EARLY AUGUST FORECAST OF ATLANTIC SEASONAL HURRICANE ACTIVITY FOR 1996

An expected year of average hurricane activity

(Next page gives forecast numbers)

(7 August 1996)

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(This forecast is based on ongoing research by the authors, together with meteorological information through July 1996)

[This write-up is also available on the World Wide Web at the following URL:
http://tropical.atmos.colostate.edu/forecasts/index.html] — also,
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ABSTRACT

This paper presents details of the authors' early August updated forecast of the amount of tropical cyclone activity expected in the Atlantic Ocean region (including the Caribbean Sea and the Gulf of Mexico) during the remainder of the 1996 hurricane season. Most Atlantic basin hurricane activity occurs after early August. This forecast is based on the authors' ongoing research relating the amount of seasonal Atlantic tropical cyclone activity to a number of local and global atmospheric circulation and oceanic conditions. We now have several new predictors not utilized in previous early August forecasts including Sea Surface Temperature Anomalies (SSTA) in two areas of the Atlantic plus last year's October-November Sea Level Pressure Anomaly (SLPA) in the eastern sub-tropical Atlantic. These new predictors are used in combination with our previous predictors which include the Quasi-Biennial Oscillation (QBO) of equatorial stratospheric winds; the El Niño-Southern Oscillation (ENSO); West African Gulf of Guinea rainfall anomalies during the previous August-November period, Western Sahel June-July rainfall, anomalous west to east gradient of temperature (ΔT) in West Africa during February through May, and Caribbean Basin June-July Sea Level Pressure and Upper Level Zonal Wind Anomalies (SLPA and ZWA).

Information received by the authors through 6 August 1996 indicates that a slightly below average amount of post 1 August hurricane activity should occur. Because of above average activity (i.e., 3 named storms and 2 hurricanes) during June-July we expect the whole 1996 hurricane activity to be a relatively average season with about 7 hurricanes or 5 more than we have so far had (total season average is 5.7), 11 named storms or 8 more than we have so far had (total season average is 9.3), a seasonal total of about 25 hurricane days (average is 23), seasonal total of 50 named storm days (average is 46) and seasonal total Hurricane Destruction Potential (HDP) of 70 (average is 68). We also expected 2 more (hence, total of 3) intense or major hurricanes of Saffir-Simpson intensity category 3, 4 or 5 (average is 2.1) and a total 4 intense hurricane days (average is 4.5). These parameters represent an overall measure of total seasonal hurricane and tropical cyclone activity which is about 105 percent of the last 45-year average. This updated forecast is very close to our early April and early June forecast of 1996 hurricane activity. The three named storms, two of which developed into hurricanes, play no role in our post 1 August forecast.

Summary of the early August 1996 forecast of seasonal Atlantic hurricane activity.

Forecast Parameter	Observed to 1 Aug	Forecast Activity After 1 Aug	Total Seasonal Activity	1950-1990 Average
Named Storms (NS)	3	8	11	9.3
Named Storm Days (NSD)	13	37	50	46.1
Hurricanes (H)	2	5	7	5.7
Hurricane Days (HD)	6	19	25	23
Intense Hurricanes (IH)	1	2	3	2.1
Intense Hurricane Days (IHD)	1	3	4	4.5
Hurricane Destruction Potential (HDP)	16	54	70	68.1
Net Tropical Cyclone Activity (NTC)	31	74	105	100
Maximum Potential Destruction (MPD)	16	49	65	61.7

DEFINITIONS

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

El Niño - (EN) A 12-18 month period during which anomalously warm sea surface temperatures occur in the eastern half of the equatorial Pacific. Moderate or strong El Niño events occur irregularly, about once every 5-6 years or so on average.

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

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

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

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

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

MATL - April-June Sea Surface Temperature anomaly in the sub-tropical Atlantic between 30-50°, 10-30°W

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.

MPD - Maximum Potential Destruction - A measure of the net maximum destruction potential during the season compiled as the sum of the square of the maximum wind observed for each named storm (see Appendix A for a listing of values for 1950-1995).

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

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

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

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

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

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

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

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

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

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.

Delta PT - A parameter which measures anomalous east to west surface pressure ($\triangle P$) and west to east surface temperature ($\triangle T$) gradients across West Africa.

TATL - April-June Sea Surface Temperature (SST) anomaly in Atlantic between 6-22°N, 18-80°W.

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

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

1 Introduction

The Atlantic basin, including the Atlantic Ocean, Caribbean Sea and Gulf of Mexico, experiences more season-to-season activity occurring 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 1995) and 9 (as in 1980, 1955), and as low as 2 (as in 1982) and 3 (1994, 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 authors (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 after 1 August

This early August seasonal forecast is based on the current values of indices derived from various global and regional scale predictive factors which the authors have previously shown statistically to be related to seasonal variations of hurricane activity. Figure 1 provides a summary of the locations of the various forecast parameters which go into the forecast. Successive sets of values of these predictive factors are obtained by the end of July. This is before the start of the active portion of the hurricane season. We statistically optimize the predictive signals from these forecast parameters. Our predictive factors include:

(a) The stratospheric Quasi-Biennial Oscillation (QBO). The QBO refers to variable east–west oscillating stratospheric winds which circle the globe near the equator. On average, there is nearly twice as much intense (category 3-4-5) Atlantic basin hurricane activity during seasons when equatorial stratospheric winds at 30 mb and 50 mb (23 and 20 km altitude, respectively) blow from a westerly as compared to an easterly direction.

