EXTENDED RANGE FORECAST OF ATLANTIC SEASONAL HURRICANE ACTIVITY AND US LANDFALL STRIKE PROBABILITY FOR 2001

A downturn is expected from the recent five (1995-96-98-99-00) very busy seasons. Although below average Atlantic basin hurricane activity is anticipated, above average probability of U.S. landfall is forecast.

This forecast is based on ongoing research by the authors,
along with meteorological information through November 2000

By

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7 December 2000

2001 ATLANTIC BASIN SEASONAL HURRICANE FORECAST

7 December 2000	
Tropical Cyclone Seasonal Forecast for 2001	
Named Storms (NS) (9.3)	9
Named Storm Days (NSD) (46.9)	45
Hurricanes (H)(5.8)	5
Hurricane Days (HD)(23.7)	20
Intense Hurricanes (IH) (2.2)	2
Intense Hurricane Days (IHD)(4.7)	4
Hurricane Destruction Potential (HDP) (70.6)	65
Net Tropical Cyclone Activity (NTC)(100%)	90

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

1) Entire U.S. coastline - 63% (average for last century is 52%)

2) U.S. East Coast Including Peninsula Florida - 43% (average for last century is 31%)

3) Gulf Coast from the Florida Panhandle westward to Brownsville - 36% (average for last century is 30%)

4) Expected average major hurricane landfall risk in the Caribbean.

(Landfall probabilities for 2001 are above average even though forecast NTC is below average; this is due to the expected ongoing contribution of the recent five-year positive North Atlantic SSTA trend which is a proxy representation of the strength of the Atlantic thermohaline circulation - see discussion in section 6. A full report on the methodology for estimating these landfall probabilities is in preparation and will be made available on this Web site.)

DEFINITIONS

ABSTRACT

Collectively, Atlantic basin Net Tropical Cyclone (NTC) activity in 2001 is expected to be about 90 percent of the long-term average. The primary cause of this suppressed hurricane activity is an anticipated weak to moderate El Niño by next summer. Negative influences associated with several lesser factors will also be present. Information obtained through November 2000 indicates that the 2001 Atlantic hurricane season will be less active than the recent, very busy 1995, 1996, 1998, 1999 and 2000 seasons but more active than the average for seasons during the recent multi-decadal period of low activity which extended from 1970 through 1994. We estimate that 2001 should see about 5 hurricanes (average is 5.7), 9 named storms (average is 9.3), 45 named storm days (average is 47), 20 hurricane days (average is 24), 2 intense (category 3-4-5) hurricanes (average is 2.2), 4 intense hurricane days (average is 4.7) and a Hurricane Destruction Potential (HDP) of 70 (average is 71). Despite predicting a ten percent below average Atlantic basin hurricane season, U.S. landfall probability is forecast to be 5-10 percent above the long period average owing to a presumed continuing strong Atlantic Ocean thermohaline circulation.

1 Introduction

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 observations as well as the rationale for this 6 to 11-month extended range seasonal forecast for 2001. This forecast is based on both statistical and analog analyses of prior hurricane seasons with atmospheric and ocean conditions similar to what we anticipate to be in place during the 2001 hurricane season.

Useful long-range predictive signals exist for seasonal tropical cyclone activity in the Atlantic basin. Our research has shown that a sizeable portion of the season-to-season variability of Atlantic tropical cyclone activity can be forecast with skill exceeding climatology by early December of the prior year. Qualitative adjustments are added to accommodate additional processes which are not yet incorporated into our statistical models. Two transient influences which will largely determine next year's Atlantic hurricane activity are:

1. The status of El Niño -Southern Oscillation (ENSO) and
2. The Atlantic Sea Surface Temperature Anomaly (SSTA) conditions which provide proxy signals for the strength of the Atlantic Ocean thermohaline circulation.

Presently, we anticipate that a 2001 El Niño will be an inhibiting influence whereas North Atlantic SSTA patterns will continue to be a positive enhancing influence as they have been for the last six years. Other, lesser factors, include the following:

3. The phase of the stratospheric Quasi-Biennial Oscillation (QBO) of zonal winds at 30 mb and 50 mb (which can be extrapolated ten months into the future).
4. Two measures of West African rainfall during the prior year (Figs. 1 and 2).
5. The strength of the Azores high October-November surface pressure anomaly and the configuration of broad scale Atlantic sea surface temperature anomaly patterns (see Fig. 3).

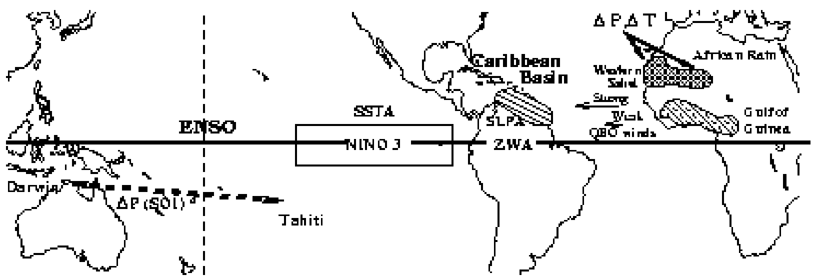

Figure 1: Meteorological parameters used in various versions of our older early August (Gray et al. 1994a) seasonal forecast.

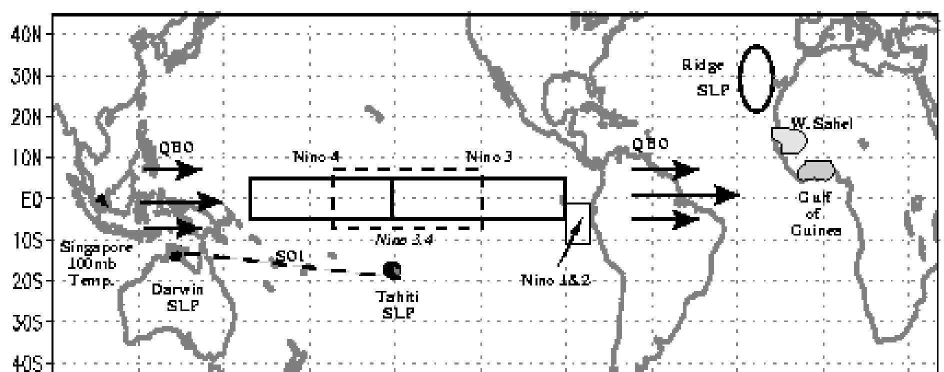

Figure 2: Additional parameters used or consulted in our extended-range forecasts.

