FORECAST OF ATLANTIC SEASONAL HURRICANE ACTIVITY FOR 1994

By
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(This forecast is based on ongoing research by the author and his research colleagues at Colorado State University, together with recent April–May 1994 meteorological information)

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DEFINITIONS

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

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) Four 6-hour periods during which a tropical cyclone is observed or estimated to have hurricane intensity winds.

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.

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

Named Storm Day - (NSD) Four 6-hour periods during which a tropical cyclone is observed or estimated to have attained tropical storm or 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 reaching at some point in its lifetime a sustained low level wind of at least 111 mph (96 kt or 50 ms^{-1}). This constitutes a category 3 or higher on the Saffir/Simpson scale (a "major" hurricane).

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

Millibar - (mb) A measure of atmospheric pressure which is often used as a vertical height designator. Average surface values are about 1000 mb; the 200 mb level is about 12 kilometers and the 50 mb is about 20 kilometers altitude. Monthly averages of surface values in the tropics show maximum summertime variations of about $\pm$ 2 mb which are associated with variations in seasonal hurricane activity.

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 5-6 years or so on average.

Delta PT - A parameter which measures the anomalous west to east surface pressure (ΔP) and surface temperature (ΔT) gradient across West Africa.

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

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 - A deviation of Caribbean and Gulf of Mexico sea level pressure from observed long term average conditions.

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

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.

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

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

ABSTRACT

This paper presents details of the author's forecast for the amount of tropical cyclone activity expected to occur in the Atlantic Ocean region including the Caribbean Sea and the Gulf of Mexico during 1994. This forecast is based on the author and colleague's ongoing research relating the amount of seasonal Atlantic tropical cyclone activity to five basic physical parameters. These are: 1) the Quasi-Biennial Oscillation (QBO) of equatorial stratospheric wind; 2) the El Niño Southern Oscillation (ENSO); 3) West African Rainfall (AR) anomalies during the previous year, 4) Anomalous west to east gradients of surface pressure and surface temperature (ΔPT) in West Africa during February through May, and 5) Caribbean Basin Sea Level Pressure and Upper Level Zonal Wind Anomalies (SLPA and ZWA respectively).

Information received by the author up to 6 June 1994 indicates that the overall 1994 hurricane season should be a below average with about 5 hurricanes (average is 5.7), 9 named storms (average is 9.3) of at least tropical storm intensity, a total of about 15 hurricane days (average is 23), 35 named storm days (average is 46) and total Hurricane Destruction Potential (HDP) of 40 (average is 68). It is also expected that there should be only one intense or major hurricane of Saffir/Simpson intensity category 3, 4 or 5 this season (average is 2.2) and only about 1 major hurricane day (average is 4.5). These parameters represent an overall measure of total hurricane and tropical cyclone activity which is only about 70% of the last 44-year average. The amount of hurricane activity in this forecast has been reduced from that in the author's 19 November 1993 forecast and update discussion of 11 March 1994 at the New Orleans National Hurricane Conference. This forecast reduction is due to the slower than anticipated dissipation of the current El Niño, new estimates of West African February through May surface east-west pressure and temperature gradients, and to above average values of April-May Caribbean basin SLPA and ZWA values.

This forecast will be updated on 5 August 1994, just before the beginning of the climatologically most active part of the hurricane season. The updated August forecast will make use of June and July data and should provide a more reliable forecast, particularly with regard to the African rainfall as it relates to prospects for intense hurricane activity. The updated forecast will also provide a much better gage on the extent of expected dissipation of the current El Niño event.

1 Introduction

The Atlantic basin, including the Atlantic Ocean, Caribbean Sea and Gulf of Mexico, experiences more season-to-season variability of hurricane activity than any other global hurricane basin. The number of hurricanes per season in recent years has ranged as high as 12 (as in 1969), 11 (as in 1950) and 9 (as in 1980, 1955), and as low as 2 (as in 1982) and 3 (1987, 1983, 1972, 1962, 1957). Until recently there has been no objective method for determining whether a forthcoming hurricane season was likely to be active, inactive, or near normal. Recent and ongoing research by the author and colleagues (see Gray, 1984a, 1984b, 1990; Landsea, 1991; Gray *et al.*, 1992, 1993a, 1994) indicates that there are surprisingly skillful 3 to 11 month (in advance) predictive signals for Atlantic basin seasonal hurricane activity.

2 Factors Known to be Associated With Atlantic Seasonal Hurricane Variability

This early June Atlantic seasonal hurricane forecast is based on the current values of indices derived from various global and regional scale predictive factors which the author and his colleagues have previously shown to be statistically related to seasonal variations of hurricane activity. Sucessive sets of values for these predictive factors are obtained by late November of the previous year, by early June, the official start of the hurricane season, and by early August, the start of the most active portion of the hurricane season. These predictive factors include the following.

(a) The stratospheric Quasi-Biennial Oscillation (QBO) influence. The QBO refers to variable east–west oscillating stratospheric winds which circle the globe over the equator. On average, there is nearly twice as much intense Atlantic basin hurricane activity during seasons when equatorial stratospheric winds at 30 mb and 50 mb (23 and 20 km altitude, respectively) are more westerly as compared to when they are more easterly directed. During the 1994 season, these QBO winds will be from an easterly direction and are expected to be a suppressing influence on this season's hurricane activity.

(b) El Niño Southern Oscillation (ENSO) influence: ENSO characterizes the presence of either warm or cold sea surface temperature anomalies in the eastern equatorial Pacific. The effects of a moderate or strong El Niño (warm water) event in the eastern equatorial Pacific act to reduce Atlantic basin hurricane activity. By contrast, seasons with cold sea surface temperatures, or La Niña years, have enhanced hurricane activity. These differences are related to alterations of upper tropospheric (200 mb or 12 km) westerly winds over the Caribbean Basin and western Atlantic. These westerly winds are enhanced during El Niño seasons. This condition creates strong vertical wind shear over the Atlantic which inhibits hurricane activity. During La Niña (or cold) years, these westerly winds and the associated vertical wind shear are reduced and hurricane activity is typically greater. It is expected that the unusually long lasting 1991-92-93 El Niño will be dissipated by the time of the most active part of the hurricane season, from 20 August to 10 October. Overall ENSO conditions are anticipated to be about neutral for this year.. Last fall and early this year (1994) it was anticipated that cold ENSO conditions would be in place by the active part of the 1994 hurricane season. New April-May data indicates that distinctly cold conditions will likely not develop. ENSO conditions are thus judged to be neither an enhancing or suppressing influence on this year's hurricane activity.

