (and possibly global) climate has shifted to a new mode of increased major hurricane activity similar to that experienced during the 1940s through the mid-1960s. Our statistical scheme has not yet been altered to handle these differences.
3. New information on the configuration of North American East Pacific SSTAs shows very cold values. These SSTAs have not yet been incorporated into our forecast model. Separate analysis of these cold SSTA arrangements indicate that 1999 should experience a very active hurricane season.

Table 6: 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

These three factors and other qualitative information lead us to believe that our statistical forecast has underestimated the amount of hurricane activity should occur this season and we have chosen to make a sizable upward adjustment in our forecast. We anticipate an abundance of low latitude hurricane formation events (from African waves) this year, resulting in a lot of persistent, long tracked tropical cyclones. Conversely, we anticipate that subtropical cyclone formation will be somewhat suppressed.

1. Low-latitude formations will dominate. Reminiscent of recent years like 1995, 1996, and 1998. This will be opposite to the early 1990s when virtually all hurricane activity formed at higher latitudes.
2. Many of the hurricanes which form will have long, westerly tracks and thus be long-lived. Therefore NS and H days will be quite numerous.
3. Certain regions will be more vulnerable this year. The Caribbean basin which witnessed a relative absence of hurricane activity in the 1980s and early 1990s should see activity more typical of the 1940s to 1960s.
4. The western Caribbean and Gulf of Mexico often see heightened activity in the late season of La Nina years and westerly QBO years - conditions of this year.

In summary, data through the end of May indicate that 1999 will experience hurricane activity significantly above that of average hurricane seasons and much more active than the average for hurricane seasons between 1970-1994 when major hurricane activity was greatly suppressed. Our forecast of an NTC of 160 and a value of SSTA* of 36 yields a combination of NTC+SSTA* of 196. SSTA* is an index of recent North Atlantic SSTA related to the multi-decadal variability of North Atlantic SSTA. Space limitation prevents a full description in this paper. This NTC+SSTA* value of 196 is the tenth highest value for this parameter during the past 100 years.

3 Analog Years

Years similar to 1999 were also explored as a way to provide guidance in Atlantic hurricane activity. Table 7 provides the top 12 analog years (in chronological order) for each of the five main environmental factors: ENSO, QBO, Atlantic ridge, Atlantic SSTs, and African rainfall which in their prior atmospheric and ocean conditions were most similar to 1999. Table 8 presents the four years which were the best analogs to the predictors in 1999. Each of these four years had three matches out of the five predictor groups. These four years were all above average in activity and three of them (1950, 1961 and 1996) were hyperactive with at least 200 percent NTC. This result supports boosting the forecasted values above those shown by the statistical model output.

Table 7: Top twelve years (listed chronologically) that are most similar for each predictor grouping to 1999.

	ENSO (Nino 3.4, GNino 3.4)	**QBO (U50, Shear)**	**Ridge (ON, M)**	**Atlantic SSTs (NATL, TATL)**	**Africa (GT, Rgc)**
1	1950	1950	1950	1951	1951
2	1955	1957	1952	1952	1954
3	1956	1961	1954	1960	1967
4	1967	1969	1955	1961	1975
5	1968	1971	1960	1962	1976
6	1971	1973	1961	1963	1978
7	1974	1980	1962	1966	1985
8	1975	1985	1964	1970	1987
9	1976	1990	1973	1978	1991
10	1985	1993	1980	1979	1992
11	1989	1995	1981	1981	1994
12	1996	1997	1997	1996	1996

Table 8: Best four analog years overall compared to 1999.

	NS	**H**	**IH**	**NTC**
1950 (ENSO, QBO, Ridge)	13	11	7	240%
1961 (QBO, Ridge, SSTs)	11	8	6	220%
1985 (ENSO, QBO, Africa)	11	7	3	110%
1996 (ENSO, SST, Africa)	13	9	6	200%
Average	12.0	8.7	5.5	192%
1999	14	9	4	160%

Our 1999 forecast, despite suggesting a very active coming hurricane season, is below that of the average for intense hurricanes and NTC of these four 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.