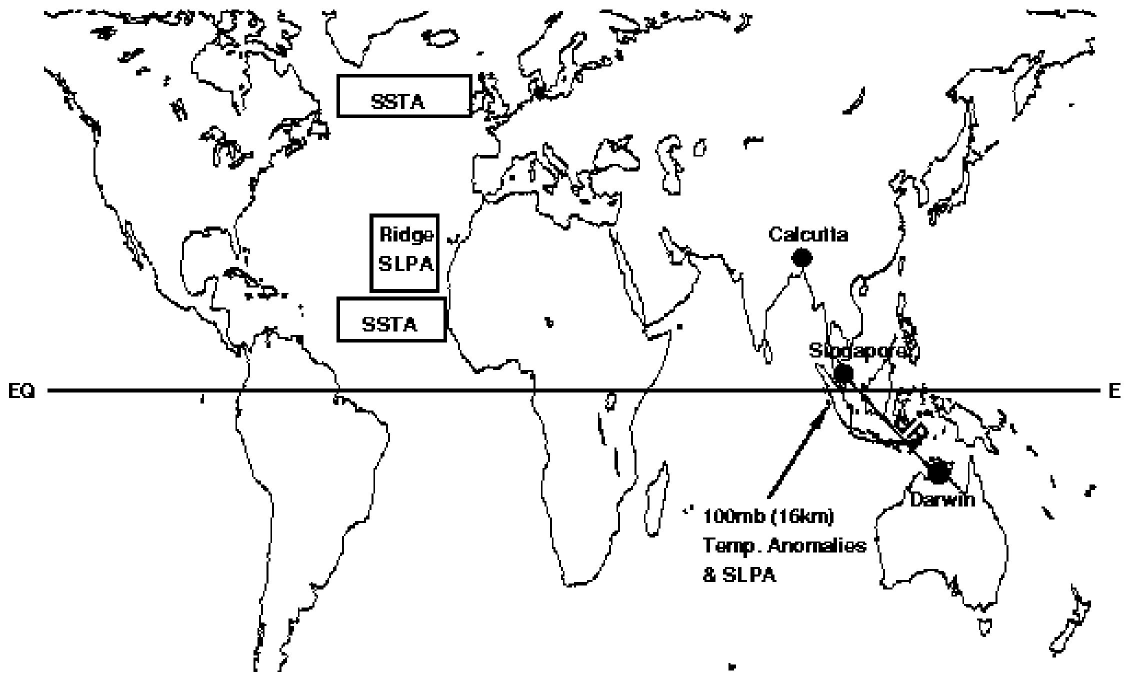

Figure 3: Additional (new) predictors which have recently been noted to be related to the upcoming Atlantic hurricane activity.

A brief summary of these predictor indices and their specific implications for the 2001 season follows.

a) ENSO

ENSO is one of the principal global-scale environmental factors affecting Atlantic seasonal hurricane activity. Hurricane activity is usually suppressed during El Niño events (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 that current (fall 2000) cool ENSO conditions will be replaced by a weak to moderate El Niño during the 2001 hurricane season. This should be a modest suppressing influence on 2001 hurricane activity.

Warming of the tropical east Pacific Ocean sea surface during El Niño events is a suppressing influence. It contributes to stronger net convective activity in this region. A portion of the upper-level outflow from this enhanced convection moves into the tropical Atlantic where it simultaneously sinks and dries the upper troposphere and strengthens upper-level (£#200 mb) westerlies. The latter effects strongly inhibit the intensification of organized westward moving (African) disturbances through vertical shear. We anticipate that during 2001, these effects (particularly in combination with the easterly QBO at 50 mb, as described below) will be a constraint on Atlantic TC activity.

We also anticipate the El Niño characteristics during 2001 will be more typical of the El Niño events of the 1950s and 1960s (i.e., 1951-53-57-63-65) wherein equatorial Pacific SST warming tends begin along the coast of Peru and spread westward with time to the Dateline (as originally) discussed by Rasmussen and Carpenter 1982). The comparatively strong and persistent multi-year El Niño events observed during the 1970s, 1980s and mid-1990s (i.e., 1972, 1982, 1983, 1986, 1987 and 1997) are believed to be less likely at present owing to the recent (likely) multi-decadal rearrangement of SSTA patterns in the Atlantic and Pacific Oceans. This re-configuration of SSTs is also reflected as concurrent changes of the North Atlantic Oscillation (NAO), the Pacific Decadal Oscillation (PDO) and the Pacific North Atlantic Oscillation (PNA).

We estimate that El Niño SSTAs during August to October 2001 will be about the average amplitude of the five one-year El Niño events between 1942 and 1968 (1951, 1953, 1957, 1963 and 1965). Table 1 shows that SSTAs associated with these 1950s and 1960s El Niño events were less intense than those of 1972, 1982, 1986, 1987 and 1997 when long term global ocean SSTA patterns were different from what is expected for next year.

Table 1: August through October NINO 3.4 SSTA in ˙C, and the individual monthly maximum anomaly observed that year (from Kaplan as provided by A. Mestas-Nuzes). Comparative NTC values are also listed for each year.

Weak and Moderate El Niño Events During Strong Atlantic Ocean Thermohaline Period			
	Aug-Oct SSTA	**Max Monthly Value During Year**	**NTC**
1951	0.60	0.71 (Aug)	120
1953	0.57	0.80 (Aug)	120
1957	1.20	1.26 (Dec)	85
1963	1.13	1.28 (Dec)	115
1965	1.55	1.80 (Nov)	85
Mean	1.01	1.17	105
Onset Strong El Niño Events During Weak Atlantic Ocean Thermohaline Period			
1972	1.59	2.32 (Nov)	28
1982	1.35	2.39 (Dec)	37
1986	0.82	1.42 (Dec)	38
1987	1.73	2.07 (Sept)	47
1997	2.51	2.98 (Nov)	54
Mean	1.60	2.24	41
4-Year Long Continuous ``Hemorrhage" El Niño Event During Weak Atlantic Ocean Thermohaline Period			
1991	0.44	1.82 (Dec)	59
1992	0.07	2.10 (Feb)	66
1993	0.44	1.36 (May)	53
1994	0.77	1.51 (Dec)	36
Mean	0.43	1.70	53

Note that the five strong El Niño events which occurred during the 1970 through the mid-1990s period (1972, 1982, 1986, 1987, 1997) had average August-October NINO 3.4 SSTAs which were 60 percent warmer than the five events between 1950s through 1965 (1951, 1953, 1957, 1963, 1965); this in addition to having numerous individual maximum monthly values which were about twice as strong. Consistent with these more recent (1970-1997) stronger El Niño events, average Atlantic basin NTC was only about 40 percent of the average using the five earlier (1951-1965) El Niños. NINO 3.4 SSTAs during the four-year (off-and-on) 1991 through 1994 El Niño event were, on average, not as warm as the average for the five individual one-year events of the 1950-1960s. However, the average of the maximum individual months during this 1991-1994 period were greater. Regardless of the strength of the El Niño warming events during 1970-1995, all nine El Niño years (i.e., 1972-82-86-87-97 and 1991 through 1994) had Atlantic basin NTC activity reductions (average NTC of nine recent El Niño years was 46 versus 105 for the five El Niño years during the 1950s and 1960s).