(c) African Rainfall (AR) influence: The incidence of intense Atlantic hurricane activity is typically enhanced during those seasons when the Western Sahel and Gulf of Guinea regions of West Africa (shaded area in Fig. 1) had above average late summer and fall precipitation during the previous year (in this case during the fall of 1993). Hurricane activity is typically suppressed if the prior fall rainfall in these two regions was below average. Rainfall amounts in the Western Sahel in August-September 1993 was –0.48 S.D. Gulf of Guinea rainfall was –0.03 S.D. in August through November 1993. From these less dry rainfall amounts we had anticipated that Western Sahel rainfall conditions will not be so dry in 1994 as in the previous years of 1991-92-93. But recent April-May meteorological data and a new Western Sahel rainfall forecast scheme has lead us to alter this assessment.

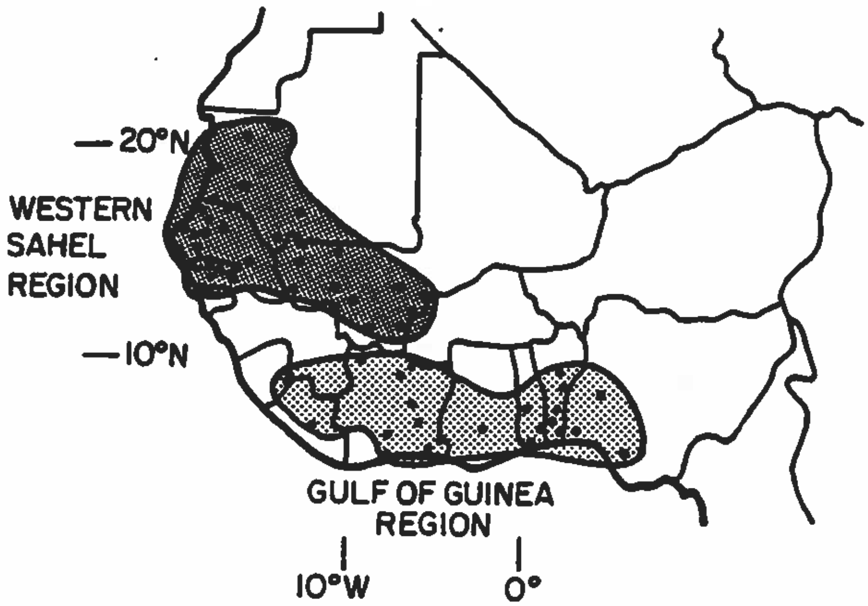

Figure 1: Locations of rainfall stations which make up the 38–station Western Sahel precipitation index and the 24-station Gulf of Guinea precipitation index. August to November rainfall within the Gulf of Guinea region provides a predictive signal for the following years hurricane activity as does prior year August-September rainfall in the Western Sahel (see Landsea, 1991; and Gray *et al.*, 1992).

(d) West Africa west-to-east surface pressure and surface temperature gradients (Δ PT) influence.
Recent project research by C. Landsea is showing that anomalous west-to-east surface pressure and surface temperature gradients across West Africa from February through May are strongly correlated with the hurricane activity which follows later in the year (see Gray *et al.*, 1994). We find that Atlantic hurricane activity is enhanced when the February to May east (Region B—see Fig. 2) minus west (Region A) pressure gradient is higher than normal and/or when the east minus west temperature gradient anomaly is below average. These pressure and temperature gradients during February and May 1994 indicate a weaker than normal North African monsoon and a below average amount of seasonal hurricane activity.

(e) Caribbean Basin Sea Level Pressure Anomaly (SLPA) and upper tropospheric (12 km) Zonal Wind Anomaly (ZWA) influence. April and May values of SLPA and ZWA have a modest predictive potential for the following season hurricane activity. Negative anomalies imply enhanced seasonal hurricane activity while positive values imply suppressed hurricane activity. April-May 1994 values of SLPA and ZWA were both above normal, indicating a suppressing influence on this season's hurricane activity.

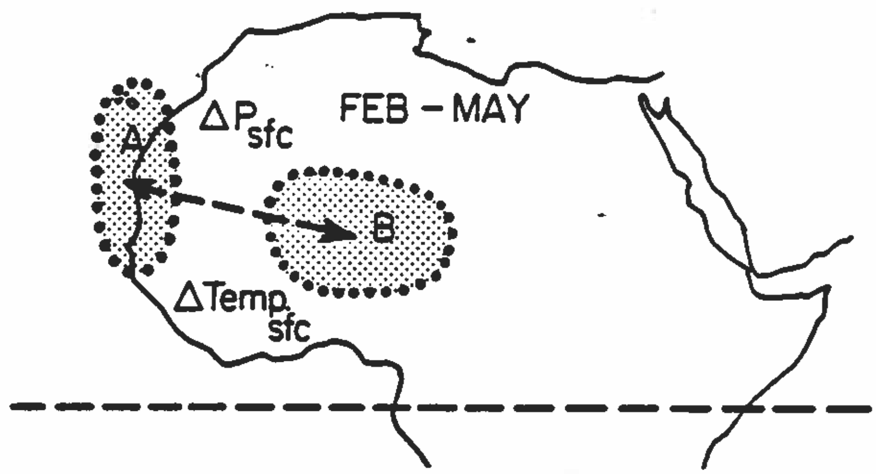

Figure 2: Portrayal of the two West African regions—west (Area A) and east (Area B)—from which multi-station surface pressure and temperature values are computed to form combined west-to-east pressure and temperature gradients or Δ PT parameter. (Gray et al. 1994).

Figure 3 provides a summary of the locations of the various forecast parameters which go into the early June forecast.

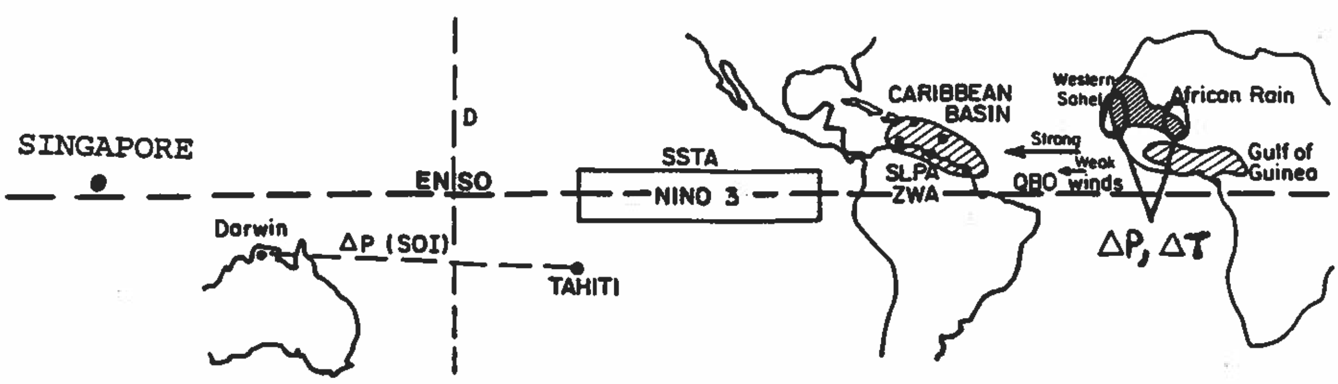

Figure 3: Locations of meteorological parameters used in the early June Atlantic basin seasonal forecast.