(b) El Niño-Southern Oscillation (ENSO): ENSO characterizes the sea surface temperature anomalies in the eastern equatorial Pacific (Fig. 1) and the value of Tahiti minus Darwin surface pressure gradient. The effects of a moderate or strong El Niño event in the eastern equatorial Pacific are to reduce Atlantic basin hurricane activity. By contrast, in those seasons with cold sea surface temperatures, and high values of Tahiti minus Darwin surface pressure occur (La Niña

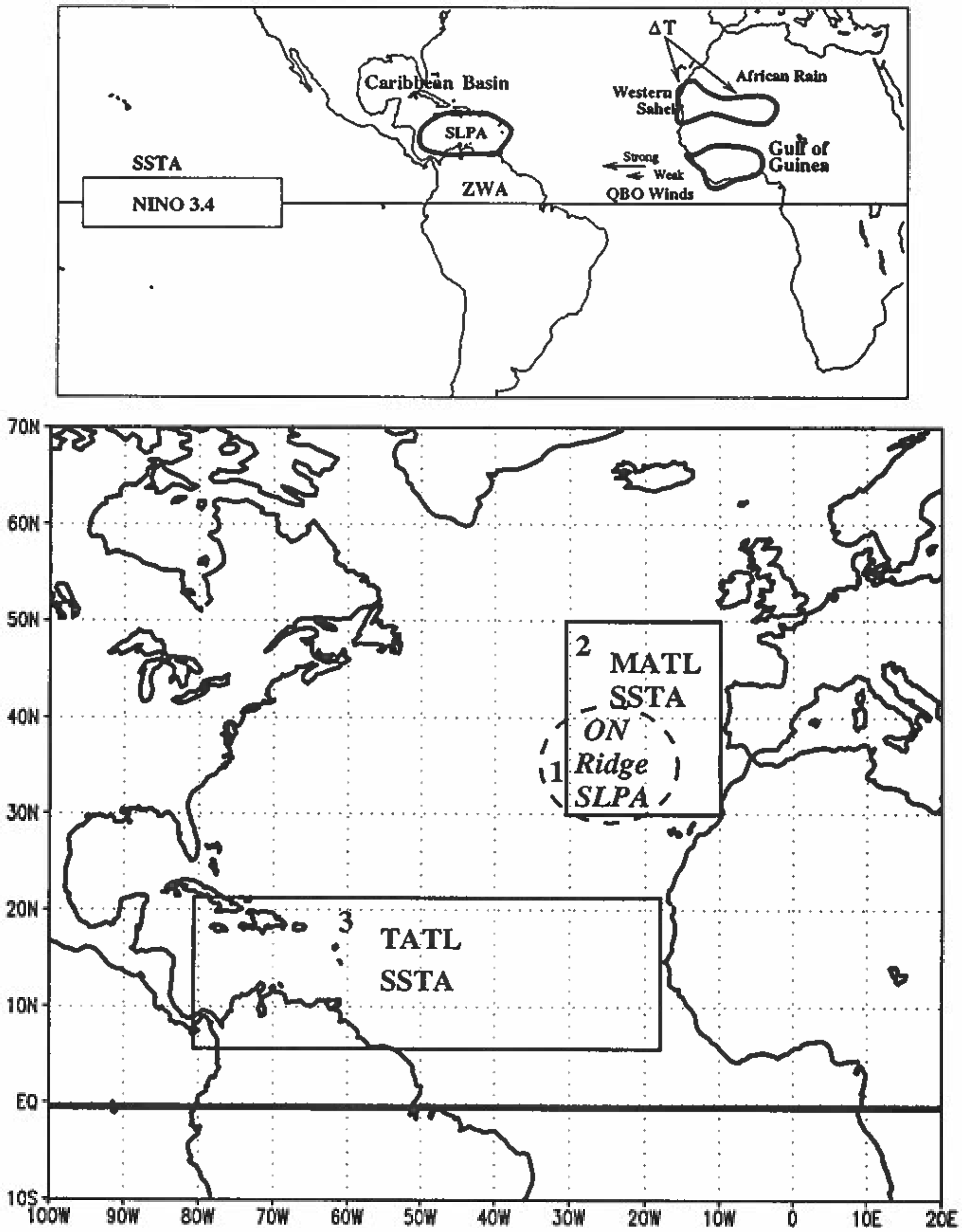

Figure 1: Locations of meteorological parameters used in the seasonal forecasts. Symbols are defined on the definitions pages (pages 3-4). The top diagram shows the locations of the global predictors. The bottom diagram shows the predictors in the Atlantic Ocean region.

years) there is typically an enhancement of Atlantic basin hurricane activity. These differences are related to alterations of upper tropospheric (200 mb or 12 km) westerly winds and surface pressure over the Caribbean Sea and western Atlantic. Westerly upper-level winds are enhanced during El Niño seasons. This condition creates strong vertical wind shear over the tropical Atlantic which inhibits hurricane activity. During La Niña (or cold) years, westerly upper-level winds and the associated vertical wind shear are reduced and hurricane activity is typically greater.

(c) African Rainfall (AR): The incidence of intense Atlantic hurricane activity is strongly enhanced during those seasons when West Africa June-July Western Sahel rainfall and previous year August-November Gulf of Guinea region rainfall (shaded area in Fig. 2) have above average precipitation. Hurricane activity is typically suppressed if the rainfall in these two regions was below average.

