EXTENDED RANGE FORECAST OF ATLANTIC SEASONAL HURRICANE ACTIVITY AND US LANDFALL STRIKE PROBABILITY FOR 2000

Yet another year of above average hurricane activity is anticipated though less active than the recent years of 1995, 1996, 1998, and 1999

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

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[This and past forecasts are available via the World Wide Web:
http://tropical.atmos.colostate.edu/forecasts/index.html] — also,

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

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8 December 1999

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2000 ATLANTIC BASIN SEASONAL HURRICANE FORECAST

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

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

1) Entire U.S. coastline – 66% (average for last century is 52%)

2) U.S. East Coast Including Peninsula Florida – 45% (average for last century is 31%)

3) Gulf Coast from the Florida Panhandle westward to Brownsville – 37% (average for last century is 30%)

4) Average activity is expected in the Caribbean (and hence average landfall probability).

(A full report on the methodology involved with these landfall probabilities is planned for the coming months and will be listed on this Web site)

DEFINITIONS

Atlantic Basin - The area including the entire North Atlantic Ocean, the Caribbean Sea, and the Gulf of Mexico.

El Niño - (EN) A 12-18 month period during which anomalously warm sea surface temperatures occur in the eastern half of the equatorial Pacific. Moderate or strong El Niño events occur irregularly, about once every 3-7 years or so on average.

Hurricane - (H) A tropical cyclone with sustained low level winds of 74 miles per hour (33 ms^{-1} or 64 knots) or greater.

Hurricane Day - (HD) A measure of hurricane activity, one unit of which occurs as four 6-hour periods during which a tropical cyclone is observed or estimated to have hurricane intensity winds.

Hurricane Destruction Potential - (HDP) A measure of a hurricane's potential for wind and storm surge destruction defined as the sum of the square of a hurricane's maximum wind speed (in 10^4 knots^2)for each 6-hour period of its existence.

Intense Hurricane - (IH) A hurricane which reaches a sustained low level wind of at least 111 mph (96 kt or 50 ms^{-1}) at some point in its lifetime. This constitutes a category 3 or higher on the Saffir/Simpson scale (also termed a "major" hurricane).

Intense Hurricane Day - (IHD) Four 6-hour periods during which a hurricane has intensity of Saffir/Simpson category 3 or higher.

MATL - Sea surface temperature anomaly in the sub-tropical Atlantic between 30-50°N, 10-30°W

MPD - Maximum Potential Destruction - A measure of the net maximum destruction potential during the season compiled as the sum of the square of the maximum wind observed (in knots) for each named storm. Values expressed in 10^3kt.

Named Storm - (NS) A hurricane or a tropical storm.

Named Storm Day - (NSD) As in HD but for four 6-hour periods during which a tropical cyclone is observed (or is estimated) to have attained tropical storm intensity winds.

NATL - Sea surface temperature anomaly in the Atlantic between 50-60°N, 10-50°W

NTC - Net Tropical Cyclone Activity - Average seasonal percentage mean of NS, NSD, H, HD, IH, IHD. Gives overall indication of Atlantic basin seasonal hurricane activity (see Appendix B).

ONR - previous year October-November SLPA of subtropical Ridge in eastern Atlantic between 20-30°W.

QBO - Quasi-Biennial Oscillation - A stratospheric (16 to 35 km altitude) oscillation of equatorial east-west winds which vary with a period of about 26 to 30 months or roughly 2 years; typically blowing for 12-16 months from the east, then reverse and blowing 12-16 months from the west, then back to easterly again.

Saffir/Simpson (S-S) Category - A measurement scale ranging from 1 to 5 of hurricane wind and ocean surge intensity. One is a weak hurricane whereas 5 is the most intense hurricane.

SLPA - Sea Level Pressure Anomaly - The deviation of Caribbean and Gulf of Mexico sea level pressure from observed long term average conditions.

SOI - Southern Oscillation Index - A normalized measure of the surface pressure difference between Tahiti and Darwin.

SST(s) - Sea Surface Temperature(s).

SSTA(s) - Sea Surface Temperature(s) Anomalies.

Tropical Cyclone - (TC) A large-scale circular flow occurring within the tropics and subtropics which has its strongest winds at low levels: including hurricanes, tropical storms, and other weaker rotating vortices.

Tropical Storm - (TS) A tropical cyclone with maximum sustained winds between 39 (18 ms^{-1} or 34 knots) and 73 (32 ms^{-1} or 63 knots) miles per hour.

TATL - Sea surface temperature anomaly in Atlantic between 6-22°N, 18-80°W.

ZWA - Zonal Wind Anomaly - A measure of upper level ($\sim$ 200 mb) west to east wind strength. Positive anomaly values mean winds are stronger from the west or weaker from the east than normal.

1 knot = 1.15 miles per hour = .515 meters per second.

ABSTRACT

Information obtained through November 1999 indicates that the Atlantic hurricane season in 2000 will be less active than the recent very busy 1995, 1996, 1998, and 1999 hurricane seasons but more active than the recent decades average for 1970 through 1994. We estimate that 2000 should see about 7 hurricanes (average is 5.7), 11 named storms (average is 9.3), 55 named storm days (average is 47), 25 hurricane days (average is 24), 3 intense (category 3-4-5) hurricanes (average is 2.2), 6 intense hurricane days (average is 4.7) and a Hurricane Destruction Potential (HDP) of 85 (average is 71). Collectively, net tropical cyclone activity in year 2000 is expected to be about 125 percent of the long term average.