Our seasonal forecast scheme has the following general form:

$$\begin{array}{ll} & \textit{Adjustment Terms} \\ \left(\begin{array}{l}\textit{Predicted Amount} \\ \textit{of TC Activity} \\ \textit{Per Season}\end{array}\right) = Ave.\ Season + (QBO + EN + AR + PT + SLPA + ZWA) & (1)\end{array}$$

where

QBO = 30 mb and 50 mb Quasi-Biennial Oscillation zonal wind anomaly influence. [(Increased hurricane activity for westerly (or positive) zonal wind anomalies; reduced hurricane activity for easterly or negative zonal wind anomalies.)]

EN = El Niño influence. (Warm surface water in the equatorial East Pacific reduces hurricane activity, cold water enhances it.)

AR = Western Sahel rainfall. (Increase activity if wet; reduced activity if dry.)

PT = West Africa west-to-east gradients of surface pressure and surface temperature during February through May. (High values of west-to-east pressure gradient and lower values of west-to-east temperature gradient indicate more hurricane activity; less hurricane activity with opposite gradients)

SLPA = Average Caribbean Sea Level Pressure Anomaly (SLPA) for Spring and early Summer. (Reduce hurricane activity if SLPA is significantly above average; add activity if SLPA is significantly below average.)

ZWA = Zonal Wind Anomaly at 200 mb (12 km) for five low latitude upper air stations in the Caribbean. (Reduce hurricane activity if positive; increase hurricane activity if negative.)

3 Discussion of the Current Characteristics of the Five Primary Early June Predictors (QBO, ENSO, AR, Δ PT, and SLPA-ZWA) as Regards the Amount of Anticipated 1994 Seasonal Hurricane Activity

3.1 QBO

Tables 1 and 2 show the absolute and relative values of the current and extrapolated 30 mb (23 km) and 50 mb (20 km) stratospheric QBO zonal winds near 11 to 13°N for 1994 during the primary hurricane period of August through October. These estimates are based on a combination of the current trends in the QBO winds combined with the annual wind cycle variations for low latitude stations at Curacao (12°N), Trinidad (11°N), and Barbados (13°N). Note that during the primary August through October hurricane season, 30 mb and 50 mb zonal wind anomalies will be from an easterly direction. This should be a suppressing influence for this year's hurricane activity.

3.2 ENSO

The long running 3-year El Niño event of 1991-92-93 appears finally to be dissipating. April-May 1994 SSTA conditions in Nino 1-2 are –0.4°C, but weak warm conditions existed in April-May for Nino-3 (+0.3°C) and Nino-4 (+0.45°C). The author anticipates a weak cooling trend to occur during the next three months with the establishment of the Asian summer monsoon. Overall ENSO conditions are expected to be about neutral for this year. The

Table 1: March through October 1994 observed and extrapolated absolute values of stratospheric QBO zonal winds (U) in the critical latitude belts between 11-13°N as obtained from Caribbean stations at Curacao (12°N), Barbados (13°N), and Trinidad (11°N). Values are in ms^{-1} (data supplied by James Angell and Colin McAdie).

	Observed			Extrapolated				
Level	March	April	May	Jun	Jul	Aug	Sept	Oct
30 mb (23 km)	-16	−20	−24	−28	−30	−30	−28	−20
50 mb (20 km)	+3	−3	−9	−16	−22	−24	−22	−19

Table 2: As in Table 1 but for the "relative" (or anomalous) zonal wind values wherein the annual wind cycle has been removed. Values are in ms^{-1}.

	Observed			Extrapolated				
Level	March	April	May	Jun	Jul	Aug	Sept	Oct
30 mb (23 km)	−11	−12	−11	−11	−12	−12	−11	−8
50 mb (20 km)	+3	−2	−3	−6	−8	−10	−12	−12

previously anticipated cold conditions are not now likely to occur for the 1994 hurricane season. It is expected, however, that the last three-year warm water El Niño conditions, which were a major inhibiting influence on hurricane activity during the 1991-92-93 seasons, likely will not be present this year. Anticipated August through October ENSO conditions would thus dictate an increase in this year's hurricane activity over what has occurred the last three seasons.

ENSO is the most important global scale environmental influence affecting Atlantic seasonal hurricane activity. Hurricane activity during the last three seasons has been much suppressed because of the persistent, continuous warm water conditions which have been present in the Nino-3 and Nino-4 (see Fig. 4) regions of the equatorial Pacific and the continuous drought conditions which have been present in the Western Sahel region of Africa. This warm ENSO pattern appears to be changing. Sea surface temperature anomaly (SSTA) conditions (in °C) in Nino-1-2, 3, and 4 since January 1994 have been as follows:

	Jan	Feb	Mar	Apr	May
Nino-1-2	0.8	0.6	−0.2	−0.3	−0.5
Nino-3	0.4	0.0	0.1	0.2	0.4
Nino-4	0.4	0.0	0.2	0.3	0.6

ENSO conditions through May 1994 are distinctly different from conditions through May of the last three years. May SSTA conditions during 1991 through 1993 in Nino-1-2 areas were 0.5, 2.3, and 1.2°C, respectively, quite different than the present May 1994 value of −0.5°C. Nino-3 May SSTA conditions during 1991 through 1993 were 1.0, 1.6, and 1.7, much higher than the present year value of 0.4°C. There has also been a tendency for the May to August SSTA values in Nino 1-2 and Nino-3 to cool appreciably during this 3-month period during the years of 1990 through 1993. For instance Nino 1-2 SSTA's experienced mean 1990-93 SSTA cooling between May and August of −1.05°C. Nino-3 May to August SSTA coolings during these same four years averaged −1.15°C. These sharp May to August SSTA coolings in Nino 1-2 and Nino-3 appear to be tied to May to August changes associated with the onset of the Asian