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.

4 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, the Caribbean and Bahamas, and along the Mexican East Coast. Hurricane landfall can never be accurately forecast in an individual year, but the yearly probability of landfall can be specified with some statistical skill. Landfall is a function of the varying climate signals. Probability specification can be accomplished by a statistical study of all Atlantic hurricane landfall named storms for the last 100 years (1899-1998). Specific landfall probabilities can be given for all cyclone intensity classes. 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) (Figs. 4 and 5).

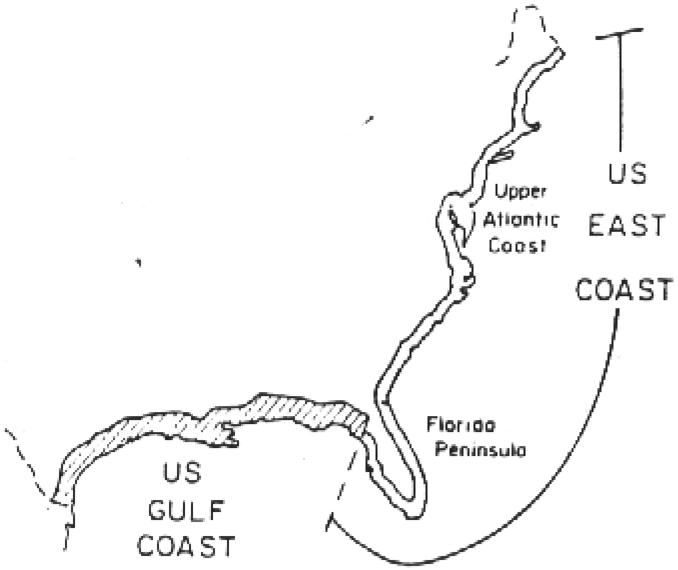

Figure 4: Portrayal of the separation of the two basic U.S. coastal areas which have different climate associations with their landfalling major hurricanes.

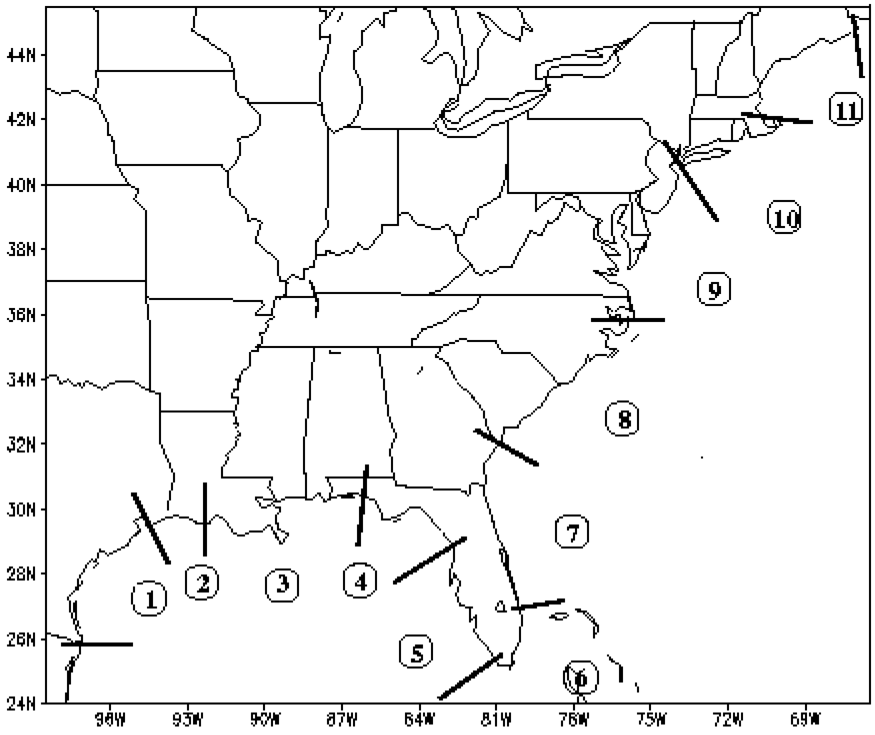

Figure 5: Location of the 11 coastal regions for which separate probability estimates are made.