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 probability. This paper presents the details of our 6–11 month extended range seasonal forecast of Atlantic tropical cyclone activity and of U.S. hurricane landfall probability during 2000. These forecasts are based on 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. We also utilize analog analysis of past seasons with long-lead time atmosphere and ocean conditions similar to what we anticipate for next season. These schemes allow estimates of seasonal Atlantic tropical cyclone activity to be made in early December of the prior year.

1 Introduction

Useful long-range predictive signals exist for seasonal tropical cyclone activity in the Atlantic basin. Our research with prior data has shown that a sizeable portion of the season-to-season variability of nine indices of Atlantic tropical cyclone activity can be skillfully (i.e., with skill exceeding climatology) estimated by early December of the prior year. The forecast technique is based on precursor signals observed in historical data which yield statistical and analog prediction schemes for estimating hurricane activity in the following year. Qualitative adjustments are added to accommodate additional processes which are not yet incorporated into our statistical models. Predictors include two measures of Western Sahel rainfall during the prior year (Figs. 1 and 2), the phase of the stratospheric Quasi-Biennial Oscillation (QBO) of zonal winds at 30 mb and 50 mb (which can be readily extrapolated ten months into the future), 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 (see Fig. 3). A brief summary of these predictor indices and their specific implications for the 2000 season follows:

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 2000, QBO winds are projected to be from an easterly direction with rather large vertical wind shear between these two levels. We extrapolate the actual 30 and 50-mb zonal winds near 11-13°N during September 2000 will be near

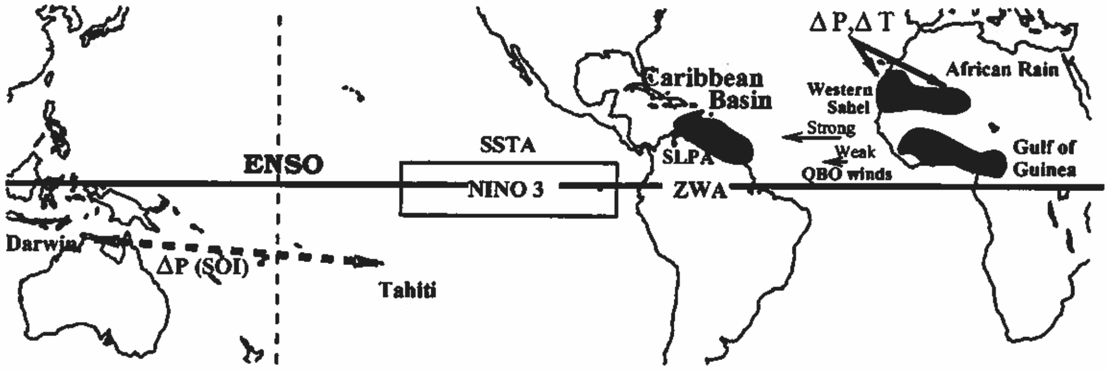

Figure 1: Meteorological parameters used in various versions of our older early August (Gray et al. 1994a) seasonal forecast.

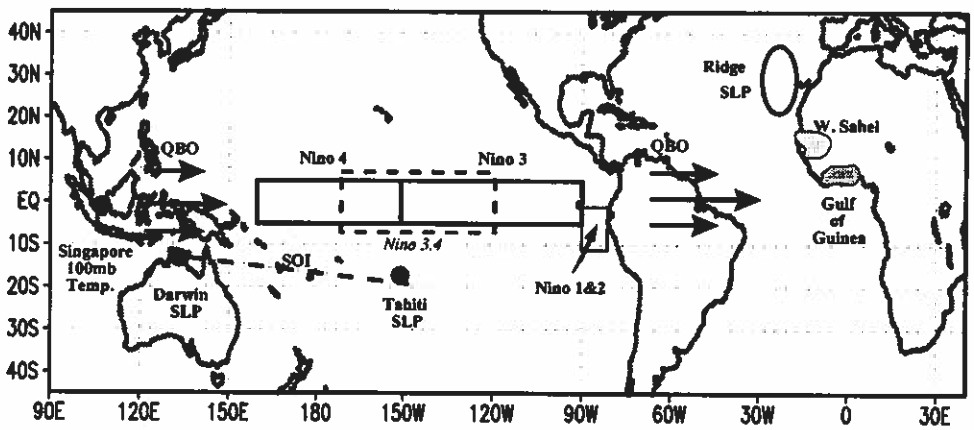

Figure 2: Additional parameters used or consulted in our extended-range forecasts.