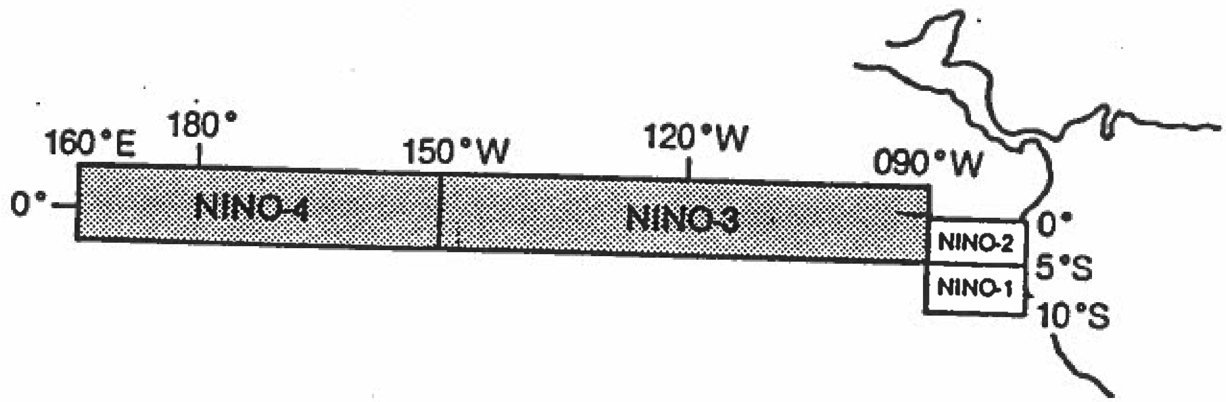

Figure 4: Equatorial Pacific sea surface temperature anomaly indices (°C) for the areas indicated.

monsoon. If this tendency for recent year May to August SSTA coolings in Nino 1-2 and Nino-3 is to continue through this year, it is to be expected that ENSO conditions will be distinctly different than they have been during the last three years. This assessment dictates a general evolution of near neutral ENSO conditions for this year. It thus appears that for the first year since 1990 the ENSO will not be an important inhibiting influence for this years Atlantic basin hurricane activity.

3.3 West African Rainfall (AR)

Substantially more intense Atlantic hurricane activity occurs when June through September West Sahel rainfall is above average as compared to those seasons when rainfall is below average (Gray, 1990; Landsea and Gray, 1992). The long running Sahel drought of 1970-87 has been associated with a great suppression of intense hurricane activity during that 18 year period. A temporary (two year) interruption of African drought conditions occurred in 1988–89, concurrent with a substantial increase in intense hurricane activity, including five Saffir/Simpson category 4-5 hurricanes. However, drought conditions have returned again during 1990-1993. The assessment for 1994 (as of the end of May) is that we will again see below average Western Sahel rainfall. Western Sahel rainfall is thus judged to be an inhibiting influence for Atlantic intense hurricane activity during 1994 in comparison to long term climatology, but is more typical of the large inhibiting influence on intense hurricane activity that has occurred since 1970.

This assessment is based upon the following considerations:

- (a) The Landsea et al. (1994) early June (1994) forecast of –0.70 S.D. of Western Sahel rainfall conditions for this year. This forecast is based on most of the same factors as the current seasonal hurricane forecast and indicates that Western Sahel rainfall conditions will be about as dry as the last four summers have been.
- (b) The present arrangement of global and Atlantic SSTA conditions, primarily in the tropical regions. The UK Meteorological Office (1994) is forecasting dry conditions for the Sahel region of West Africa. This forecast is based on global SSTA patterns of a warm Indian Ocean, warm central Pacific Ocean, warm South Atlantic, and cool North Atlantic through April of this year. This forecast was issued in mid-May and is based on meteorological data through April of this year.

Our last winter forecast of Western Sahel rainfall (based on data through November 1993) indicated June through September Western Sahel rainfall amounts of but –0.10 S.D., substantially more rain than has occurred in recent years. This would indicate a break in the last four years (1990-1993) of rather severe drought conditions. New information through April-May 1994 however indicates that June-September Western Sahel rainfall will likely be considerably drier than that indicated by our earlier extended range forecast. For many of the same reasons that the seasonal hurricane forecast is reduced, a decrease in now also expected in Western Sahel June to September rainfall for this year. These continued dry conditions indicate an associated reduced probability of Atlantic basin hurricane activity.

3.4 West Africa Δ P and Δ T

The anomalous west-to-east surface pressure and temperature gradients which become established across West Africa during February through May are good indicators of the hurricane activity to be expected in the late summer-fall period. Figure 2 showed the west-and-east areas of Africa from which these surface pressure and temperature gradients are taken. Hurricane activity is highest when the east (Region B) minus west (Region A) pressure gradient deviations are most positive and/or when the west-minus-east temperature gradients are positive.

Given the typical inverse relationship between land surface temperature and surface pressure, positive west-to-east pressure gradients are typically associated with positive east-to-west temperature gradients and vice versa. A positive value of west to east Δ P and east to west Δ T would act to enhance southerly winds and thus a comparatively moist low level flow over West Africa. More Sahel rainfall and Atlantic hurricane activity would result. When west to east ΔP and east to west Δ T are negative, West Africa would have anomalously northerly and dry winds; this is conducive to dry conditions and fewer Atlantic seasonal hurricanes and this year's Western Sahel rainfall conditions. February through May 1994 west to east Δ P was –1.4 and Δ T was –0.3 S.D. Both of these values are indicative of a suppressing influence on this season's hurricane activity.

3.5 SLPA and ZWA

Two Caribbean parameters which contribute to the early June forecast are Caribbean Basin Sea Level Pressure Anomalies (SLPA) and 200 mb (12 km) Zonal Wind Anomalies (ZWA). The April-May 1994 five-station tropical (Trinidad, Barbados, Curacao, San Juan and Cayenne) SLPA's were quite high (+0.80 mb) and the five-station April-May (Trinidad, Curacao, Barbados, Kingston and Balboa) ZWA values had a small value of +1.5 mb. These two April-May measurements indicate a general suppression of this year's hurricane activity.

4 New 1 June Forecast Scheme

Over the last year and a half the author and his CSU research colleagues, Christopher Landsea, Paul Mielke, Jr., and Kenneth Berry have been working to improve the skill of the early June forecast. We have recently identified the additional predictor of West African ΔP, Δ T and have found a way to quantitatively represent ENSO conditions. A new journal paper discussing these results has recently been published (Gray, Landsea, Mielke and Berry, 1994). This new, and more skillful early June forecast takes the following form:

(Hurricane Activity) =

$$\begin{aligned} &\beta_0 + \beta_1(a_1 U_{50} + a_2 U_{30} + a_3|U_{50} - U_{30}|) \\ &\quad + \beta_2(a_4 R_s + a_5 R_g + a_6 \Delta_x \mathrm{P} + a_7 \Delta_x \mathrm{T}) \\ &\quad + \beta_3(a_8 \mathrm{SLPA} + a_9 \mathrm{ZWA} + a_{10} \mathrm{SST} + a_{11} \Delta_t \mathrm{SST} + a_{12} \mathrm{SOI} + a_{13} \Delta_t \mathrm{SOI}) \end{aligned} \tag{1}$$

where

β's and α's are empirically derived coefficients for prior years of data

U_{50}, U_{30} are extrapolated September QBO zonal winds at 30 and 50 mb at 10°N