ENSO Is Not the Only Consideration

Although ENSO conditions are the most important single parameter dictating Atlantic seasonal hurricane variability, other properties of the atmosphere and ocean can be preeminent in some years. Table 2 shows years with active hurricane seasons which occurred during El Niño conditions as well as very inactive hurricane seasons during cool La Niña conditions. Note in Table 2 that despite NINO 3.4 SSTA conditions which are, on average, nearly 2˙C warmer, NTC activity was 2.6 times greater during this collection of exceptional warm years compared to the conversely exceptional cold years.

Table 2: Unusual years in which warm El Niño and cool La Niña (NINO 3.4) conditions occur but with TC activity trends opposite what is typically observed.

Year	**Aug-Oct NINO 3.4 SSTA (˙C)**	**NS**	**H**	**NTC**
Cool (La Niña) Seasons With Little TC Activity				
1890	-1.00	1	1	13
1892	-1.07	9	4	78
1956	-0.61	8	4	69
1970	-1.01	10	5	64
1973	-1.56	7	4	51
Average	-1.05	7	3.6	55
Warm (El Niño) Seasons With Much TC Activity				
1896	1.22	6	6	141
1899	1.07	6	5	144
1953	0.64	14	6	120
1969	0.68	17	12	155
Average	0.90	10.8	7.2	140

Thus, even if our projection of a weak to moderate El Niño event of next summer-fall is exactly correct, this in itself does not guarantee that we will have an inactive hurricane season; exceptionally strong anomalies for other large scale atmosphere/ocean anomaly features (such as Atlantic basin SST, SLPA and zonal winds) can play a dominant role in some years.

b) 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 (hereafter, the ``westerly QBO''). Conversely, seasonal hurricane activity is typically reduced during the easterly QBO phase (large easterly wind shear between 30- and 50 mb).

During 2001, we anticipate that the easterly QBO phase will be in place in the lower stratosphere below 30 mb throughout the hurricane season. In our evolving view on how the QBO interacts with the tropical troposphere to influence hurricane activity, we infer that

1. Enhanced subsidence circulations due to this QBO configuration will be fairly effective in suppressing the off-equator tropical convective activity which often develops into tropical storms.

2. The east phase QBO will enhance convective regimes in the east Pacific convergence zone and in northern South America. The resulting upper-level outflow from the latter appears to enhance the upper (200 mb) westerlies in the Caribbean and tropical Atlantic and inhibit TC development in the deep tropical portion of the Atlantic basin. Hence, we view the QBO as being a slight negative factor for 2001 TC activity.

c) 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. Two such rainfall-linked signals include:

(1) June-September Western Sahel Rainfall. The Western Sahel area (see Fig. 2) experiences large year-to-year persistence of rainfall trends. Wet years tend to be followed by wet years (e.g., in the 1950s and 1960s) with enhanced hurricane activity while dry years are typically followed by dry years (e.g., during the 1970s, 1980s and first half 1990s) and suppressed hurricane activity. Since the rainfall in this region is positively related to 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 (2000) rainfall over the Western Sahel during June-September was -0.70 SD below average and thus is a negative factor for 2001 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. This rainfall relationship has not worked as well during the active hurricane seasons of the last few years (1995-2000) as it had in earlier decades. Since 1994 West Sahel rainfall has been generally higher than it was during the 1970 to 1993 priod, however. The 2000 August-November Gulf of Guinea rainfall was below average (-0.50 SD), implying a negative influence on next year's hurricane activity.

d) October-November Atlantic Subtropical Ridge (Azores High) Between 20-30°W

High surface pressure between 20-30°W associated with the Azores high is positively related to stronger east Atlantic trade winds which, in turn, enhance upwelling of cold water off the coast of northwest Africa. Colder sea surface temperatures created by this enhanced ocean upwelling are often associated with higher surface pressures during the following spring which can then create a self-enhancing (positive feedback) process ultimately resulting in higher Caribbean pressures during the summer (Knaff 1999). By this mechanism, positive ridge index values in fall are thus associated with an enhanced Azores high the following spring, stronger trade winds and, thereby, generally reduced hurricane activity. The long-term memory and feedback effects of this association make it a useful parameter for predicting next year's seasonal hurricane activity. Ridge strength during October-November 2000 was high, +1.1 SD above the long-term mean. Consequently, this factor is presently judged to be a negative influence for 2001 hurricane activity.

2 Most Recent Extended-Range Statistical Regression Forecast Scheme

A new version of our extended range forecasting scheme differs from the original (Gray et al. 1991) 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 with ever-decreasing true skill. Given the limited pool of hindcast years (46) from which to develop our scheme (1950-1995), degradation of true skill occurs when the scheme is applied to independent data if using too many predictors (i.e., the overfitting effect). Consequently, to maximize true skill, it becomes 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 and Table 4 shows the predictors chosen for each of our ten forecast hurricane activity parameters. Table 5 shows the predictions for the 2001 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 than our original 1 December forecast scheme as discussed by Gray et al. (1992). But our newer scheme also appears to underestimate 2001 activity for reasons we do not yet fully understand.

Table 3: Predictor values for 2001 forecast.

Predictor No.	**Predictor**	**Predictor Values for 2000 Fcst**
Pool of 10 Potential Predictors		
(1)	U_{50}	-12 m/s
(2)	U_{30}	-10 m/s
(3)	$\lvert U_{50} - U_{30} \rvert$	2 m/s
(4)	Guinea Rain (Aug-Nov)	-0.50 SD
(5)	West Sahel rain (Jun-Sept)	-0.70 SD
(6)	Atlantic Ridge (Oct-Nov)	+1.10 SD
(7)	Darwin (May-Jul) SLPA	+0.8 mb
(8)	Nino-4 Trend (Aug-Oct)-(May-Jul)	+0.5°C
(9)	SOI (Aug-Oct)	+0.8 SD
(10)	SOI Trend (Aug-Oct)-(May-Jul)	+1.1 SD

Table 4: (Most skillful) Predictors selected for 2001 forecast.

	Predictors chosen for each forecast variable									
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: Statistical summary for our second extended range forecast scheme for 2001 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	Most Recent Statistical Regression Scheme	Amount of non-degraded Variance Explained	Expected Independent Forecast Skill
NS	7.0	.519	.332
NSD	33.7	.547	.374
H	4.4	.494	.297
HD	13.0	.536	.358
IH	1.8	.436	.196
IHD	4.4	.417	.160
HDP	23.9	.492	.294
NTC	63.3	.528	.350

Application of any statistical regression scheme to independent data (i.e., the future) usually entails forecast skill degradation such that the amount of real forecast skill turns out to be less than was found for the developmental set. Our hurricane forecast for 1997 is a classic example. In our developmental data set, there were no El Niño events nearly so strong as occurred that year.