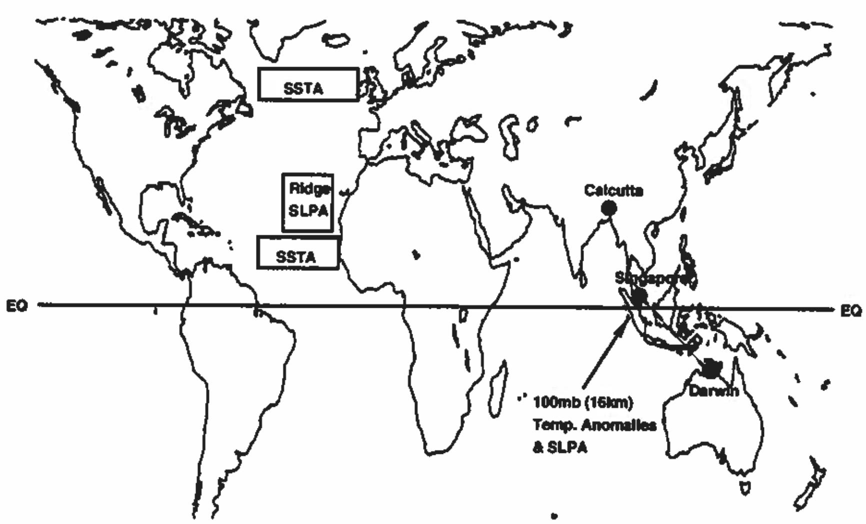

Figure 3: Additional (new) predictors which have recently been noted to be related to the upcoming Atlantic hurricane activity.

zero at 50 mb (a -18 m/s zonal wind speed relative to the average September wind) and -30 m/s at 30 mb . These relatively easterly winds should be a suppressing 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), predictive signals for seasonal hurricane activity occur in West African rainfall data during the mid-summer to fall period of the prior year. These rainfall-linked signals include:

(1) June–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) with 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, year-to-year 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 (1999) rainfall over the Western Sahel during June-September was +0.15 SD above average and thus is a weak positive factor for 2000 hurricane activity.

(2) August–November Rainfall in the Gulf of Guinea. Landsea (1991) and Gray and Landsea (1992) documented a strong African rainfall - intense hurricane lag relationship using August through November rainfall along the Gulf of Guinea (see Fig. 2). 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 this rainfall relationship has not worked very well during the last few years (1995–1999) it is being given qualitatively less weight in the 2000 forecast. For the record, the 1999 August-November Gulf of Guinea rainfall was below average (–0.60 SD), implying a slight negative influence on next year's hurricane activity.

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

ENSO is one of the principal global-scale environmental factors affecting Atlantic seasonal hurricane activity. Hurricane activity is usually suppressed during El Niño seasons (e.g., 1997) when anomalously warm surface water is present in the equatorial eastern and central Pacific. Conversely, activity tends to be enhanced during seasons with cold (or La Niña) water conditions as occurred during 1998 and 1999. We expect the current strong cold ENSO to relax to weak cool conditions through the key months of August through October 2000 and thus, to be only a modest enhancing influence for 2000 hurricane activity. We do not project an El Niño for next year.

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 can then create a self-enhancing (positive feedback) response resulting in higher Caribbean pressures during the summer (Knaff 1999). 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 in this Azores high area during the prior fall portends reduced hurricane activity the subsequent year and vice versa. Ridge strength during October-November 1999 was slightly below (–0.14 SD) the long-term mean . Consequently, this factor is presently judged to be a slight positive influence for 2000 hurricane activity. Negative ridge index values are associated with a reduced Azores high, weaker trade winds and, thereby, generally enhanced hurricane activity.

e) Other Potential Long Range Predictors

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

- The broadscale configuration of SST anomaly patterns over much of the high and low latitude (6-22°N, 10-50°W) 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 indicates a reduction of next year's hurricane activity. Summer and fall 1999 SST anomaly patterns have been anomalously warm in the Atlantic and are expected, through persistence, to be an enhancing influence on next summer's hurricane activity.
- Middle latitude circulation patterns through November 1999. When middle latitude zonal oceanic wind patterns are more westerly, and both the Aleutian low and the Icelandic low are stronger (eg., blocking action in Atlantic is reduced), 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 since 1995 have been more typical of increased hurricane activity.

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:

$$(Seasonal\ Forecast) = \beta_o(1 + a_1U_{50} + a_2U_{30} + a_3|U_{50} - U_{30}|$$

$$+ a_4R_s + a_5R_G \qquad (1)$$

where

1. U_{50} = 10 month extrapolated 50 mb QBO zonal wind near 10°N for September 2000
2. U_{30} = 10 month extrapolated 30 mb QBO zonal wind near 10°N for September 2000
3. $|U_{50} - U_{30}|$ = 10 month extrapolated 50 mb minus 30 mb QBO absolute value of zonal wind for September 2000 shear
4. R_s = Measured standard deviation of previous year August-September 1999 Western Sahel rainfall
5. R_G = Measured standard deviation of previous year August-November 1999 Gulf of Guinea rainfall

The β_o and "a" coefficients are determined to maximize the hindcast predictive signals. Different β_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 2000 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 2000. 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 2000 forecast are as follows:

1. U_{50} = -18 m/s
2. U_{30} = -30 m/s
3. $|U_{50} - U_{30}|$ = 12 m/s
4. Sahel (R_s) (June-Sept, 1999) = +0.15 S.D.
5. Gulf of Guinea (R_G) (Aug-Nov, 1999) = -0.60 S.D.