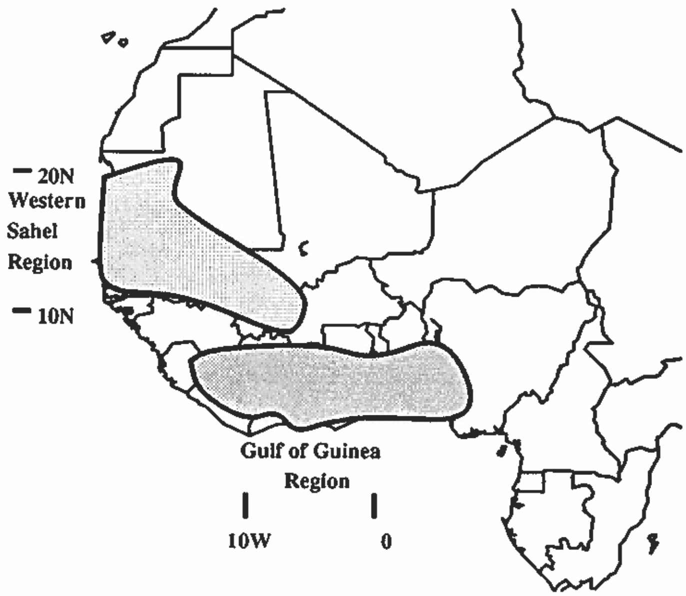

Figure 2: Regions which are used to create a 38-station Western Sahel precipitation index and a 24-station Gulf of Guinea precipitation index. August to November rainfall within the Gulf of Guinea region provides a predictive signal for the following years hurricane activity as does the early season June-July rainfall in the Western Sahel for the current season (see Landsea 1991; and Gray et al. 1992).

(d) Previous Year October-November northeast Atlantic Subtropical Ridge Strength (ONR). When this pressure ridge is anomously weak during the previous autumn period, the eastern Atlantic trade winds are weaker. This condition reduces cold water advection and upwhelling off the northwest African coast as well as the evaporative cooling rate of this area of the Atlantic. This process leads to warmer sea surface temperatures which carry over into the following summer period and lead to more season hurricane activity. Weaker hurricane activity occurs when the October-November ridge has anomalously high pressure.

(e) Atlantic Sea Surface Temperature Anomalies (SSTA) in the two regions (MATL; 30-50°N, 10-30°N and TATL; 6-22°N, 18-82°W) during April through June: See Fig. 1 (bottom) for the location of these areas. Higher SSTAs enhance deep oceanic convection and, other factors aside, provide conditions more conducive for tropical cyclone activity.

(f) Caribbean Basin Sea Level Pressure Anomaly (SLPA) and upper tropospheric (12 km) Zonal Wind Anomaly (ZWA): June-July values of SLPA and ZWA have a moderate predictive potential for hurricane activity occurring during the following August through October months. Negative anomalies (i.e., low pressure and easterly zonal wind anomalies) imply enhanced seasonal hurricane activity while positive values imply suppressed hurricane activity.

(g) Influence of West Africa west-to-east surface pressure and temperature gradients (Δ PT): Project research has shown that anomalous west-to-east surface pressure and temperature gradients across West Africa from February through May are well 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 – in Fig. 3) minus west (Region A) pressure gradient is higher than normal and/or when the east minus west temperature gradient anomaly is below average.

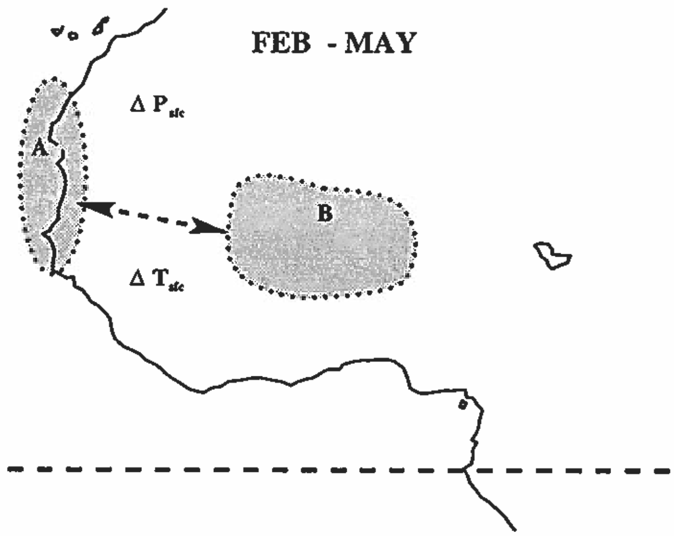

Figure 3: Map showing of the two West African regions—west (Area A) and east (Area B)—from which multi-station surface pressure and temperature values are computed to form combined west-to-east pressure and temperature gradients or Δ PT parameter. (Gray et al. 1994).