Table 6 provides a comparison of forecasts by both statistical regression and analog forecast schemes and then shows our qualitative adjustments to obtain the actual 2001 seasonal forecast. Column 3 shows the final 2001 forecast whereas, column 4 gives 1950-1990 climatology, column 5 gives the 2001 forecast activity expressed as percent of the 1950-1990 average season and column 6 gives our 2001 forecast in terms of the percentage of the average of the last three seasons. Note, in column 6, that 2001 hurricane activity is expected to be only about half as much as the average seasonal activity of the last three seasons. Net Tropical Cyclone (NTC) activity for 2001 is expected to be about 90 percent of the average for the 1950-1990 hurricane seasons.

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

Forecast Parameter	(1) Newer 1 Dec Statistical Fcst Scheme	(2) 1 Dec Analog Fcst Scheme	(3) Qualitatively Adjusted 2001 Fcst	(4) 1950-1990 Average	(5) 2001 Forecast as Percent of Ave. Season between 1950-1990	(6) 2001 Forecast as Percent of Ave. Season of 1998-2000 seasons
NS	7.0	9.4	9	9.3	97	66
NSD	33.7	50.6	45	46.6	97	61
H	4.4	5.6	5	5.8	86	57
HD	13.0	27.8	20	23.9	84	48
IH	1.8	2.0	2	2.2	91	54
IHD	4.4	5.5	4	4.7	85	41
HDP	23.9	83.0	65	71.2	91	52
NTC	63.3	105.0	90	100	90	54

Rationale for Upward Adjustments of 2000 Statistical Regression Forecast. We believe that the 2001 hurricane season will be more active than the values indicated by our statistical regression scheme. It appears that the training data sets for our statistical schemes, developed from 1950-1995 do not fully capture conditions associated with the unusually enhanced hurricane activity of the last six years. In addition, our statistical schemes have systematically underestimated the seasonal hurricane activity in four of the last five seasons (likely owing to the changing of strength of the Atlantic thermohaline circulation). The one exception to this during this period was the year of the very strong El Niño, 1997. These considerations and the results of our analysis of analog years (discussed below) lead us to increase our 2001 forecast over that specified by our statistical scheme.

3 Anticipated Weak to Moderate El Niño Conditions for During 2001

We anticipate that a weak to moderate El Niño event will develop in the tropical Pacific next summer. Our reasoning is as follows:

1. Four years will have passed since the onset of the very strong 1997 El Niño. El Niño's tend to be irregularly spaced at 3-5 year intervals. Moreover, we are in a period of strong Atlantic Ocean thermohaline conditions during which El Niño frequency and strength tend to be somewhat diminished. For example, there were 10 El Niños (or 0.208 per year) during the aggregate 48-year period of 1926-1968 and 1995-1999 (and only a few of these were strong) when the Atlantic thermohaline circulation is inferred to have been relatively strong. By contrast, there were 26 El Niños (0.464 per year and more events strong) during the aggregate 56 year period (1896-1925 and 1969-1994) when the Atlantic thermohaline circulation is presumed to have been weak; the difference is greater than two-to-one. A discussion of these associations appears in a conference paper by the first author (Gray 1998) and in a more extended report (Gray et al. 1996). Allowing that we are in a period of relatively strong Atlantic thermohaline circulation, we expect that only a weak to moderate El Niño event is likely to occur during the 2001 hurricane season.

2. Various ENSO prediction groups have recently begun to predict an El Niño for 2001 (as discussed on the Internet) .

3. Presently, (late November 2000), a fairly powerful westerly wind burst is underway in the Indonesia-tropical West Pacific region. This sort of event at this time of year is believed to be important in initiating some El Niños, and enhances our confidence that summer 2001 will indeed have at least a weak El Niño event in place in the tropical East Pacific.

4 Hurricane Activity During 2001 as Inferred from (Prior) Analog Years

Certain years in the historical record have global oceanic and atmospheric trends similar to 2000/2001. These years provide useful clues as to likely trends that the forthcoming 2001 hurricane season may bring. Although some of the physical associations involved with these relationships may be only partly understood, they are useful for extended range prediction. For this (1 December) extended range forecast, we project atmospheric and oceanic conditions into the following August through October period and determine which of the prior years in our data base have similar environmental conditions and then study the hurricane activity that occurred in those years.

<u>Analog Years Selected</u>. We find that since 1949, there were five years which were fairly similar to November 2000 wherein

- the North Atlantic (50-60°N, 10-50°W) had persistent warm SST anomalies during the prior 5-6 years and (as is expected) remained warm into the following year. This assumes that a strong decadal thermohaline circulation will persist in the Atlantic next year.
- The current general conditions of the NAO, PNA, PDO, and AO will also persist in their present mode through fall 2001 (i.e., in a global atmosphere and ocean circulation regime typical of the 1940s and 1950s).
- QBO 50 mb winds in September are projected to be from an easterly direction. We view this as an enhancing factor for the development of an El Niño in 2001.
- Netural prior year October-November East Atlantic subtropical SLPA ridge conditions. This is the only analog condition that does not fit our 2001 analog year. October-November 2000 ridge conditions are +1.1 SD above average.
- Warm El Niño conditions are projected for next year.

There were also five hurricane seasons since 1949 with characteristics similar to what we anticipate for summer/fall 2001. These analog years include July through October 1951, 1953, 1957, 1963, and 1965. None of these five 2001 analogs seasons has strongly suppressed hurricane activity (see Table 7). Based on the values in Table 7, we expect the 2001 season to approximate the average value for these five analogs. We believe this to be a more reliable forecast than the generally lower levels of activity predicted by our statistical schemes as discussed previously. Thus, based on this analysis we expect that 2001 should be less active than the five recent busy hurricane seasons but more active than the average seasons during the inactive 1970-1994 period.

Table 7: Best analog years for 2001 with the associated hurricane listed for each year.

	NS	NSD	H	HD	IH	IHD	HDP	NTC
1951	10	58	8	36	2	5.00	113	120
1953	14	65	6	18	3	5.50	59	120
1957	8	38	3	21	2	5.25	67	85
1963	9	52	7	37	2	5.50	103	115
1965	6	40	4	27	1	6.25	73	85
Mean	9.4	50.6	5.6	27.8	2	5.5	83	105

2001 Forecast	9	45	5	20	2	4	65	90

5 Major Reconfiguration of Atlantic Basin SSTs and Long Term Trends in Hurricane Activity

Recent observations indicate increased salinity in upper layers of the North Atlantic. Greater salinity increases water density of these surface layers which are 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 compensating equatorward transport of deep cold water) is the principal manifestation of the Atlantic Ocean thermohaline (``Conveyor'') circulation. A strong conveyor circulation transports greater quantities of heat to high latitudes. Hence, slowly rising salinity values in the far North Atlantic during recent years indicates the development of a stronger thermohaline circulation and a warmer North Atlantic. The effects of a stronger thermohaline circulation have been evident in the region since the spring of 1995 where, as noted before, the best proxy for this increased circulation has been warm North Atlantic SST anomalies.