Table 2: Statistical prediction for the 2000 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 2000	Amount of Hindcast Variance Explained	Expected Independent Forecast Skill
Named Storms (NS)	6.3	.44	.17
Named Storm Days (NSD)	19.3	.51	.30
Hurricanes (H)	4.2	.45	.18
Hurricane Days (HD)	6.9	.49	.26
Intense Hurricanes (IH)	1.0	.47	.22
Intense Hurricane Days (IHD)	2.2	.45	.19
Hurricane Destruction Potential (HDP)	25.8	.44	.18
Net Tropical Cyclone Activity (NTC)	49.5	.53	.33

2.2 Other 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 leads to 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., the overfitting effect). Consequently, it is prudent to limit the number of predictors, 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 2000 hurricane season obtained 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 methodology may also underestimate 2000 activity as it does not incorporate our consensus belief that the current cold La Niña conditions will persist through the heart of the 2000 hurricane season and our expectation of a continuation of warm North Atlantic SST anomalies.

Table 3: Predictor values for 2000 forecast.

Predictor No.	Predictor	Predictor Values for 2000 Fcst
	Pool of 10 Potential Predictors	
1 =	U_{50}	–18 m/s
2 =	U_{30}	–30 m/s
3 =	$\|U_{50} - U_{30}\|$	12 m/s
4 =	Guinea Rain (Aug-Nov)	–0.60 SD
5 =	West Sahel rain (Jun-Sept)	+0.15 SD
6 =	Atlantic Ridge (Oct-Nov)	–0.14 SD
7 =	Darwin (May-Jul)	+0.8 mb
8 =	Nino-4 Trend (Aug-Oct)-(May-Jul)	+0.1°C
9 =	SOI (Aug-Oct)	+0.3 SD
10 =	SOI Trend (Aug-Oct)-(May-Jul)	+0.1 SD

Table 4: Most skillful predictor values for 2000 forecast.

Number Predictors	Top predictors chosen for each forecast variable: 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	

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 2000 seasonal forecast. The third column shows our 2000 forecast, column four gives 1950-1990 climatology and column five gives the 2000 forecast

Table 5: Statistical summary for our second extended range forecast scheme for 2000 hurricane activity with the amount of non-degraded forecast variance explained. Developmental data includes the years 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	Amount of non-degraded Variance Explained	Expected Independent Forecast Skill
NS	7.2	.519	.332
NSD	29.4	.547	.374
H	4.8	.494	.297
HD	13.6	.536	.358
IH	1.3	.436	.196
IHD	2.1	.417	.160
HDP	41.3	.492	.294
NTC	73.3	.528	.350
MPD	49.4	.660	.523

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.

Forecast Parameter	(1) Older 1 Dec Fcst Scheme	(2) Newer 1 Dec Fcst Scheme	(3) Qualitatively Adjusted 2000 Fcst	(4) 1950–1990 Average	(5) Forecast Percent of 1950–1990 Period
NS	6.3	7.2	11	9.3	118
NSD	19.3	29.4	55	46.6	118
H	4.2	4.8	7	5.8	121
HD	6.9	13.6	25	23.9	105
IH	1.0	1.3	3	2.2	136
IHD	2.2	2.1	6	4.7	128
HDP	25.8	41.3	85	71.2	126
MPD	—	49.4	70	66.0	106
NTC	49.5	73.3	125	100	125

Reasons for Upward Adjustments of 2000 Statistical Forecasts. We believe that the 2000 hurricane season will be more active than is indicated by our statistical schemes owing to several new and likely hurricane enhancing features not fully incorporated in our statistical forecasts. These include the persistence of warm north and tropical Atlantic SSTA patterns (associated with an enhanced Atlantic thermohaline circulation) which are expected to continue as well as below average eastern North Pacific (La Niña) SST conditions through October 2000.

Both of these basic climate signals are expected to enhance 2000 hurricane activity to higher levels than is indicated by our statistical scheme. It appears that the training data sets for our statistical schemes, developed for periods of 1950–1990 and 1950–1995 did not contain the unusually enhancing hurricane activity of the last five years. In addition, our statistical schemes have underestimated the seasonal hurricane activity in four of the last five seasons (likely owing to the proxy association of strength of the Atlantic thermohaline circulation). The one exception to this was the very strong El Niño year of 1997. This and the results of our analysis of analog years (to be discussed) has lead us to increase our 2000 forecast over that specified by our statistical scheme.

3 Expected Continuation of Weak Cool La Niña Conditions for August Through October 2000

Based on all available data, we are predicting that there will be no El Niño event next year. Rather, the current La Niña, or cool surface temperatures in the eastern equatorial Pacific should continue through next hurricane season, though possibly in a diminished state from the very cold conditions presently observed, for the following reasons:

1. Only three years will have passed since the (1997) onset of the strongest (by a factor of two) El Niño on record in terms of August through October anomalies. El Niño's tend to be irregularly spaced at 3-5 year intervals; 3-year intervals between successive El Niño events are shorter than normal, especially during periods of warm North Atlantic SST anomalies. We are in a period of strong (hence warm) Atlantic Ocean thermohaline conditions. As noted above, El Niño variability is significantly less during strong versus weak thermohaline periods. For example, there were 10 El Niños (or 0.208 per year) during the aggregate 48-year period of 1926–1968 and 1995–1999 when the thermohaline circulation was judged to be strong but 26 El Niños (0.464 per year) during the 56 year period (1896–1925 and 1969–1994) when the Atlantic thermohaline circulation was judged to be weak. This is a difference of over two-to-one. The likely physics of this association has been described in a conference paper by the first author (Gray 1998). On this basis, it is less likely that an El Niño will occur during the 2000 hurricane season. The years 2001 and 2002 appear to be much more likely for the next El Niño event. Records indicate that a strong thermohaline circulation is associaed with longer periods between El Niños. Examples include the El Niño hiatus between 1931–1939 (nine years), 1942–1950 (nine years) or 1889–1894 (6 years). We judge that the thermohaline circulation and North Atlantic temperatures during these periods were similar (strong).