As shown in Table 9, 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. Many active Atlantic hurricane seasons may bring no landfalling hurricanes, and 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 North Atlantic SSTA 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 10 and 11 summarize the links between hurricane and tropical storm landfall showing how the combined influences of NTC and North Atlantic SSTA cause very large differences in landfall, especially along the Florida and the U.S. East coast. Atlantic basin NTC can be skillfully predicted and the strength of the Atlantic Ocean thermohaline circulation can be inferred from prior years of North Atlantic Sea Surface Temperature (SST) anomalies. These predictive relationships can, thereby, be utilized to make probability estimates of U.S. landfall .

Table 9: 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 10: 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.

Indensity 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 11: 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

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. Research is progressing to give landfall probabilities in each of these 11 U.S. coastal locations.

Table 12 lists landfall probabilities for a range of TS, Cat 1-2, Cat 3-4-5, NS, and total hurricanes impacting the whole U.S. coastline, the Gulf Coast (Regions 1-4) and Florida and the East Coast (Regions 5-11) for 1999. The average annual probability of the last 100 years is given in parentheses.

Table 12: Estimated percent probability 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 1999. The last 100 year mean annual probability of one or more landfalling systems is given in parentheses).

Coastal Region	**TS**	**Catagory 1-2 HUR**	**Catagory 3-4-5 HUR**	**All HUR**	**Named Storms**
	1999 Ave	**1999 Ave**	**1999 Ave**	**1999 Ave**	**1999 Ave**
Entire U.S.	87% (84%)	81% (67%)	72% (50%)	94% (84%)	99% (97%)
Gulf Coast	69% (59%)	55% (42%)	40% (30%)	73% (60%)	91% (83%)
Florida plus East Coast	58% (49%)	60% (43%)	54% (31%)	81% (61%)	92% (79%)

Table 13 gives a similar probability of Caribbean and Bahama hurricane passage and landfall along the Mexican East Coast. Figure 6 shows these Caribbean-Bahama and Mexican East Coast regions.

Table 13: Estimated percent probability of the center of one or more hurricanes and/or category 3-4-5 hurricanes passing within the various regions shown in Fig. 6 for 1999. The values in parentheses represent the average annual probability for the last 100 years. Calculations were made for hurricanes. The probability of major (category 3-4-5) hurricanes was determined under the assumption that major hurricanes make up 38 percent of all hurricane numbers.

Region	**Hurricanes**	**Major (cat 3-4-5) Hurricanes**
Northern (N)	86% (64%)	52% (33%)
Eastern (E)	47% (29%)	21% (12%)
Southern (S)	3% (2%)	1% (?#6%)
Western (W)	41% (25%)	19% (11%)
Mexican Coast (M)	56% (37%)	28% (16%)
Sum of N+E+S+W	97% (84%)	73% (50%)
Sun of Five Regions	98% (90%)	80% (59%)