Three decades have passed since these SST anomaly patterns have been this warm. Figure 4 shows changes in the mean SST anomalies between 1990 to 1994 and 1995 to 1999. During June through September 1999 SSTA values in the North Atlantic (50-60°N, 10-50°W) were nearly 1°C warmer than in the earlier five-year (1990-1994) period. These warmer SSTAs are presumably a result of a stronger Atlantic Ocean thermohaline circulation which has also led to a 0.5°C warming of the tropical Atlantic (6-22°N, 18-50°W). 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 since 1900, respectively. It is assumed that the current warm conditions will continue through 2001.

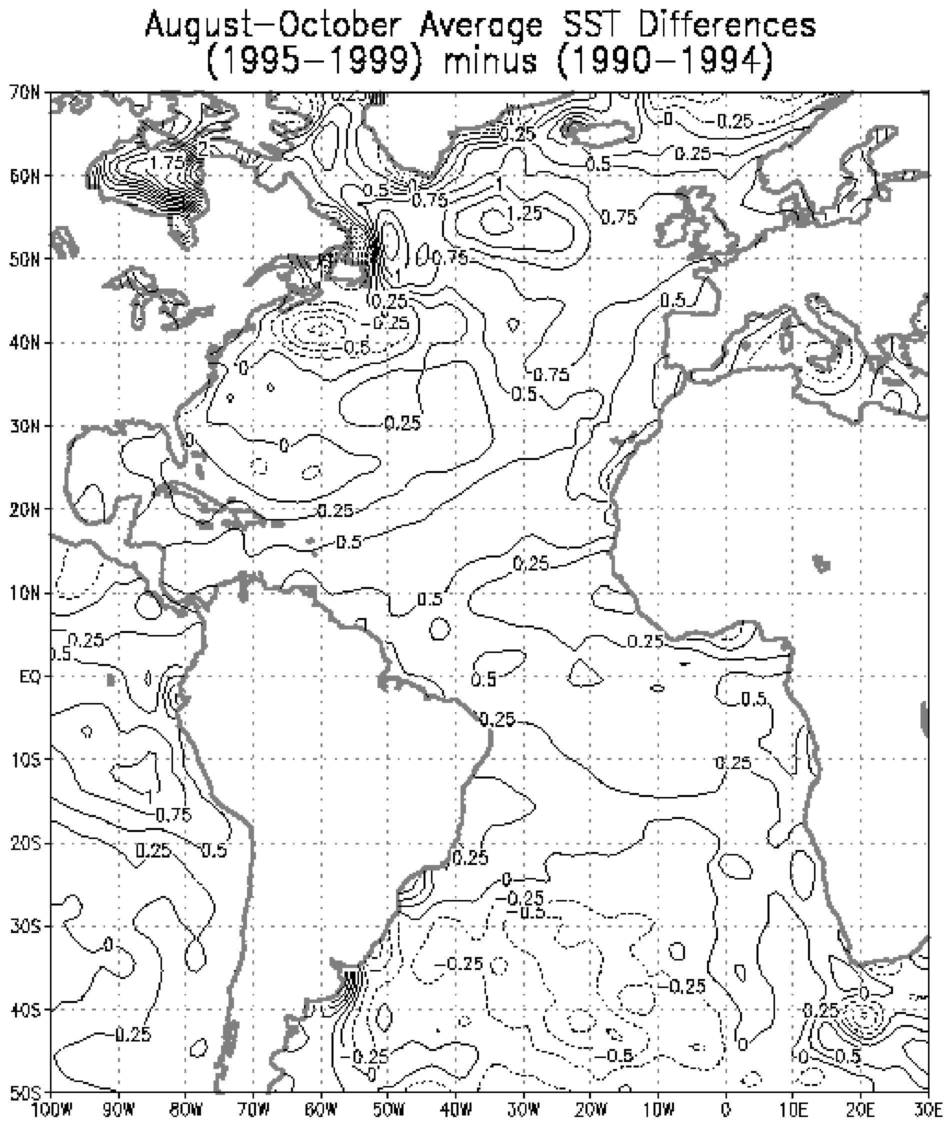

Figure 4: Differences (in ˙C) in August through October SST between the two five-year periods 1995 to 1999 minus 1990 to 1994. Warm (positive) differences are shown with solid contour.