$|U_{50} - U_{30}|$ absolute value of the extrapolated vertical wind shear between 50 and 30 mb
R_s is the western Sahel precipitation in the previous August and September
R_g is the previous year August to November precipitation in the Gulf of Guinea region
ΔP is West African anomalous east-west pressure gradient deviation in February through May
ΔT is West African anomalous west-east temperature deviation in February through May
SLPA is the April-May Sea Level Pressure Anomaly in the lower Caribbean basin
ZWA is the April-May Zonal Wind Anomaly in the Caribbean basin
SOI is the April-May normalized Tahiti minus Darwin Sea Level Pressure differences
SSTA is the April-May Sea Surface Temperature Anomaly in Nino 3
ΔSOI is the recent months change in SOI from January-February to April-May
ΔSSTA is the recent months change in SSTA from January-February to April-May.

Figure 3 illustrates the source areas from which the data for these predictors are obtained.

Based on cross-validated (or jackknife) hindcasts tests for 42 seasons spanning 1950-1991, we find that we can explain a substantial amount of the variance in individual season hindcast tests (see Table 3). Although these 13 variables are not independent, when taken together, each variable contributes to the forecast skill.

Table 3: Percent of cross-validated variance explained explained by 1 June forecast scheme (Eq. 1) as determined in hindcasts made for the years of 1950-1991.

Forecast Parameter	Percent of Variance Explained
Named Storms (N)	51
Named Storm Days (NS)	66
Hurricanes (H)	62
Hurricane Days (HD)	70
Intense Hurricanes (IH)	64
Intense Hurricane Days (IHD)	61
Hurricane Destruction Potential (HDP)	71
Net Tropical Cyclone Activity (NTC)*	72
*See Appendix A	

Based on data through the end of May 1994, the 1 June predictors for Equation (1) have the values as listed in Table 4. Substitution of these variables into equation (1) with the coefficients listed in Appendix B gives 1994 seasonal hurricane activity forecast summarized in Table 5. The coefficients used in Equation (1) are given in Appendix B. The right column of Table 5 shows the author's qualitative adjustment of the statistical forecast leading to the actual forecast for this season. Table 6 expresses each parameter in this adjusted forecast as a percentage of the last 44-year average. Note that all forecast parameters are below the long period average. Table 7 compares this early June forecast to the author's late November 1993 forecast (Gray, 1993) of last year. The November 1993 forecast anticipated cold ENSO conditions to be in place during the height of the 1994 hurricane season. This is in contrast to the near neutral conditions which are now expected. This factor, together with the negative values of February to May West African Δ P and Δ T gradient conditions and high values of April-May Caribbean SLPA and ZWA are responsible for the downward estimate of this early June forecast. Table 8 gives a comparison of this year's seasonal activity forecast with the amount of hurricane activity which has occurred during past years. Note that the 1994 season, despite the below average forecast, is still expected to be more active than the last three hurricane seasons have been.

Table 4: Predictors for the early June 1994 forecast which are substituted into Equation (1).

	U_{30}	−28 m/s	
QBO Predictors	U_{50}	−22 m/s	extrapolated to Sept. 1994
	$\|U_{50}$ - $U_{30}\|$	6 m/s	
	R_s	−0.48 S.D.	Aug.-Sept. 1993
	R_g	−0.03 S.D.	Aug.-Nov. 1993
West African Predictors	ΔP	−1.4 S.D.	
	ΔT	−0.3 S.D.	Feb. through May 1994
Caribbean and ENSO	SLPA	+0.80 mb	April-May 1994 value
Predictors	ZWA	+1.5 m/s	April-May 1994 value
	SOI	$-14.0\ 10^{-1}$S.D.	April-May 1994 value
	SSTA	$+30 \times 10^{-2}$ °C	April-May 1994 value
	ΔSOI	-12.0×10^{-1} S.D.	(Apr-May) - (Jan-Feb) 1994
	ΔSSTA	$+ 10 \times 10^{-2}$ °C	(Apr-May) - (Jan-Feb) 1994

Table 5: The 1994 seasonal forecasts obtained by substitution of the parameter values in Table 5 into Equation (1). The author's qualitative adjustments and actual forecast are shown on the right column.

Forecast Parameter	Table 5 Values in Eq. 1	Qualitative Adjustment and Actual Forecast
Named Storms (N)	8.85	9
Named Storm Days (NS)	28.03	35
Hurricanes (H)	4.73	5
Hurricane Days (HD)	12.20	15
Intense Hurricanes (IH)	0.60	1
Intense Hurricane Days (IHD)	0.15	1
Hurricane Destruction Potential (HDP)	30.18	40
Net Tropical Cyclone Activity (NTC)*	64.78%	70%
Western Sahel rainfall forecast	−0.70 S.D.	−0.70

*See Appendix A

5 Analog Years

The strongest components in year to year Atlantic basin hurricane activity variations are the ENSO, the stratospheric QBO, and the Western Sahel (AR) rainfall. Since 1950 there have been four years during which each of these basic hurricane modulating parameters were similar to the anticipated conditions for 1994. Prior analog years for 1994 are 1968, 1970, 1974, and 1979. Each of these four years had nearly identical 70 mb to 10 mb stratospheric QBO wind conditions. Each of these four years had dry June through September Western Sahel rainfall values (−0.75, −0.45, −0.23, −0.54) which are all similar to that which is anticipated for this

Table 6: 1994 Atlantic basin seasonal forecast values and the percent of the long term (1950-1993) average.

	Forecast	%
Named Storms (N)	9	97
Named Storm Days (NS)	35	76
Hurricanes (H)	5	88
Hurricane Days (HD)	15	65
Intense Hurricanes (IH)	1	45
Intense Hurricane Days (IHD)	1	22
Hurricane Destruction Potential (HDP)	40	59
Net Tropical Cyclone Activity (NTC)	70%	70%

Table 7: Comparison of current, early June 1994, seasonal predictions with the 1994 seasonal predictions made in late November 1993 and discussed on 11 March 1994 at the New Orleans National Hurricane Conference.

Forecast Parameter	19 Nov. 1993 Fcst.	Current 1994 Early June Fcst.	Changes in 7 June 94 Fcst. from 19 Nov. 1993 Fcst.
Named Storms (N)	10	9	–1
Named Storm Days (NS)	60	35	–25
Hurricanes (H)	6	5	–1
Hurricane Days (HD)	25	15	–10
Intense Hurricanes (IH)	2	1	–1
Intense Hurricane Days (IHD)	7	1	–6
Hurricane Destruction Potential (HDP)	85	40	–45
Net Tropical Cyclone Activity (NTC)	110%	70%	–40%

Table 8: Comparison of early June 1994 seasonal prediction with activity in previous years.