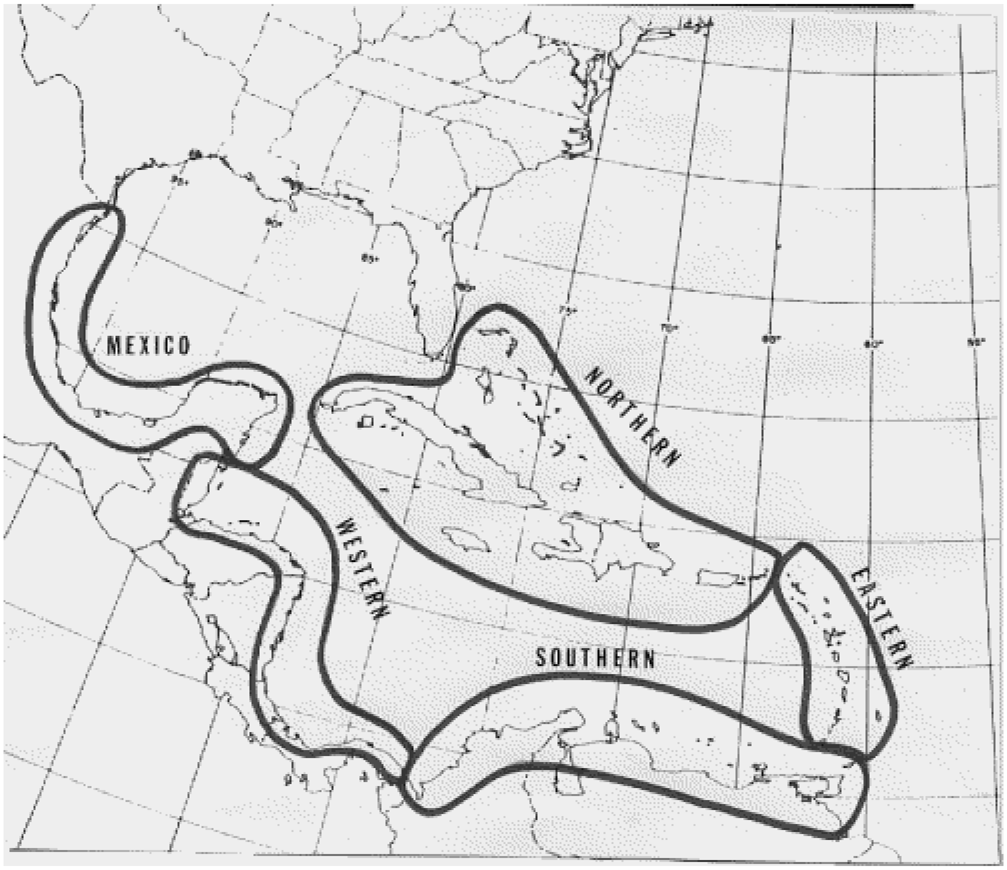

Figure 6: Caribbean Basin areas for which the probability of hurricanes and major hurricane passage through these areas are specified in Table 13.

The equations specifying these probability values will be discussed in a forthcoming paper which will be listed on the Web site. Probability numbers are given by the general equation of the form:

$$(\text{Annual} \quad \text{Number}) = T (1 + K F) \qquad\qquad (1)$$

where

T = the average annual number of various category cyclones for the last 100 years (1899-1998)

K = an empirically determined constant from statistics of the last 100 years

$F = [\ [((NTC + SSTA^*) - 100)/ 100]\ ]$.

The 1999 values of F with the NTC forecast to be 160 and SSTA* measured to be 36 is thus 0.96. The average values of F and SSTA* over the last 100 years are zero. The average value of NTC over the last 100 years is 100.

By substitution, the current 1999 forecast value of F (0.96) into the various forecast, a specification of the number of current year IH, Category 1-2 hurricanes, TS, NS and total hurricanes is given. This number is then multiplied by 100, and a Poisson distribution calculation is made to specify the probability of having one or more landfalling cyclones along a specified coastline or of the passage of cyclones through a specified area as seen for the Caribbean Basin.

5 Comparison of 1999 Landfall Probabilities With Values for Earlier Periods

The expected major hurricane landfall probabilities by the above method for Florida and the U.S. East Coast for 1999 is between 3 and 4 times larger than the landfall probability in the average season for the quarter century period 1970-1994 when the mean NTC was 75 (instead of the forecast value of 160 for this year) and there was a weak (rather than strong) Atlantic Ocean thermohaline circulation was in place. North Atlantic SST anomalies during 1970-1994 were negative. Thus, our forecast numbers of category 3-4-5 hurricane landfalls for the Gulf Coast for 1999 are 3-4 times higher than they were during the typical hurricane season as much as the mean between 1970-1994.

When the Atlantic Ocean thermohaline circulation is 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.