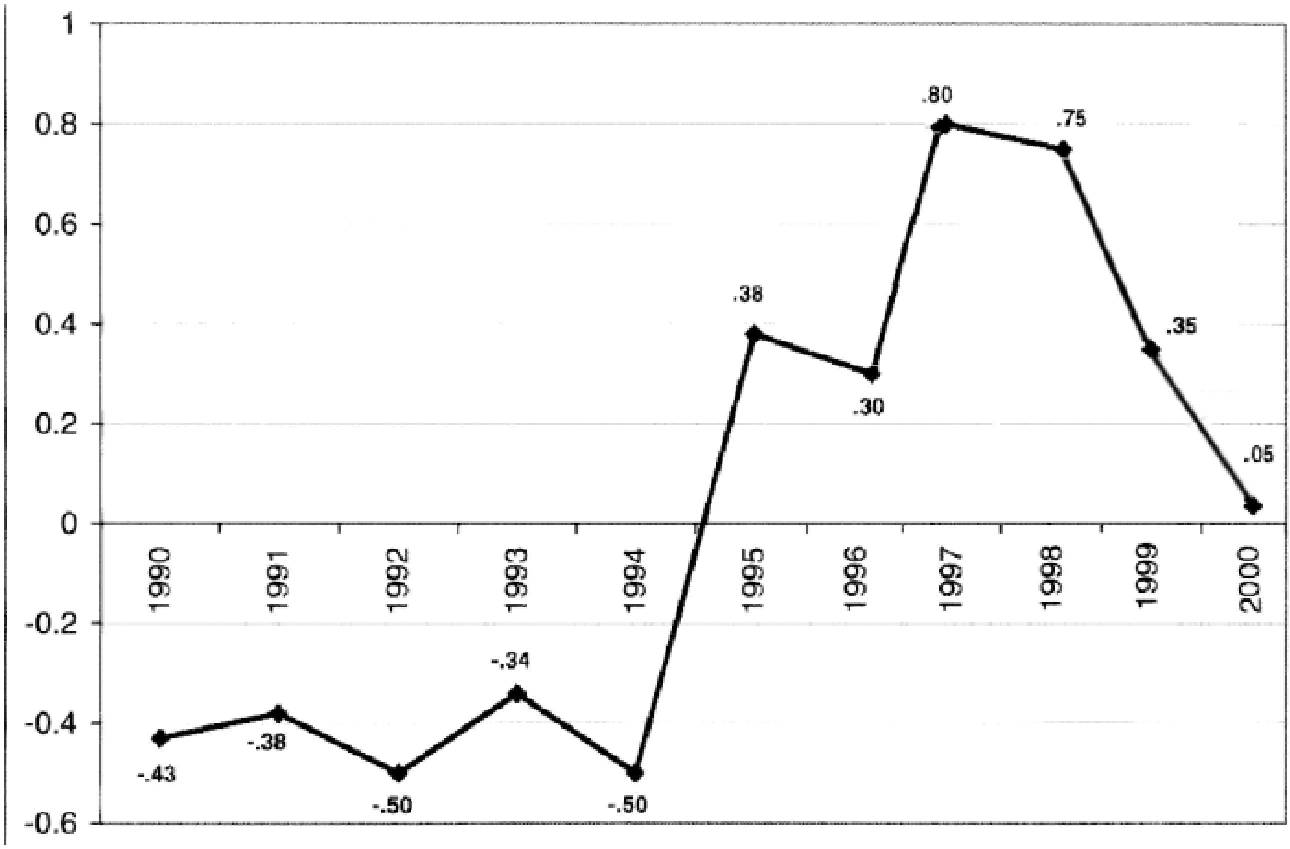

Figure 5: Time series of North Atlantic annual averages SST (in ˙C) anomalies in the area between 50-60˙N, 10 -50˙W for 1990 to 2000.

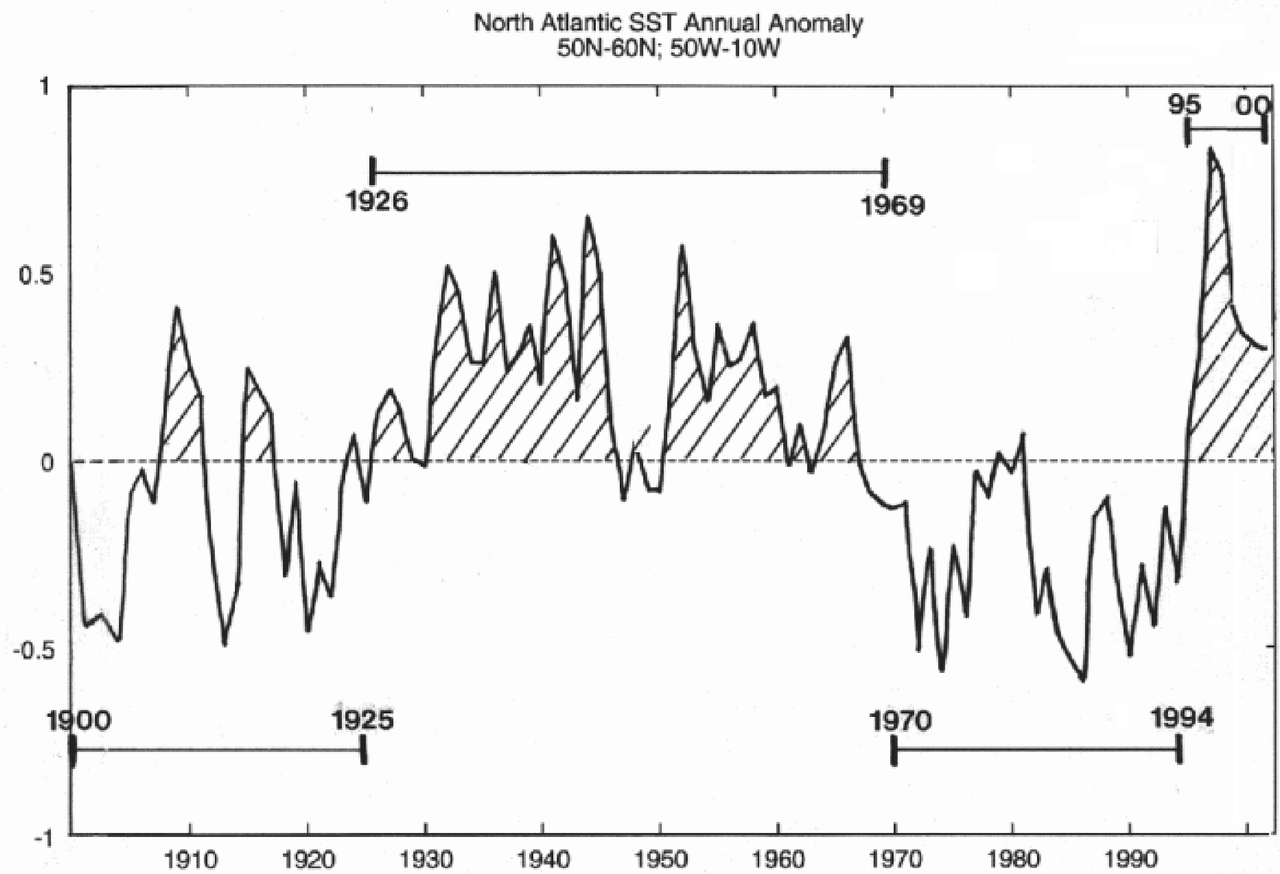

Figure 6: Time series of North Atlantic annual average SST (in ˚C) anomalies in the area between 50-60˚N, 10-50˚W for 1900 to 2000. The periods of positive SST anomalies are hatched.

Despite El Niño-linked reductions of hurricane activity during 1997, the last six years (2000) are together the most active five (consecutive) year period on record. This includes the total number of named storms (79), hurricanes (49), major hurricanes (category 3-4-5) (23), major hurricane days (56.25) and Net Tropical Cyclone activity (976) which occurred during the last six years. Despite the weak 1997 hurricane season, the annual average of NS, H, HD, IH, IHD and NTC during the last six years are 146, 163, 239, 329, 331 and 214 percent (respectively) of the average hurricane activity for the six-year period of 1989-1994. The annual average NS, H, IH, IHD and NTC during the last six years has been 153, 165, 247, 250, 373 and 217 percent of the average for the previous 25-year period (1970-1994). The largest increases have come with IH and IHD activity. See our 21 November 2000 verification of our 2000 forecast (available on the Web) for more documentation and discussion on this topic.

The general warming of the North Atlantic that has taken place during the last six years is in concurrence with increased incidence of major hurricanes, an association similar to what occurred during the most active hurricane seasons of 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 (1970-1994) era of reduced Atlantic intense (category 3-4-5) hurricane activity 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.

6 Landfall Probabilities for 2001

A new aspect of our research involves efforts to develop forecasts of the probability of hurricane landfall along the U.S. coastline. Whereas individual yearly hurricane landfall events will never be able to accurately forecast landfall in advance, the seasonal probability of landfall can be forecast with statistical skill. With the observation that, statistically, landfall is a function of varying climate conditions, a probability specification has been developed through a statistical analysis of all U.S. hurricane and named storm landfalls during the last 100 years (1900-1999). Specific landfall probabilities can be given for all cyclone intensity classes for a set of distinct U.S. coastal regions.