3 Forecast Methodology

Our early August seasonal forecast scheme has the following general form:

$$\begin{pmatrix}\textit{Predicted Amount} \\ \textit{of TC Activity} \\ \textit{Per Season}\end{pmatrix} = \textit{Ave. Season} + \overbrace{(QBO+EN+AR+ONR+MATL,\ TATL\ etc.)}^{\textit{Adjustment Terms}} \quad (1)$$

Each adjustment term has a weighted coefficient associated with it. We statistically test for the best individual predictor, the best two predictor combination, the best three predictor combinations, etc. For each additional predictor added, we require that the predictor improve the forecast by at least five percent of the remaining variance. Unless such an improvement occurs, we stop adding new predictors. The number of predictors accepted under this criteria is typically four to six. In some cases we use only three predictors, in one case we use up to seven predictors.

We use the above factors to make nine separate predictions or measures of seasonal hurricane activity. This includes separate predictions of the seasonal number of

NS	–	Named Storms
NSD	–	Named Storm Days
H	–	Hurricanes
HD	–	Hurricane Days
IH	–	Intense Hurricanes
IHD	–	Intense Hurricane Days
HDP	–	Hurricane Destruction Potential
NTC	–	Net Tropical Cyclone Activity
MPD	–	Maximum Potential Destruction

Research has shown that those prior atmospheric and oceanic conditions which are associated with large numbers of named storms can have different prediction characteristics than those seasons associated with large amounts of intense hurricane activity. There are also latitude differences as well. Those hurricanes forming from African waves typically have longer tracks and more days of activity than hurricanes forming at higher latitudes. As the damage a hurricane does typically increases with the square, cube, or higher power of its wind speed, we have developed separate parameters such as HDP and MPD which better reflect this exponential damage rise with wind speed. It is for these reasons that we make separate multi-parameter forecasts of the different measures of Atlantic basin seasonal activity.

Recent research has been directed towards improving our 1 August forecast methodology. This work has involved the addition of new predictors and changing of statistical procedures. Our earlier 1 August forecast scheme (Gray et al. 1993) was developed on hindcast information for the 41-year period of 1950-1990. It used the same nine predictors for each forecast parameter. It did not distinguish between hurricane activity occurring before and after 1 August. It did not predict the new measure of seasonal hurricane activity of Maximum Potential Destruction (MPD). Table 1 shows the nine forecast parameters we used and the estimated amount of hindcast variance explained by this earlier 1 August scheme. Our hindcast skill for most parameters was between 50-60 percent.

Table 1: List of nine predictors and amount of hindcast variance explained in our earlier (Gray et al. 1993) 1 August seasonal forecast scheme.

Predictors	Predictants	Hindcast Amount of Variance Explained
1. QBO 50 mb U	NS	0.447
2. QBO 30 mb U	NSD	0.608
3. Ab. Shear of 50-30 mb U	H	0.472
4. Western Sahelian Rainfall (June-July)	HD	0.505
5. Gulf of Guinea (Aug-Nov of previous year)	IH	0.586
6. SLPA - June-July	IHD	0.540
7. ZWA - June-July	HDP	0..549
8. SOI - June-July	NTC	0.581
9. SSTA - June-July for Nino 3		

Newer analysis has shown that this nine parameter scheme likely leads to an exaggeration of our true forecast skill when applied to future (and independent) data sets.

This forecast degradation made it desirable that we make new studies of ways in which we might reduce our number of predictors and still retain or improve our hindcast skill.

Newer Forecast Scheme. We have now developed a second and improved 1 August forecast scheme which includes three new and important physical predictors. This new forecast scheme also employs an improved statistical approach which chooses the best predictors from a large pool of known precursor signals. We order our predictors by the amount of added forecast skill which each contributes. This new scheme adopts a regression procedure which chooses the best 1, 2, 3, 4, 5, 6, etc. predictors from a pool of 12 predictors shown in Table 2. This new prediction scheme has allowed us to reduce our number of predictors from nine to four to seven. This reduces the forecast shrinkage when applied to independent data. Other improvements involve the optimizing of our forecasts to include hurricane activity occurring only after 1 August and the use of 46 rather than 41 years in the developmental data set. We are confident that this newer prediction scheme is superior to our earlier scheme which we developed four years ago.

Table 2: Listing and description of the pool of twelve potential 1 August predictors. See Fig. 1 for the location of these predictors.

1 = U_{50}	July to August extrapolated September QBO zonal winds at 50 mb near 10°N in m/s
2 = U_{30}	July to August are extrapolated September QBO zonal winds at 30 mb near 10°N in m/s
3 = AS	absolute value of the extrapolated vertical wind shear between 50 and 30 mb
4 = R_S	Western Sahel June-July precipitation in Standard Deviation (S.D.),
5 = R_G	previous year August to November precipitation in the Gulf of Guinea region,
6 = SSTA	June-July Sea Surface Temperature Anomaly in Nino 3.4 of West Pacific,
7 = ZWA	June-July Zonal Wind Anomaly in the lower Caribbean basin,
8 = SLPA	June-July Sea Level Pressure Anomaly from five lower Caribbean basin stations,
9 = Δ T	West African anomalous east-west temperature gradient deviation in February through May in S.D.
10 = ONR	Previous year October-November SLPA of eastern Atlantic subtropical ridge (see Fig. 1)
11 = MATL	Eastern Mid-Atlantic SSTA - see Fig. 1.
12 = TATL	Tropical Atlantic SSTA - see Fig. 1.

Table 3 provides details of the various predictors chosen for each of the different forecast measures of activity (NS, NSD, H, etc.). Some predictors (such as Gulf of Guinea rainfall, 30 mb zonal winds) are selected for nearly every predicted measure of activity, while other predictors (such as SLPA, ΔT) are only selected by one or two of our forecast equations. Table 3 also lists the hindcast measure of agreement or amount of variance explained. Note that for HDP, NTC and MPD we are able to explain nearly two-thirds of the hindcast variance.