	7 June Forecast 1994	Observed 1993	1992	1991	Average Season 1970-87	Average Season 1950-69	44–Year Ave.
Hurricanes	5	4	4	4	4.9	6.5	5.7
Named Storms	9	8	6	8	8.3	9.8	9.3
Hurricane Days	15	10	16	8	15.5	30.7	23.0
Named Storm Days	35	30	38	22	37.3	53.4	46.1
Hurr. Dest. Pot. (HDP)	40	23	51	23	42.7	100.0	68.1
Intense Hurricanes (Cat. 3-4-5)	1	1	1	2	1.6	3.4	2.1
Intense Hurricane Days	1	0.75	3.25	1.25	2.1	8.8	4.5
Net Tropical Cyclone Activity (NTC)	70%	55%	62%	59%	73%	123%	100%

year's Western Sahel rainfall conditions. And, each year also had near neutral August-October Nino-3 sea surface temperature anomaly conditions (+0.56, −0.81, −0.41, +0.48°C), close to what is expected for this coming August-October 1994 period.

Table 9 shows the eight seasonal hurricane parameters were during each of the four analog to 1994 years. Note how the four-year average value of each of these parameters is very close to this year's early June forecast. It is gratifying that these analogue years agree so well with the current forecast.

Table 9: Atlantic basin tropical cyclone activity which occurred during four previous analog years when ENSO, QBO, and Western Sahel rainfall were all similar to the expected values of these parameters for 1994.

Year	NS	NSD	H	HD	IH	IHD	HDP	NTC
1968	7	26	4	10	0	0	18	41
1970	10	24	5	7	2	1	18	65
1974	7	32	4	14	2	4.25	46	76
1979	8	44	5	22	2	5.75	73	96
4-Year Average	8	31.5	4.5	13.25	1.5	2.75	38.75	69.5
1994 Early June Fcst	9	35	5	15	1	1	40	70
Fcst. Minus Mean of Analog Years	1	3.5	−0.5	1.75	−0.5	−1.75	1.25	0.5

6 Strong Suppression of Intense (or Major) Low Latitude Atlantic Basin Hurricane Activity During the Last Three Years (1991-1993)

There has been a total of only 4 intense (or major) category 3-4-5 hurricanes and only 5.25 intense hurricane days during the last three years. The climatology of the last 44 years would have specified 6.6 intense hurricanes (65 percent more) and 13.5 (105 percent more) intense hurricane days during this period. Additionally all of the intense (category 3-4-5) hurricanes during 1991-1993 developed into intense storms poleward of 25°N. Climatology would specify that only about one-third, or about 1.3 intense or major hurricanes (maximum sustained winds > 115 mph) would reach this level of intensity at these higher latitudes. There is an inverse association between low (< 25°N) and high (> 25°N) latitude Atlantic basin hurricane activity; when the low latitudes are active, higher latitudes are typically suppressed. When the low latitudes are inactive, as during the last three seasons, then hurricane activity at higher latitudes is typically enhanced. The two seasons of 1988 and 1989 saw the formation of a total of five intense (or major) hurricanes at latitudes equatorwards of 25°N. Goldenberg and Shapiro (1993) have provided strong evidence that interannual vertical shear differences force this inverse association between the low and high latitudes.

Table 10 illustrates the unusually large reduction in hurricane activity south of 25°N during the last three hurricane seasons in comparison with the average three year period between 1950-1990. Only one hurricane (Gert 1993, southwestern Gulf of Mexico) formed south of 25°N during these three years when, from climatology, one would have expected about 11 hurricanes to form. No major hurricanes formed during this three-year period south of 25°N when, from past climatology, one would have expected 4-5 major hurricanes to form.

The recent long running El Niño has been a major suppressing influence for low latitude and Caribbean basin hurricane activity during the last three years. Continued Western Sahel drought conditions have also been an important contributing factor to the suppression of low

Table 10: Summary of latitude during distribution of Atlantic basin hurricane activity north or south of 25°N including the Gulf of Mexico during the three seasons of 1991-1993

	No. becoming of hurricane intensity		No. becoming intense (or major) cat. 3-4-5 hurricanes	
	South of 25°N	North of 25°N	South of 25°N	North of 25°N
1991	0	4	0	2
1992	0	4	0	1
1993	1	3	0	1
Total	1	11	0	4
Expected three-year total based on the period 1950-1990	11.4	6.0	4.5	1.8

latitude Atlantic hurricane activity. Hurricane Andrew (1992) developed into an intense hurricane at relatively high latitudes and, given the environmental conditions as an El Niño and West African dry weather during 1992, was an anomaly. With the anticipated demise of the current El Niño during 1994, it is expected that this year will see more low latitude hurricane activity than has occurred during the last three years. But this does not mean that low latitude hurricane activity will be very prevalent. Activity should still be below the long period mean.

7 Discussion

If this below average forecast for the 1994 season is verified, then we will have had four consecutive years of below normal hurricane seasons. It is uprecidented to have four consecutive seasons in which hurricane activity and particularly, low latitude hurricane activity, is so low. This is attributed to the exceptionally long running El Niño event of 1991-93, in combination with continuous and strong Western Sahel drought conditions. The expected dissipation of the El Niño this year does not greatly improve the prospects for enhanced 1994 hurricane activity over that of 1991-93 seasons because this season's QBO will be strongly easterly and Western Sahel drought conditions are also expected to continue to be moderately to strongly dry. Both QBO and drought conditions are unfavorable for hurricane activity. There are also other inhibiting factors for this year (i.e., the SLPA and ZWA in the Caribbean basin).

The downward adjustment of extended range forecast from that issued on 19 November 1993 is due to a combination of April-May observations which could not be anticipated with the last November forecast. These include:

1. Lack of evidence for a distinctly cold ENSO event during the coming August-October period, as was anticipated (by the author) in late November and which had been forecast last fall and winter by some ENSO modelers.

2. Likely unrepresentativeness of Western Sahel August-September 1993 rainfall (–0.48 S.D.) and Gulf of Guinea August-November 1993 (–0.03 S.D.) rainfall for this coming season's June-September Western Sahel rainfall. Our new early June Western Sahel rainfall predictions indicate drier conditions (–0.70 S.D.) than anticipated last November.

3. Unfavorable values of West Africa east-west surface and pressure gradients during February-May 1994. These gradients indicate both suppressed Western Sahel rainfall and suppressed seasonal hurricane activity.