2. The majority of the coupled ocean and dynamic model simulations for the period of August through October 2000 (as discussed in the October 1999 NOAA Climate Diagnostic Bulletin) do not anticipate an El Niño event.

Thus, our best estimate is that the probability of an El Niño event for next summer is fairly remote. We anticipate a continuation of the cool to neutral ENSO conditions that have been in place during the 1998 and 1999 seasons. However, persistence of the recent very strong La Niña is also suggested by some analogs and therefore is the most uncertain element of our forecast.

4 Year 2000 Hurricane Activity as Inferred from Prior Analog Years

We find that certain years in the historical records have similar (3-12 month) global oceanic and atmospheric trends which provide useful clues as to what the coming season may bring. Although the physical associations involved with these earlier to later relationships are not completely understood, they are useful for extended range prediction. We study two classes of analog years for 2000. In the first class (current analog years), we look for atmospheric and oceanic conditions resembling Novembers prior to the year to be forecast. In the other class (expected analog years) we project atmospheric and oceanic conditions into the following August through October period and observe which of the past years have had similar environmental conditions. We then study the hurricane activity that has occurred in these selective years.

Current Analog Methodology. We find that since 1949, there were been five November periods similar to November 1999 wherein

- the North Atlantic (50-60°N, 10-50°W) had persistent warm SST anomalies during the prior year,
- La Niña conditions (likely to persist) were present,
- westerly QBO winds were present at 30 and 50 mb (implying easterly conditions next year), and
- A very active hurricane season has just ended.

The currently relevant analog years are 1950, 1955, 1961, 1964, and 1995. Table 7 lists the hurricane activity which occurred in the five seasons which followed. Note that seasonal hurricane activity varies widely between these five seasons. An El Niño developed during 1965 and the 1956 and 1962 seasons were inexplicably suppressed while the seasons of 1951 and 1996 had above average activity. This scatter diminishes our confidence.

Table 7: Atlantic basin tropical cyclone activity during current analog seasons to 2000

	NS	NSD	H	HD	IH	IHD	HDP	NTC
1951	10	58	8	36	2	5.00	113	120
1956	8	30	4	13	2	2.25	39	69
1962	5	22	3	11	0	0.00	26	33
1965	6	40	4	27	1	6.25	72	85
1996	13	78	9	45	6	6.00	135	204
Total	42	228	28	132	11	19.5	386	511
Average	8.4	45.6	5.6	26.4	2.2	3.9	77.2	102

Expected Analog Years. As noted above we picked a second set of analog years reflecting the three basic climate conditions we expect to be present the following August through October period. These include warm North Atlantic SSTA, easterly QBO conditions, and (projected) weak La Niña conditions in years following a La Niña event.

There have been six hurricane seasons since 1949 with these characteristics including 1952, 1956, 1962, 1989, 1996 and 1998. Four of these seasons were rather active while two (1956, 1952) were inactive. The hurricane activity occurring during these six (judged to be the best analogs for 2000) is given in Table 8. Based on these analogs, we expect the 2000 hurricane season to manifest conditions more like the average of these six analog years than the lesser amounts of activity predicted by our two statistical schemes (previously discussed). While the two suppressed analog years (1956 and 1962) cause us concern, the weight of the other analogs however favor a more active 2000 season. Thus, based on this analysis we expect that next year should be less active than the busy seasons of 1995–1996 and 1998–1999, but distinctively more active than the average of the 1970–1994 seasons.

Table 8: Best similar or analog years to 2000 with the associated hurricane activity which occurred in these years.

	NS	NSD	H	HD	IH	IHD	HDP	NTC
1952	7	40	6	23	3	4.00	70	97
1956	8	30	4	13	2	2.25	39	69
1962	5	22	3	11	0	0.00	26	33
1989	11	66	7	32	2	10.75	108	140
1996	13	78	9	45	6	6.00	135	204
1998	14	84	10	49	3	9.25	145	173
Total	58	320	39	173	16	32.25	523	716
Ave. all 6 years	9.7	53	6.5	29	2.7	5.4	87	119
Comparison with 2000 Forecast	11	55	7	25	3	6	85	125

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 North Atlantic. Higher salinity increases water density in these surface layers which is then more able to sink to great depth, thereby increasing compensating northward flow of warm (and salty) replacement water at upper ocean levels. 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 recent years suggest the development of conditions whereby the Atlantic Ocean develops a stronger thermohaline circulation. The effects of a stronger thermohaline circulation have been evident in the region since the spring of 1995. The best proxy signal for this circulation is the North Atlantic SST anomalies.