Table 3: Details of a new 1 August forecast scheme utilizing a variable number of predictors in order to maximize the forecast skill or measure of hindcast variance explained while limiting the number of predictors.

Forecast Parameter	No. of Predictors	Hindcast Measure of Agreement	Predictors
Named Storms (NS)	5	.534	U_{50} U_{30} R_g MATL ONR
Named Storm Days (NSD)	4	.569	U_{50} R_g MATL ONR
Hurricanes (H)	5	.538	U_{50} U_{30} R_g MATL ONR
Hurricane Days (HD)	6	.625	U_{30} R_g SLPA MATL TATL ONR
Intense Hurricanes (IH)	7	.641	U_{30} R_g ΔT ZWA SSTA3.4 MATL TATL
Intense Hurricane Days (IHD)	4	.614	R_g SLPA MATL TATL
Hurricane Destruction Potential (HDP)	6	.673	U_{30} R_g SLPA MATL TATL ONR
Net Tropical Cyclone Activity (NTC)	4	.662	U_{50} U_{30} R_g MATL
Maximum Potential Destruction (MPD)	4	.654	U_{30} R_g MATL ONR

A new aspect of our research is a thorough study of the anticipated statistical forecast skill reduction which occurs when a dependent data sample (such as the historical hurricane information of 1950-1995 used to develop our hindcast equations) is applied to independent data sets such as the forthcoming 1996 season. This process has been discussed in recent papers by Mielke et al. (1996, 1997). We plan future research on this topic. Anticipated forecast skill reduction (or skill "degradation") from that obtained in the developmental data set is known to be more of a problem when the number of predictors is large and the number of years of developmental data is small.

Table 4 presents the expected forecast skill degradation due to the forecast application of our scheme to independent data. As we gain more years of developmental data sets (now 46) and, as we reduce the number of variables, the amount of estimated real forecast skill, although impossible to determine in an individual year, should not undergo undue reduction. Note that our independent or degraded forecast skill is substantial, explaining over 47 1/2 of the variance for six of our nine predictors. The right column of Table 4 shows the improvement of our independent forecast skill with the use of our newer scheme in comparison with the older one.

Table 4: Hindcast skill and independent forecast skill for our newer 1 August forecast.

	Full Set of Predictors			
Forecast Parameter	Hindcast Skill	No. of Predictors	Expected Independent Fcst Skill	Improvement of Newer Minus Older Independent Fcst Skill
NS	.534	5	.360	.280
NSD	.569	4	.415	-.004
H	.538	5	.366	.167
HD	.625	6	.482	.224
IH	.641	7	.499	.112
IHD	.614	4	.475	.159
HDP	.673	6	.543	.213
NTC	.662	4	.536	.157
MPD	.654	4	.526	—

4 Forecast Parameters for 1 August 1996 Prediction

The following are our measurements of after 1 August predictors. We have utilized meteorological data through July.

4.1 QBO

Tables 5 and 6 show the absolute and relative (anomalous) values of the current and extrapolated 30 mb (23 km) and 50 mb (20 km) stratospheric QBO zonal winds near 11 to 13°N latitude during the primary hurricane period of August through October 1996. These estimates are based on a combination of the current trends in the QBO winds plus the annual wind cycle variations for the low latitude stations of 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 winds will be from a relative easterly direction and hence will be a suppressing influence upon this year's hurricane activity.

4.2 ENSO

Sea surface temperature anomaly (SSTA) conditions (in °C) in Nino-1-2, 3, 3.4 and 4 as well as the SOI values since April 1996 are shown in Table 7. Weak cold water conditions are present. This should be a weak enhancing influence on this year's hurricane activity.

Table 5: March through October 1996 observed and extrapolated absolute values of stratospheric QBO zonal winds (U) in the critical latitude belts between 11-13°N as obtained from the Caribbean stations of 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	−21	−27	−31	−31	−32	−33	−30
50 mb (20 km)	+8	+4	−6	−12	−15	−21	−20	−18

Table 6: As in Table 5 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)	−12	−13	−14	−14	−13	−15	−15	−13
50 mb (20 km)	+8	+5	0	+−2	−3	−7	−10	−11

Table 7: April through July Niño area sea surface temperature anomalies in °C along with the Tahiti minus Darwin (SOI) surface pressure difference in S.D.

	Apr	May	June	July
Nino-1-2	−1.6	−0.9	−1.1	−1.4
Nino-3	−0.2	−0.5	−0.4	−0.2
Nino-3.4	−0.3	−0.3	−0.2	0.0
Nino-4	−0.4	−0.2	−0.1	−0.1
SOI	0.5	0.0	1.3	0.8

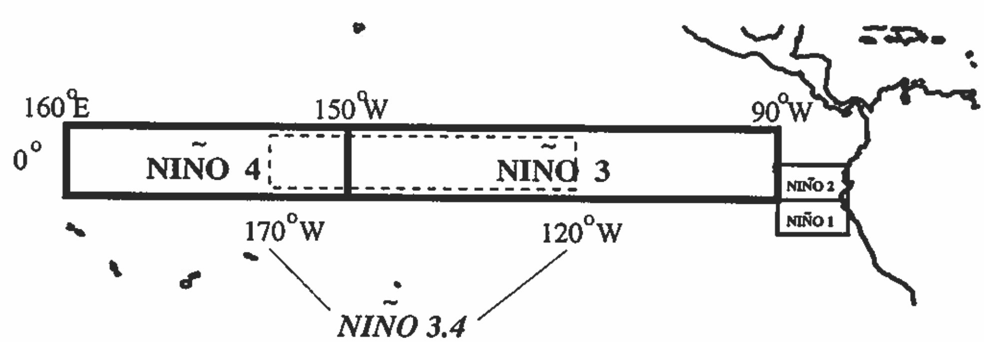

Figure 4: Equatorial Pacific sea surface temperature anomaly indices (°C) for the areas indicated.