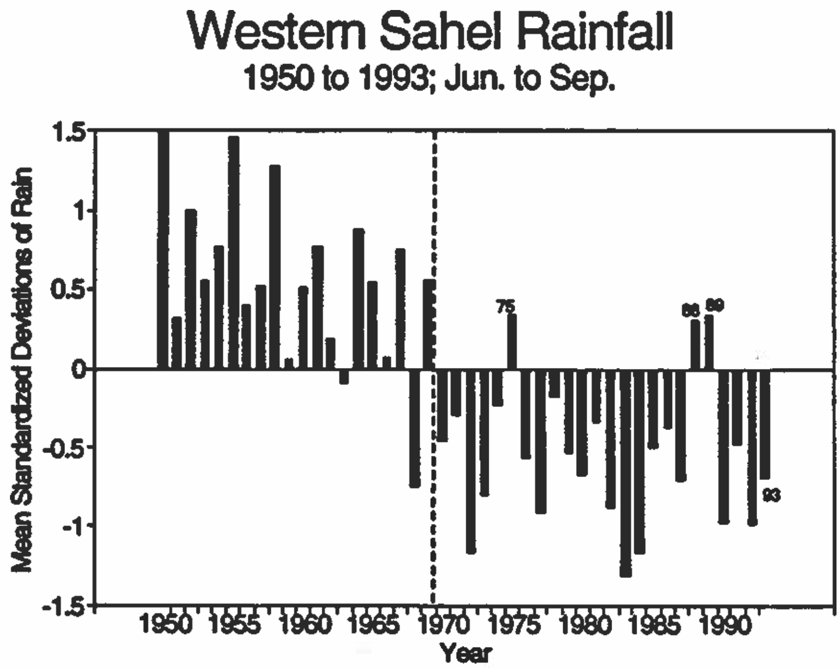

Figure 5: Rainfall anomalies in the Western Sahel during the last 47 years, expressed in terms of standardized deviations from the long period mean.

4. High values of Caribbean basin April-May SLPA of +0.80 mb and 200 mb ZWA of +1.5 m/s.

5. High values of Singapore (1.5°N, 104°E) 100 mb (16.5 km altitude) temperature anomaly during December 1993 through May 1994 (+1.0°C). Recent research indicates a strong out-of-phase relationship between this equatorial station's December-May mean 100 mb temperature anomalies and the following August-October Atlantic basin hurricane activity. December 1993 to May 1994 values would indicate a below normal season.

Consideration of these five changes in atmospheric conditions warrant the reduction in the forecast of seasonal hurricane activity, as indicated in Table 7.

8 Schedule of Updated Seasonal Hurricane Forecasts of 1994

An updated forecast, before the start of the most active part of the hurricane season, will be issued on Friday August 5, 1994. A verification report on the 1994 hurricane season and forecast for the 1995 hurricane season will be issued in late November of this year. In addition, seasonal forecasts for 1995 ENSO conditions and 1995 Sahel rainfall conditions will also be issued in late November of this year.

9 Cautionary Note

It is important that the reader realize that this seasonal forecast is based on a statistical scheme which will fail in some years. This forecast also does not specifically predict where within the Atlantic basin storms will strike. Even if 1994 should prove to be a below average hurricane season, there are no assurances that several hurricanes will not strike along the US or Caribbean Basin coastline and do much damage. Or, if 1994 should prove to be a very active hurricane season there is no assurance that any storms will come ashore.

10 Outlook for 1995

Presently it is anticipated that the 1995 hurricane season will be much more active than have the hurricane seasons of 1991-1993 and the expected below average 1994 seasonal hurricane activity. The stratospheric QBO will be in a more favorable (for hurricane activity) westerly phase during 1995 and these stratospheric wind conditions will also be favorable for the enhancement of cool ENSO conditions. Cool ENSO conditions and a westerly stratospheric QBO also act to enhance Sahel rainfall. Such cool ENSO, westerly QBO and reduced drought conditions typically lead to greater seasonal hurricane activity.

11 Likely Increase of Landfalling Major Hurricanes in Coming Decades

There has been a great lull in the incidence of intense (category 3-4-5) landfalling hurricanes on US East Coast, Florida and Caribbean Basin during the last 25 years. We see this as a natural consequence of the slowdown in the Atlantic Ocean (thermohaline) Conveyor Belt circulation and its closely related consequences for Sahel drought, increased El Nino activity and other related global scale circulation changes which have occurred over the last 25 years (Gray and Landsea 1992).

Historical and geological records indicate that this lull in major landfalling hurricane activity should not be expected to continue indefinitely. A return of increased major landfalling hurricane activity should be expected within the next decade or two. When this happens, (because of the large coastal development during the last 25-30 years), the US will see hurricane destruction as never before experienced. Research on the causes and the likely time frame for this change-over is desperately needed. This is a real and more of an immediate natural threat to the US than that of greenhouse gas warming and other environmental problems which are receiving so much more attention in comparison to the hurricane threat.

12 Verification of Past Seasonal Forecasts

The author has now issued seasonal hurricane forecasts for the last eleven years. In most of the (prior) ten forecasts, predictions have been superior to climatology, which was previously the only way to estimate future hurricane activity (see Table 11). The six seasonal forecasts for 1985, 1986, 1987, 1988, 1991 and 1992 were quite accurate; the forecasts for 1984 and 1990 were only marginally successful and the two seasonal forecasts for 1989 and 1993 were failures. The 1989 forecast was a failure because of the excessive amounts of rainfall which fell in the Western Sahel that year. Prior to 1990, our seasonal forecast did not include African rainfall as a predictor. We have corrected this important omission and forecasts since 1990 have included Western Sahel rainfall estimates. Extended range seasonal hurricane forecasts from late November have only been issued for the 1992, 1993, and 1994 seasons. The failure of the 1993 seasonal forecast is attributed to our failure to anticipate the resurgence and continuation of El Niño conditions through the whole of the 1993 hurricane season. In particular, the author failed to anticipate the re-emergence of stronger El Niño conditions after the middle of August 1993. It is very unusual to have an El Niño last as long as the recent event has. This failure motivated us to develop a new extended range ENSO prediction scheme.

Table 11: Verification of past year forecasts (1984-1993).