Three decades have passed since the SST anomaly patterns of the Atlantic Ocean have been so warm. Figure 4 shows changes of the mean SST anomalies for 1990 to 1994 versus 1995 to 1999. June through September 1999 SSTA values in the North Atlantic (50-60°N, 10-50°W) were nearly 1°C warmer in the later rather than the earlier five-year period. These warmer SSTAs are a direct result of a stronger Atlantic Ocean thermohaline circulation. And this stronger thermohaline circulation has also led to a warming of the tropical Atlantic (6-22°N, 18-50°W) ocean SSTAs of about 0.5°C. Figures 5 and 6 show time series of the SST anomaly changes in the North Atlantic (50-60°N, 10-50°W) during the last 10 years and the changes since 1900, respectively. It is assumed that these warm conditions will continue through 2000. Note the general warming of the North Atlantic that has taken place during the last five years when the incidence of major hurricanes also increased to levels similar to those of the most active hurricane seasons from the 1930s to the 1960s. This trend manifests itself primarily in the form of more hurricanes forming at low latitudes, more intense hurricanes, and as more major hurricanes landfalling along the US East Coast, Florida, and in the Caribbean Sea. The Gulf Coast is less effected by these changes. We expect that this trend will continue for several decades.

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

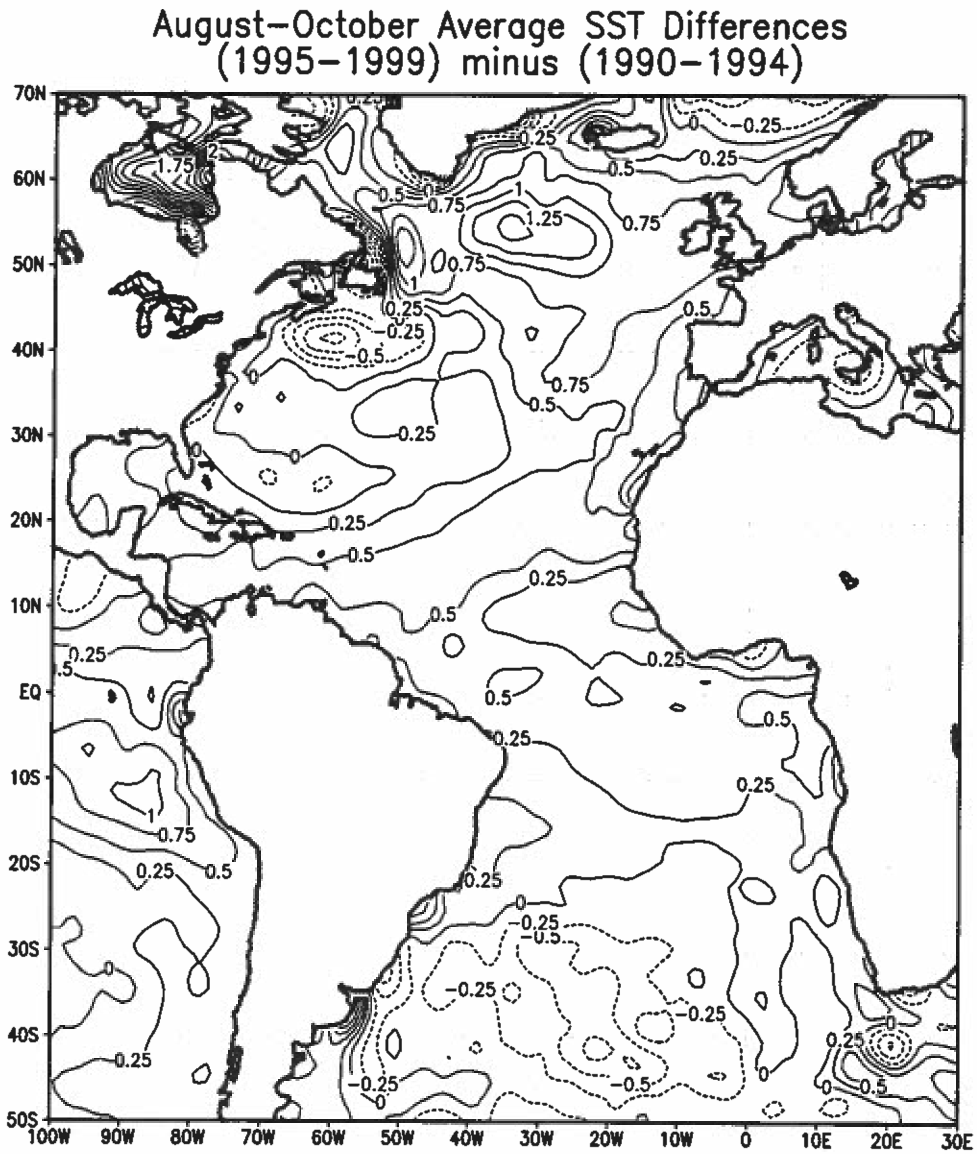

Figure 4: August through October SST differences (in °C) for the two five-year periods of 1995 to 1999 minus 1990 to 1994.