6 Forthcoming Information on Prediction for U.S. Hurricane Landfall Probabilities

Full documentation of this hurricane landfall probability methodology is not complete at this time. The first author will try to finish this study by early July and make it available on the internet. These landfall probabilities will include probability forecasts for tropical storms (TS) and hurricanes of category 1, 2, 3, 4-5 for the following specific areas: the entire U.S. coastline, the Florida Coast and U.S. East Coast separately and the Gulf Coast shown in Fig. 4, the 11 units of the U.S. coastline shown in Fig. 5, and for each 100 km (65 mile) segment of U.S. coastline.

These U.S. landfall probability forecasts will be converted to probabilities for each 100 km wide coastal segment receiving gale force winds (,40 mph), sustained hurricane force winds (,75 mph) and major hurricane (category 3-4-5) winds (,115 mph).

7 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 then can sink to great depth, thereby increasing equatorward flow of deep water and a compensating northward flow of warm (and comparatively salty) replacement water near the surface. The resulting net northward transport of upper-layer warm water into the high North Atlantic and sub-surface equatorward transport of deep cold water is the principal manifestation of the Atlantic Ocean thermohaline (``Conveyor Belt'') circulation. A strong ``conveyor'' circulation increases surface water temperatures in the high latitude areas of the North Atlantic and thus transports more heat to these high latitude areas. Hence, slowly increasing 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 7 shows the difference between 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 during which time the incidence of major hurricanes has also increased to levels similar to the period spanning the 1930s through 1950s. The presence of these new SSTA patterns 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 the Caribbean basin. 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 hurricane activity (which occurred between approximately 1970-1994) would inevitably end and that Atlantic coastal region should expect an eventual long-term increase in landfalling major hurricane activity. This outlook is especially ominous because, when normalized by increased coastal populations, 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.