1984		Prediction of 24 May and 30 July Update		Observed
No. of Hurricanes		7		5
No. of Named Storms		10		12
No. of Hurricane Days		30		18
No. of Named Storm Days		45		51
1985		**Prediction of 28 May**	**Updated Prediction of 27 July**	**Observed**
No. of Hurricanes		8	7	7
No. of Named Storms		11	10	11
No. of Hurricane Days		35	30	21
No. of Named Storm Days		55	50	51
1986		**Prediction of 29 May**	**Updated Prediction of 28 July**	**Observed**
No. of Hurricanes		4	4	4
No. of Named Storms		8	7	6
No. of Hurricane Days		15	10	10
No. of Named Storm Days		35	25	23
1987		**Prediction of 26 May**	**Updated Prediction of 28 July**	**Observed**
No. of Hurricanes		5	4	3
No. of Named Storms		8	7	7
No. of Hurricane Days		20	15	5
No. of Named Storm Days		40	35	37
1988		**Prediction of 26 May and 28 July Update**		**Observed**
No. of Hurricanes		7		5
No. of Named Storms		11		12
No. of Hurricane Days		30		24
No. of Named Storm Days		50		47
Hurr. Destruction Potential(HDP)		75		81
1989		**Prediction of 26 May**	**Updated Prediction of 27 July**	**Observed**
No. of Hurricanes		4	4	7
No. of Named Storms		7	9	11
No. of Hurricane Days		15	15	32
No. of Named Storm Days		30	35	66
Hurr. Destruction Potential(HDP)		40	40	108
1990		**Prediction 5 June**	**Updated Prediction of 3 August**	**Observed**
No. of Hurricanes		7	6	8
No. of Named Storms		11	11	14
No. of Hurricane Days		30	25	27
No. of Named Storm Days		55	50	68
Hurr. Destruction Potential(HDP)		90	75	57
Major Hurricanes (Cat. 3-4-5)		3	2	1
Major Hurr. Days		Not Fcst.	5	1.00
1991		**Prediction 5 June**	**Updated Prediction of 2 August**	**Observed**
No. of Hurricanes		4	3	4
No. of Named Storms		8	7	8
No. of Hurricane Days		15	10	8
No. of Named Storm Days		35	30	22
Hurr. Destruction Potential(HDP)		40	25	23
Major Hurricanes (Cat. 3-4-5)		1	0	2
Major Hurr. Days		2	0	1.25
1992	**Prediction of 26 Nov 1991**	**Prediction 5 June**	**Updated Prediction of 5 August**	**Observed**
No. of Hurricanes	4	4	4	4
No. of Named Storms	8	8	8	6
No. of Hurricane Days	15	15	15	16
No. of Named Storm Days	35	35	35	38
Hurr. Destruction Potential(HDP)	35	35	35	51
Major Hurricanes (Cat. 3-4-5)	1	1	1	1
Major Hurr. Days	2.0	2.0	2.0	3.25
1993	**Prediction of 24 Nov 1992**	**Prediction 4 June**	**Updated Prediction of 5 August**	**Observed**
No. of Hurricanes	6	7	6	4
No. of Named Storms	11	11	10	8
No. of Hurricane Days	25	25	25	10
No. of Named Storm Days	55	55	50	30
Hurr. Destruction Potential(HDP)	75	65	55	23
Major Hurricanes (Cat. 3-4-5)	3	2	2	1
Major Hurr. Days	7	3	2	0.75

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APPENDIX A

Measures of seasonal tropical cyclone activity include the seasonal total number of named storms (NS), hurricanes (H), intense (or major) hurricanes (IH), named storm days (NSD), hurricane days (HD), intense hurricane days (IHD), and hurricane destruction potential (HDP). Definitions of these hurricane indices are given at the beginning of this report. More detailed information is contained in Gray et al. (1992, 1994) and in Landsea (1993).

It is desirable to define a single number which provides a simple but comprehensive expression of net season tropical cyclone activity in terms of a percentage difference from a long term mean. To this end, we propose a new parameter of seasonal activity termed the "Net Tropical Cyclone activity" (NTC) which is defined as:

$$NTC = (\%NS + \%H + \%IH + \%NSD + \%HD + \%IHD)/6$$

Table 12: Listing of Seasonal Net Tropical Cyclone activity (NTC) values between 1950-1993.

Year	NTC (%)	Year	NTC (%)	Year	NTC (%)
1950	243	1964	168	1978	86
1951	121	1965	86	1979	96
1952	97	1966	140	1980	135
1953	121	1967	97	1981	114
1954	127	1968	41	1982	37
1955	198	1969	157	1983	32
1956	69	1970	65	1984	77
1957	86	1971	95	1985	110
1958	140	1972	28	1986	38
1959	99	1973	52	1987	48
1960	101	1974	76	1988	121
1961	222	1975	92	1989	140
1962	33	1976	85	1990	104
1963	116	1977	46	1991	59
				1992	62
				1993	55

where each season's percentage departure values from the long term mean are used as the six measures of seasonal activity. The NTC value is useful as a seasonal tropical cyclone measure because it combines most of the other tropical cyclone parameters of interest into a single measure of activity. There are many seasons in which a single parameter, say for example, the number of hurricanes, is not well representative of the actual character of the overall tropical cyclone activity for that year. We propose the use of this single (NTC) index as a measure of tropical cyclone activity. This single index has the highest forecast skill. Table 11 lists the values of NTC for 1950-1993.

Note that the last three hurricane seasons have had net seasonal hurricane activity averaging only 59 percent of the 1950-1993 average, when the seasonal hurricane activities in the previous three seasons of 1988-1990 averaged 122 percent or twice as much.

APPENDIX B

Weights of β_i and a_i coefficients used in Eq. (1).

	β_0	β_1	β_2	β_3
NS	12.3781	.1651	.6312	-.2714
NSD	68.8556	1.0409	.7985	-19.5133
H	9.7544	.1389	.5074	-2.5884
HD	41.2690	.6513	3.8807	-13.1287
IH	2.5199	.0252	-.4059	.0187
IHD	6.3386	.1527	-1.6019	-1.0636
HDP	112.9477	1.5122	8.5714	-34.8274
NTC	146.7669	2.0802	-2.2472	-17.0237

	NS	NSD	H	HD	IH	IHD	HDP	NTC
QBO								
a_1	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
a_2	-.0714	-.0729	-.3662	-.3971	.4160	-.2182	-.3153	-.1021
a_3	-.9199	-1.2538	-2.1072	-2.0173	.2899	-.7551	-1.8143	-1.1884
a_4	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
a_5	2.4308	8.4673	.5335	.5796	-2.4883	-1.0317	1.3122	-7.7489
a_6	-.0478	1.0972	-1.3485	-.4836	-2.4395	-1.6112	.2809	-5.4734
a_7	-.6367	7.2463	.8690	1.4982	-.6668	-.9943	2.7448	-9.3565
a_8	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
a_9	-.1987	-.0294	.0667	-.0667	5.8344	-.6537	-.0889	-.0824
a_{10}	.0713	.0054	-.0012	-.0055	-.6297	.0103	-.0016	.0098
a_{11}	-.0430	.0002	.0016	.0113	.0171	.0167	.0088	.0024
a_{12}	.7902	-.0037	-.0521	-.1327	-1.4853	-.1748	-.1166	-.0687
a_{13}	-.4711	.0437	.0631	.1258	.1546	.2521	.1199	.1416