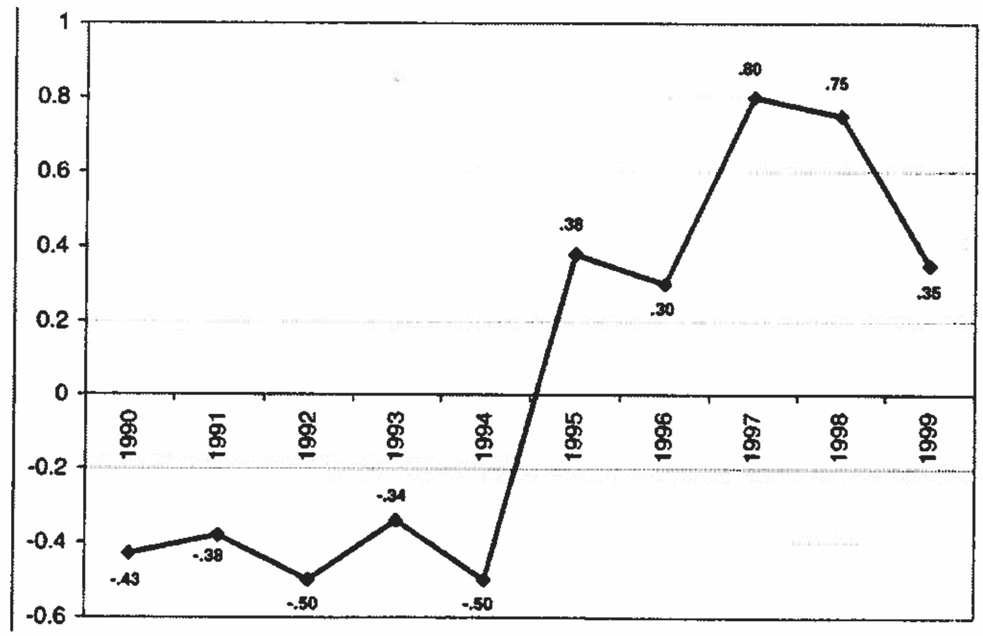

Figure 5: Time series of North Atlantic annual average SST (in °C) anomalies in the area between 50-60°N, 10-50°W for 1990 to 1999.

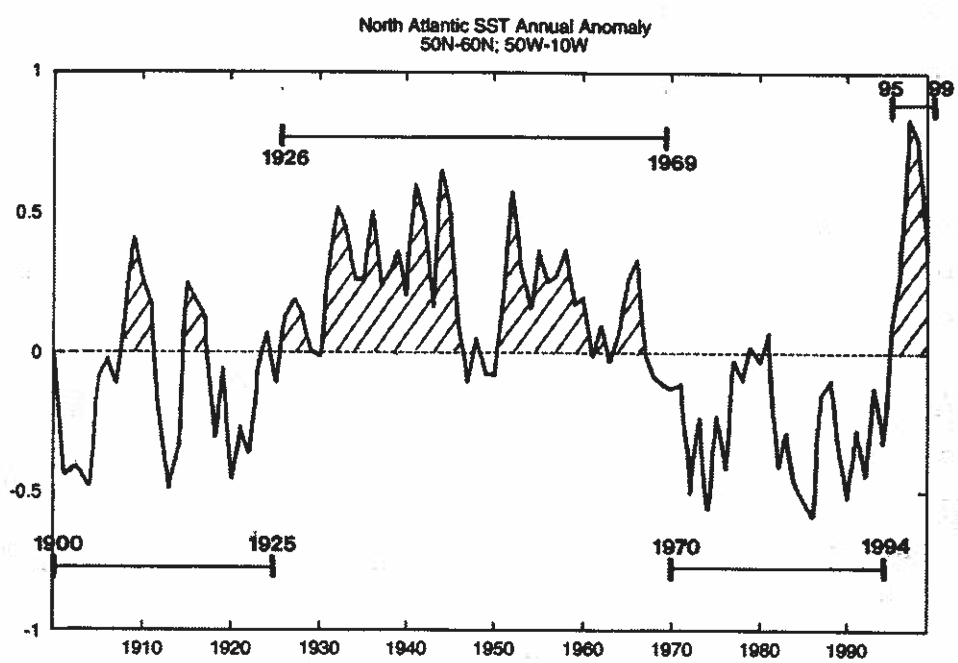

Figure 6: Time series of North Atlantic annual average SST (in °C) anomalies in the area between 50-60°N, 10-50°W for 1900 to 1999. The periods of positive SST anomalies are hatched.

was likely ending and that Atlantic coastal residence should expect an eventual long-term increase of landfalling major hurricanes. This outlook is especially ominous because, when normalized by increased coastal population, inflation, and wealth per capita, [see Pielke and Landsea (1999) and Gray (1999)] major hurricanes are observed to cause 80 to 85 percent of all US tropical cyclone linked destruction.

Despite El Niño-linked reductions of hurricane activity during 1997, the last five years (1995–1999) are together the most active five (consecutive) year period on record. This includes the total number of named storms (65), hurricanes (41), major hurricanes (category 3-4-5) (20), major hurricane days (51) and Net Tropical Cyclone activity (842) which occurred during the last five years. Despite the weak 1997 hurricane season, the annual average of NS, H, IH, IHD and NTC during the last five years are 155, 178, 400, 816 and 311 percent (respectively) of the average hurricane activity for 1990–1994. And, the annual average NS, H, IH, IHD and NTC during the last five years has been 151, 165, 257, 263, 405 and 224 percent of the average for the previous 25-year period (1970-1994). The largest increases have come with IH and IHD activity. See our 24 November 1999 verification of our 1999 forecast (available on the Web) for more documentation and discussion on this topic. Also see the new paper by Landsea et al. (1999) for documentation and discussion of changing Atlantic climate patterns.