4.3 West African Rainfall (AR)

Western Sahel June-July rainfall conditions indicate weak drought conditions. Although below normal, we expect that these weak drought conditions will not be a strong inhibiting influence on Atlantic intense hurricane activity during 1996. June-July 1996 rainfall in the Western Sahel averaged –0.6 S.D. below the 1950-1990 average. June-July rainfall represents only 36 percent of the average June-September rainfall which falls in the Western Sahel. Hence, we expect Western Sahel rainfall conditions to pick up in the months of August and September but to still average slightly below the long term mean.

4.4 West Africa Δ T

There has been no change in these conditions since our early June forecast — –0.3 SD. This indicates a slight suppressing influence on hurricane activity.

4.5 SLPA and ZWA

Two Caribbean parameters which contribute to the early August hurricane forecast are Caribbean Basin Sea Level Pressure Anomalies (SLPA) and 200 mb (12 km) Zonal Wind Anomalies (ZWA). The June-July 1996 five-station tropical (Trinidad, Barbados, Curacao, San Juan and Cayenne) SLPA's were above average (+ 0.6 mb). A second six-station surface pressure average made up of Brownsville, Miami, Merida (Yucatan), San Juan, Barbados, and Trinidad gives a pressure anomaly for June-July of +0.3 mb. These higher pressures should be a suppressing influence on this year's hurricane activity.

The five-station June-July (Trinidad, Curacao, Barbados, Kingston and Balboa) ZWA values were also negative –1.4 m/s indicating the lack of El Niño influence. These two June-July measurements indicate a slight enhancing influence on this year's hurricane activity.

These SLPA and ZWA measurements (see Table 8), though somewhat mixed, are indicative of the near average hurricane activity we expect for this season.

Table 8: April through July 1996 Sea Level Pressure Anomaly (SLPA) and Zonal Wind Anomaly (ZWA).

	April	May	June	July
5-Station SLPA of Tropical Average (mb)	0.9	1.3	0.6	0.6
6-Station SLPA of Tropical and Sub-Tropical Average (mb)	0.8	1.2	0.1	0.5
5-Station Zonal Wind Anomaly (ZWA) (m/s)	–0.7	–0.7	1.8	–4.6

4.6 Atlantic Ocean Predictors

October-November Ridge (ONR). The 1995 October-November SLPA between 20-30°W of the northeast Atlantic subtropical anticyclone (see Fig. 1b) was quite low, –1.84 S.D. This indicates the likelihood of more hurricane activity this year.

Middle ATLantic SSTA (MATL). April through June 1996 SSTA for this area is +0.17°C. This indicates a slight enhancement of this season's hurricane activity.

Tropical ATLantic SSTA (TATL). April through June 1996 SSTA for this area was 0.22°C, indicating a slight enhancement of this season's activity.

4.7 Summary of After 1 August Predictors

Table 9 lists the pool of thirteen 1 August predictors from which we choose our best predictors for both the older and newer scheme.

Table 9: Listing of 1 August 1996 predictors.

U_{50}	–20 m/s
U_{30}	–33 m/s
AS	13 m/s
R_s	–0.60 SD
R_g	0.10 SD
Δ T	–0.3 SD
SLPA	0.6 mb
ZWA	–1.4 m/s
SOI	1.3 SD
SSTA	–0.08 °C
ONR	–1.84 SD
MATL	0.17°C
TATL	0.22°C

5 1996 Forecast for Post 1 August Activity and Total Season Activity

Table 10 lists both our older and newer quantitative forecasts for post 1 August hurricane activity. Because of the hurricane activity which has already occurred (before 1 August), a slightly below average amount of activity is being forecast after 1 August. This suggests that the total seasonal activity for 1996 is likely to be near the climatological average. During average seasons, approximately 85 percent of named storms, 91 percent of hurricanes and 98 percent of intense hurricanes occur after 1 August. The last column on the right gives our qualitatively adjusted post 1 August forecast. Note that our new post 1 August forecast scheme is very close to that specified by climatology.

Discussion. Our earlier forecast scheme did not include the two new predictors of SSTA and October-November surface pressure anomaly of the eastern Atlantic subtropical ridge. We have found these to be powerful predictions. All three of these predictors indicate greater hurricane activity will occur in 1996. This is the primary reason why our newer forecast scheme calls for more hurricane activity. Our analysis of the six analog years with similar 1 August predictors also helps to verify the likelihood of our newer scheme giving a superior forecast of after 1 August 1996 activity.

Table 11 shows the activity before 1 August and our forecast of after 1 August activity. The last column gives our total seasonal forecast. These total seasonal numbers are very close to climatology.