Net landfall probability is statistically related to the overall Atlantic basin Net Tropical Cyclone Activity (NTC) and to climate trends linked to multi-decadal variations of the Atlantic Ocean thermohaline circulation as measured by recent past years of North Atlantic SSTA*. SSTA* is an index of recent year North Atlantic SSTA in the area between 50-60°N, 10-50°W. Higher values of SSTA* generally indicate greater Atlantic hurricane activity, particularly major hurricane activity. Atlantic basin NTC can be skillfully predicted and the strength of the Atlantic Ocean thermohaline circulation can be inferred as SSTA* from North Atlantic SST anomalies from prior years. These relationships are then utilized to make probability estimates of U.S. landfall. The current (November 2000) value of SSTA* is 57. Hence, in combination with a new prediction of NTC of 90 for 2001, a combination of NTC+SSTA* of (90 + 57) yields a value of 147.

As shown in Table 8, NTC is a combined measure of the year-to-year mean of six indices of hurricane activity, each expressed as a percentage differences from the long-term average. Whereas many active Atlantic hurricane seasons feature no landfalling hurricanes, some inactive years have experienced one or more landfalling hurricanes. Long term statistics show that, on average, the more active the overall Atlantic basin hurricane season is, the greater the probability of U.S. hurricane landfall. For example, landfall observations during the last 100 years show that a greater number of intense (Saffir-Simpson category 3-4-5) hurricanes strike the Florida and U.S. East Coast during years of (1) highest NTC and (2) when above average North Atlantic SSTA* conditions are in place. The 33 years with the combined highest NTC (during the last 100) and strongest thermohaline circulation had 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 three such intense hurricane hits; a difference of 8 to 1.

Table 8: NTC activity in any year consists of the seasonal average of the following six parameters expressed in terms of their long-term averages. A season with 10 NS, 50 NSD, 6 H, 25 HD, 3 IH, and 5 IHD, would then be one-sixth of the 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 9: Number of Florida Peninsula and U.S. East Coast (regions 5 through 11) hurricane landfall events by intensity class during the 33 highest versus the 33 lowest values of NTC plus Atlantic thermohaline circulation (SSTA) of the last century.

Intensity Category	Sum of Lowest 33 Years	Sum of Highest 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 10: Number of Gulf (regions 1 through 4) hurricane landfall events by intensity class during the seasons with the 33 highest and 33 lowest NTC values during this century.

Intensity Category	Sum of Highest 33 Years	Sum of Lowest 33 Years	Ratio of Highest/Lowest 33 Years
IH (Category 3-4-5)	18	5	3.6
H (Category 1-2)	22	11	2.0
NS	28	27	1.0

Tables 9 and 10 summarize the links between hurricane and tropical storm landfall and the combined influences of NTC and thermohaline circulation (i.e., North Atlantic SSTA* effects) for Florida, the U.S. East coast and (NTC only) for the Gulf Coast.

Landfall characteristics for the Gulf Coast (Fig. 7) or (regions 1-4) from north of Tampa, FL to westwards to Brownsville, TX (36 total category 3-4-5 hurricane landfalls of this century) and the rest of the U.S. coast from north of Tampa, FL to Eastport, ME (37 landfalls in regions 5-11). These differences are due primarily to the varying incidence of category 3-4-5 hurricanes in each of these areas. The locations of these 11 coastal zones (Fig. 7) for which regression equations have been developed relating forecasts of NTC (NTC_f) and measured values of SSTA* to landfall probability are shown.

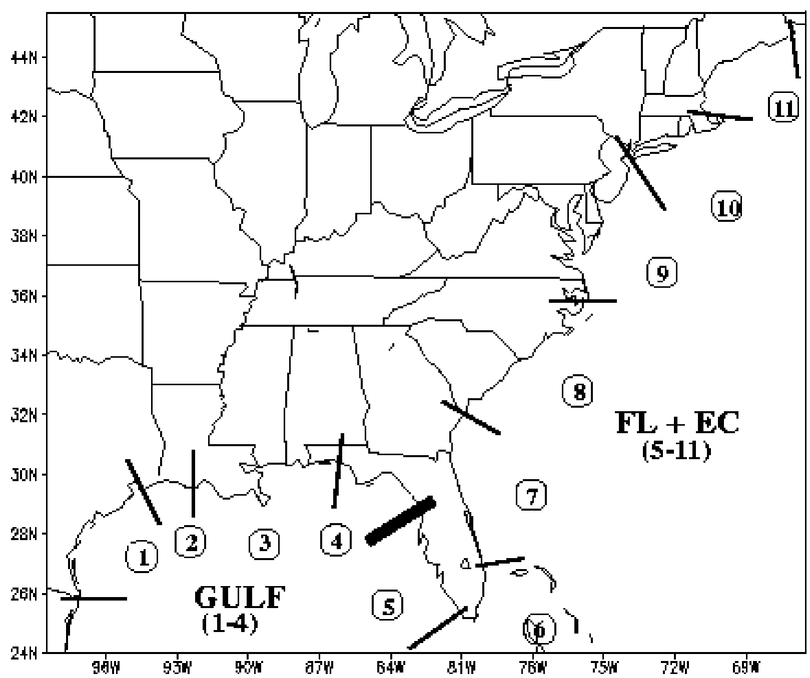

Figure 7: Location of the 11 coastal regions for which separate hurricane landfall probability estimates are made.

Figure 8 gives a flow diagram outlining the procedures by which these forecasts are made. Using NTC alone, a similar set of regression relationships has been developed for the landfall probabilities of category 1-2 hurricanes and TSs along the Gulf Coast (regions 1-4) and along Peninsula Florida and East Coastlines (regions 5-11). Current research is directed to making landfall probabilities available for 11 distinct Gulf Coast and U.S. East Coast regions extending from Brownsville, TX to Eastport, ME. Table 11 lists strike probabilities for different TC categories for the whole U.S. coastline, the Gulf Coast and Florida and the East Coast for 2001. The mean annual probability of one or more landfalling systems is given in parentheses. Note that although Atlantic basin NTC activity is expected to be about 10 percent below average, U.S. hurricane landfall probability is expected to be 5-10 percent above average. This is due to North Atlantic SSTAs being above average in recent years (Fig. 6). During periods of positive North Atlantic SSTA, a higher percentage of Atlantic basin hurricanes cross the U.S. coastline for a given level of NTC activity.