6 Landfall Probability

The major hurricane landfall probability forecast for 2000 on page 2 comes out of an extensive analysis of U.S. hurricane landfall over the last century by the first author. This research is showing the strong impact of yearly and decadal changes of atmospheric and oceanic climate signals on landfall probability. Large climate-linked alterations of landfall probabilities are observed. The methodology and general results of this research is too extensive to discuss here. This research is expected to be completed in the next several months and will be disseminated on our Web site.

7 Discussion

Since 1995 we appear to have entered a new active era for major hurricane activity, similar to that which occurred during the 1930s through early 1960s when the Atlantic thermohaline circulation was also judged to be strong. This active period was characterized by warm North Atlantic SSTAs (50-60°N, 10-50°W). These North Atlantic SSTAs appear to be a very good proxy for the strength of the Atlantic thermohaline or "conveyor belt" circulation. This ocean area has had positive SSTAs since April 1995 and is projected to remain warm for all of 2000. This will be an important enhancing component to Atlantic 2000 major hurricane activity.

Hurricane activity during the last two years started relatively late in the season ($\sim$ 20 August) and was greater than average throughout the remainder of the season. There were few high latitude tropical storm developments during the last two years. Because of the anticipated easterly QBO in 2000 and somewhat reduced La Niña conditions, we expect that there will be less low latitude activity than in 1998–99 but increased incidence of weaker systems occurring at higher latitudes. In general, we expect the heart of the hurricane season (roughly 20 August to 10 October) to be less active than during the last two seasons (see Kimberlain et al. 2000).

Figure 6 illustrates North Atlantic 50-60°N, 10-50°W SST anomalies for 1900–1999. During the aggregate multi-decadal 51 year period including 1900–1925 and 1970–1994, when North Atlantic SSTAs were generally negative, there were 73 major (category 3-4-5) hurricanes (average of 1.43 per year). In contrast, during the aggregate 49-year period of generally warm Atlantic SSTAs between 1926–1969 and 1995–1999 there were 142 Atlantic basin major hurricanes (2.90 per year), twice the number as occurred during the period of cold North Atlantic SSTs. Contrasting hurricane activity during the recent years (1990–1994) (cold North Atlantic anomaly) with the warm anomaly period 1995–1999, we see a 4-fold (20 to 5) warm versus cold difference in major storms. Projecting warm North Atlantic SST anomalies to continue at least through the 2000 hurricane season, we forsee the probability of major hurricane activity to be somewhat higher than the long-term average despite the presence of easterly QBO conditions.

8 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. At this time we are less confident in this year's forecast than we were last year. Moreover, these forecasts do not explicitly predict specifically where within the Atlantic basin storms will strike. Landfall probability estimates at any one location along the coast are very low and reflect the fact that in any one season, most US coastal areas will not feel the effects of a hurricane no matter how active the individual season is. It must be emphasized that a low probability does not insure that a hurricane will not come ashore, however. Regardless of how active 2000 hurricane season should be, a finite probability always exists that one or more hurricanes may strike along the US or Caribbean Basin coastline and do much damage.

9 The Active 1995–1999 Hurricane Seasons and Global Warming

Some may interpret the recent large upswing in Atlantic hurricane activity (since 1995) as being in some way related to increased human-induced greenhouse gases such as carbon dioxide (CO_2). Such an interpretation of the recent sharp upward Atlantic hurricane activity since 1995 is not plausible. By contrast, the tropical cyclone activity in the other global basins has shown a downward trend since 1995. See our 24 November 1999 verification on this Web site for more discussion.

10 Schedule for 2000 Forecast Updates

This 8 December 1999 forecast will be updated on 7 April 2000, 7 June 2000 and 4 August 2000. These revisions will allow us to make adjustments as newer information becomes available. A verification of this forecast will be issued in late November 2000 and a seasonal forecast for the 2001 hurricane season will be issued in early December, 2000.

11 Acknowledgements

John Sheaffer and John Knaff have made important contributions to the conceptual and scientific background for these forecasts. The authors are indebted to a number of meteorological experts who have furnished us with the data necessary to make this forecast or who have given us valuable assessments of the current state of global atmospheric and oceanic conditions. We are particularly grateful to Arthur Douglas, Richard Larsen, Ray Zehr and Vern Kousky for very valuable climate discussions and input data. We thank Colin McAdie and Jiann-Gwo Jiing who have furnished data necessary to make this forecast and to Gerry Bell, James Angell, and Stan

Goldenberg for input data and helpful discussions. Richard Taft has provided valuable data development and computer assistance. We wish to thank Tom Ross of NCDC and Wassila Thiao of the African Desk of CPC who provided us with West African and other meteorological information. In addition, Barbara Brumit and Amie Hedstrom have provided excellent manuscript and data analysis assistance. We have profited over the years from many indepth discussions with most of the current NHC hurricane forecasters. These include Lixion Avila, Miles Lawrence, Richard Pasch, Edward Rappaport, John Guiney, Jack Beven and James Franklin. The first author would further like to acknowledge the encouragement he has received for this type of forecasting research applications from Neil Frank, Robert Sheets, and Robert Burpee, former directors of the National Hurricane Center (NHC) and from current NHC director Jerry Jarrell and the Deputy Director, Max Mayfield.

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

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Verification of All Past Seasonal Forecasts

See the 24 November 1999 write-up of our 1999 seasonal verification on this same Web site for all of our seasonal forecasts and verifications for the period 1984–1999.