Table 12 compares this early August forecast with our earlier 30 November 1995, 4 April 1996 and 6 June 1996 forecasts. All three of our previous forecasts anticipated about an average 1996

Table 10: Summary of older (for the whole season) and newer scheme (after 1 August activity) forecasts of after 1 August activity.

Forecast Parameter	Original (Gray et al. 1993) Whole Season Forecast	Post 1 Aug Newer Statistical Scheme	After 1 Aug Climatology	Qualitative Adjusted After 1 Aug Forecast
Named Storms (NS)	7.19	8.06	7.8	8
Named Storm Days (NSD)	21.90	43.07	41.1	37
Hurricanes (H)	3.83	4.85	5.1	5
Hurricane Days (HD)	7.02	18.24	21.4	19
Intense Hurricanes (IH)	0.98	1.63	2.0	2
Intense Hurricane Days (IHD)	-1.30	3.57	4.4	3
Hurricane Destruction Potential (HDP)	15.99	52.49	64.4	54
Net Tropical Cyclone Activity (NTC)	52.72	73.20	86.0	74
Maximum Potential Destruction (MPD)	—	59.48	57.1	49

Table 11: After 1 August forecast of hurricane activity based on a variable number of predictors, the activity which occurred before 1 August and total seasonal hurricane activity we expect in 1996.

Forecast Parameter	Activity Before 1 August	After 1 August Adjusted Forecast	1996 Total Seasonal Forecast
Named Storms (NS)	3	8	11
Named Storm Days (NSD)	13	37	50
Hurricanes (H)	2	5	7
Hurricane Days (HD)	6	19	25
Intense Hurricanes (IH)	1	2	3
Intense Hurricane Days (IHD)	1	3	4
Hurricane Destruction Potential (HDP)	16	54	70
Net Tropical Cyclone Activity (NTC)	31	74	105
Maximum Potential Destruction (MPD)	16	49	65

hurricane season. This table also expresses each parameter in this adjusted forecast as a percentage of the last 45-year average.

Table 13 compares this year's forecast seasonal activity with the amount of hurricane activity which occurred during past years. The 1996 season is expected to be much more active than the four hurricane seasons of 1991-1994 as well as more active than most of the hurricane seasons since 1970. It is expected that the 1996 hurricane season will be considerably less active than last year.

Table 12: Comparison of the current early August total seasonal predictions versus climatology as well as the forecasts for 1996 issued 30 November 1995, 4 April 1996 and early June 1996.

Forecast Parameter	Earlier Forecasts 30 Nov 95 Fcst	4 Apr 95 Fcst	7 Jun 96 Fcst	Current Total Season 7 August Fcst	7 August Fcst Total Season Fcst in % of 1950-1990 Average
Named Storms (NS)	7	11	10	11	118
Named Storm Days (NSD)	40	55	45	50	108
Hurricanes (H)	5	7	6	7	123
Hurricane Days (HD)	20	25	20	25	109
Intense Hurricanes (IH)	2	2	2	3	143
Intense Hurricane Days (IHD)	5	5	5	4	89
Hurricane Destruction Potential (HDP)	50	75	60	70	103
Net Tropical Cyclone Activity (NTC)	85%	105%	95%	105%	105
Maximum Potential Destruction (MPD)	55	75	60	65	105

Table 13: Comparison of total season early August 1996 seasonal prediction with activity in previous years.

	7 Aug Forecast 1996	Observed 1995	1994	1993	Average Season 1970-87	Average Season 1950-69	Ave. (1950-90)
Hurricanes (H)	7	11	3	4	4.9	6.5	5.7
Named Storms (NS)	11	19	7	8	8.3	9.8	9.3
Hurricane Days (HD)	25	62	7	10	15.5	30.7	23.0
Named Storm Days (NSD)	50	121	28	30	37.3	53.4	46.1
Hurr. Dest. Pot. (HDP)	70	172	15	23	42.7	100.0	68.1
Intense Hurricanes (Cat. 3-4-5) (IH)	3	5	0	1	1.6	3.4	2.1
Intense Hurricane Days (IHD)	4	11	0	0.75	2.1	8.8	4.5
Net Tropical Cyclone Activity (NTC)	105%	243%	37%	55%	73%	123%	100%

5.1 Forecast Confidence Limits

Table 14 lists our total seasonal forecast along with 25 and 75 percent confidence limits. These values are based on the spread of observed versus predicted forecasts during 1950-1995. For instance, our statistical analysis shows that there is a 50 percent probability that we will have between 10.3 and 12.0 named storms this year. There is also a 25 percent probability that we will have more than 12 named storms or less than 10.4 named storms.

Table 14: Our current forecast along with its 50 percent confidence limits. These limits are based on the observed spread of observed versus predictor hindcasts during 1950-1995.

	Lowest 25% Below	Best Seasonal Forecast	Highest 25% Above
NS	10.3	11	12.0
NSD	46.7	50	57.3
H	6.4	7	8.2
HD	22.0	25	27.3
IH	2.7	3	3.4
IHD	2.7	4	4.6
HDP	64.5	70	86.1
NTC	92.6	105	119.3
MPD	57.1	65	78.5

5.2 Relevance of Prior 1 August Tropical Cyclone Activity

The early season of 1996 has been above average, including three named storms and two hurricanes (Bertha and Cesar). There have been ten previous years (1966, 1968, 1959, 1944, 1936, 1934, 1933, 1926, 1916, 1908) when two or more hurricanes formed before 1 August. While many of these years continued having active August through November hurricane seasons, more than half had August through November activity which were below average. Thus, hurricane activity before 1 August has no correlation with later season hurricane activity. Some of the most active hurricane seasons, such as 1961, didn't experience their second hurricane until September and there have been many active seasons when no hurricane activity occurred until after the middle of August.