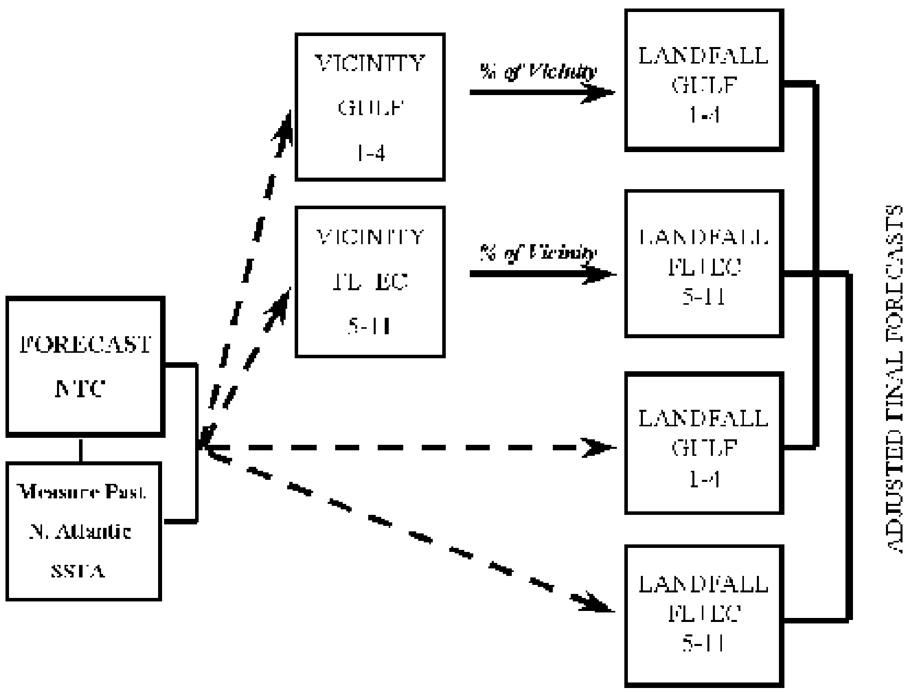

Figure 8: General flow diagram illustrating how forecasts of U.S. hurricane landfall probabilities are made. We forecast NTC and use an observed measure of the last few years of North Atlantic (50-60°N, 10-50°W) SSTA*. Regression equations are then developed from the combinations of forecast NTC and measured SSTA* values. A regression is then developed from U.S. hurricane landfall measurements of the last 100 years and separate equations are derived for the Gulf and for Florida and the East Coast (FL+EC).

Table 11: Estimated probability (percent) of one or more U.S. landfalling Tropical Storms (TS), category 1-2 hurricanes, and category 3-4-5 hurricanes, total hurricanes and named storms along the entire U.S. coastline, along the Gulf Coast (region 1-4), and along the Florida and the East coastline (Regions 5-11) for 2001. The mean annual number of one or more landfalling systems during the last 100 years is given in parentheses.

Coastal Region	TS	Category 1-2 HUR	Category 3-4-5 HUR	All HUR	Named Storms
Entire U.S. (Regions 1-11)	84% (80)	75% (68)	63% (52)	91% (84)	98% (97)
Gulf Coast (Regions 1-4)	64% (59)	48% (42)	36% (30)	67% (61)	88% (83)
Florida plus East Coast (5-11)	55% (51)	52% (45)	43% (31)	73% (62)	88% (81)

7 Abnormal Reduction in U.S. Major Hurricane Landfall of the Last Four Decades

Official records indicate that over the last century (1900-2000) there have been 218 major hurricanes in the Atlantic basin and of these category 3-4-5 storms, about one-third (73) have come ashore along the U.S. coastline. In the last six years (1995-2000) there have been 23 major hurricanes within the Atlantic basin but only three (Opal, 1995; Fran, 1996; and Bret, 1999) have come ashore. If the typical one out of three ratio of major hurricane landfall events of the last six years had taken place, then we should have experienced 7-8 major hurricane landfall events, not just three that did come ashore.

We have been fortunate that an upper-air trough has been located along the U.S. East Coast during a high percentage of time during the last six hurricane seasons. The fortuitous frequent location of this upper-level East Coast trough has caused a large portion of otherwise northwest moving major hurricanes to be recurved to the north before they reach the U.S. coastline. But this luck can not be expected to continue. Very few residents of the southeastern U.S. coastline are likely aware of how fortunate they have been over the last 3-4 decades.

Given the U.S. major hurricane landfall numbers of the last century, our luck at beating the long period climatology odds has now extended about four decades. For example, in the 30-year period of 1971-2000, the U.S. experienced 15 major landfall events, or 0.50 per year. This is only 62 percent of the annual incidence of major hurricane landfall events which occurred in the previous 72 years of 1900-1971.

With regard to the Florida Peninsula and the U.S. East Coast, the situation is even more skewed. In the last 40 years (1961-2000), there have been only six landfalling major hurricanes (average 0.15 per year) along the Florida Peninsula and U.S. East Coast. Between 1900-1960 there were 31 major landfall events along this same coastline (or 0.51 per year). The first six decades of the 20th century had 3.4 times the annual average of major hurricane landfall events along the Florida Peninsula and East Coast than occurred in the last four decades. This long downturn in U.S. major hurricane landfall events along the Florida Peninsula and East Coast is unlikely to continue. Climatology will eventually right itself and we must expect a great increase in landfalling major hurricanes in the coming decades. With exploding southeast coastal populations we should see levels of hurricane damage never before experienced.

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 similar 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 the individual season is. However, it must also be emphasized that a low probability does not insure that a hurricane will not come ashore. Regardless of how active 2001 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 1995-2000 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 21 November 2000 verification on this Web site for more discussion.

10 Schedule for 2001 Forecast Updates

This 7 December 2000 forecast will be updated on Friday 6 April 2001, Friday 8 June 2001 and Friday 3 August 2001. The 3 August package will also include a forecast of August only activity. These revisions will allow us to make adjustments as newer information becomes available. A verification of this forecast will be issued in late November 2001 and a seasonal forecast for the 2002 hurricane season will be issued in early December, 2001.

11 Acknowledgements

John Sheaffer, John Knaff, Todd Kimberlain, and William Thorson have made many important contributions to the conceptual and scientific background for these forecasts. The authors are indebted to a number of meteorological experts who have furnished us with the data necessary to make this forecast or who have given us valuable assessments of the current state of global atmospheric and oceanic conditions. We are particularly grateful to Arthur Douglas, Richard Larsen, David Masonis, Vern Kousky, Ray Zehr and Mark DeMaria 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, Jack Beven, James Franklin, and Stacy Stewart. The first author would further like to acknowledge the encouragement he has received for this type of forecasting research applications from Neil Frank, Robert Sheets, Robert Burpee, Jerry Jarrell, former directors of the National Hurricane Center (NHC), and from the current director, Max Mayfield.

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12 Additional Reading

Verification of All Past Seasonal Forecasts

See the 21 November 2000 write-up of our 2000 seasonal verification on this same Web site for all of our seasonal forecasts and verifications for the 17 forecast years of 1984-2000. We have made early December forecasts since 1992.