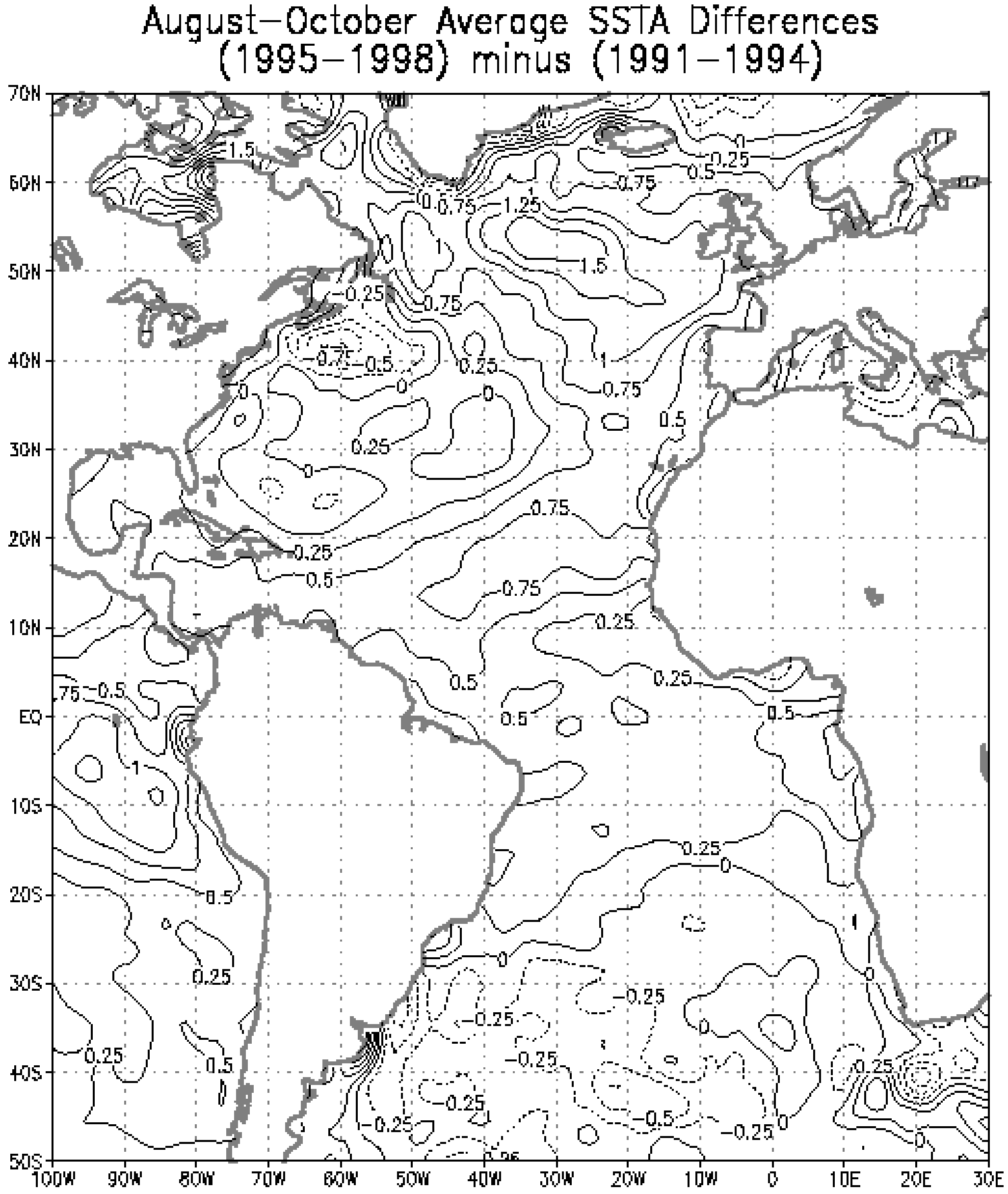

Figure 7: August through October SST differences in °C for 1995 to 1998 minus 1991 to 1994. Solid contours show areas of warming; dashed contours indicate cooling.

Despite El Niño-linked suppression of hurricane activity during 1997, the last four years (1995-1998) are together the most active four (consecutive) year period on record. Total numbers include 53 named storms, 33 hurricanes, 15 major hurricanes, 36 major hurricane days and Net Tropical Cyclone activity value of 653 during the last four years. Despite the weak 1997 hurricane season, the annual average NS, H, IH, IHD and NTC values 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 values for NS, H, IH, IHD and NTC during the last four years were 154, 160, 250, 419 and 216 percent of the average for the previous 25-year (1970-1994) period; the greatest increases occurring for IH and IHD activity. The three recent active hurricane seasons (1995, 1996 and 1998) had 311 and 524 percent of average intense hurricanes and intense hurricane days (respectively) relative to the means prior 25-year period 1970-1994. This trend towards increased hurricane activity supports the notion that an abrupt climate shift began during 1995, one manifestation of which is increased major hurricane activity that was typical of the 1940s and 1950s.

8 The 1999 Hurricane Season and Global Warming

Some individuals will interpret the great upswing in 1995 hurricane activity as being related in some way to increased man-made greenhouse gases like carbon dioxide (CO_2). Such individuals are sometimes driven more by a political than a scientific agenda or do not fully understand the physics of tropical cyclones. There is no reasonable way that such an interpretation can be made. Anthropogenic greenhouse gas warming, even if a physically valid hypothesis, is a very slow and gradual process that, at best would only be expected to bring about small changes in global circulation over periods of 50 to 100 years. This would not result in the abrupt and dramatic one year upturn in hurricane activity as occurred between 1994 and 1995. And, even if man induced greenhouse increases were to be interpreted as causing global mean temperature increase over the last 25 years, there is no way to relate such a small global temperature increases to more intense Atlantic basin hurricane activity during this same period. Atlantic intense (or category 3-4-5) hurricane activity showed a substantial decrease during 1970-1994 to only about 40 percent of the amount of intense hurricane activity which occurred 25-50 years ago. These up-and-down multi-decadal changes have occurred many times in the past and are considered to be natural.

9 Forecast Theory and Cautionary Note

The foregoing 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.

10 Schedule of Forecast Updates

This 4 June 1999 seasonal forecast will be updated on 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.

11 Acknowledgements

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12Additional 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.