Our forecast of about an average 1996 hurricane season is not based on the amount of early season activity which occurred this year. It is based on the measured atmospheric and oceanic parameters, which, in the past years have been associated with after 1 August hurricane frequency.

6 Analog Years to 1996

Since 1950 there have been six years during which the conditions of most of our 1 August hurricane prediction parameters were similar to what is observed for 1996. The analog years for 1996 include 1954, 1956, 1970, 1974, 1979, 1989. Each of these six analogs had nearly identical easterly phase stratospheric QBO wind conditions. Most of these six years also had similar ENSO, African rainfall, and other features. Table 15 shows ten of our pool of primary forecast parameters for these six analog years. Note how close their average values are to the 10 early August forecast values for 1996. Table 16 shows values for the nine 1 August seasonal hurricane parameters were during each of these six analog to 1996 years. Note how the six-year average value of each of these parameters are close to this year's early August forecast. Our forecast for 1996 is higher in some categories than for the six analog years. This is a consequence of the SLPA, ZWA and African rainfall indicating higher activity than that of the average analog years. It is gratifying that these analog years, particularly for the expected activity after 1 August, generally agree with and lends confidence to our current forecast.

7 Verification of 1996 Forecasts

We will issue a verification of this year's 1996 seasonal hurricane forecast via the World Wide Web and e-mail on 26 November 1996.

Table 15: Atlantic basin 1 August forecast parameters in six prior years that were similar to the 1 August forecast parameters for 1995.

Year	50mb	30mb	R_g	MATL SSTA	ONR	TATL SSTA	Nino3.4 SSTA	SLPA	ZWA	Rs
	m/s	m/s	SD	degC	mb	degC	degC	mb	m/s	SD
1954	–22	–32	–.14	.08	.14	.00	–.49	–0.8	–3.0	–.14
1956	–17	–28	.43	–.11	–2.42	–.11	–.49	0.2	–0.7	.08
1970	–14	–24	–.30	–.19	–.90	.34	–.49	–0.1	–2.1	–.30
1974	–13	–27	.45	–.60	–.17	–.73	–.27	0.4	2.8	–.43
1979	–17	–27	–.72	–.15	.62	.36	.13	0.4	–3.6	.40
1989	–14	–27	.36	.40	–1.51	–.32	.00	0.6	0.5	.47
Ave.	–16.1	–27.5	0.01	–.02	–.71	–0.08	–0.27	0.1	–1.0	.01
1 Aug Fcst Parameters	–20	–33	.10	.17	–1.84	0.22	–0.08	0.6	–1.4	–0.6

Table 16: After 1 August Atlantic basin tropical cyclone activity which occurred during six previous analog years when our 1 August forecast parameters were similar to the 1 August forecast parameter of the prior analog years.

Year	NS	NSD	H	HD	IH	IHD	HDP	NTC	MPD
1954	9	44	7	27	2	8.50	84	116	60
1956	6	27	3	12	2	2.25	38	60	41
1970	8	19	4	7	2	1.00	17	55	51
1974	7	32	4	14	2	4.25	46	75	50
1979	5	38	4	21	2	5.75	72	84	53
1989	8	60	6	31	2	9.75	106	124	71
Ave.	7.2	36.7	4.7	20.3	2	5.25	58.8	85.7	54.3
Newer Scheme Fcst	8.06	43.08	4.85	18.24	1.63	3.57	52.49	73.19	59.48

8 Prospects for Increased Landfalling Major Hurricanes in Coming Decades

There has been a significant lull in the incidence of intense category 3-4-5 hurricanes striking the US East Coast, Florida and Caribbean basin (except for 1995) during the last 25 years. We see this trend as a natural consequence of the slowdown in the Atlantic Ocean (thermohaline) Conveyor Belt circulation which appears to be associated with a long list of concurrent global circulation changes during the last quarter century. These include the Sahel drought, increased El Nino activity, Pacific and Atlantic middle latitude zonal wind increases among numerous other changes. Both historical and geological (proxy) records indicate that this lull in major hurricane activity will not continue indefinitely; the return of increased major landfalling hurricane activity should be expected within the next decade or so. More research on the causes and the likely timing of this change-over to decades long period of increased intense hurricane activity is desperately needed. Increased intense hurricane activity striking US coastal areas is an assured threat to the US much more so than earthquakes, greenhouse gas warming and other environmental problems which are receiving comparatively much greater attention.

Changes in the North Atlantic. We may now be seeing the early stages of a transition to enhanced Atlantic thermohaline (Conveyor Belt) circulation from a recent three decade long slowing. There are reports of decreased ice flow through the Fram Strait (the North Atlantic passage between Greenland and Spitzbergen) which thereby, reduces the introduction of fresh water leading to increased surface salinity values in the North Atlantic. Recent observations report increased surface water salinity in the deep water formation areas of the North Atlantic during the recent years. Rising salinity increases water density. Chilling of high salinity surface water then creates very dense water which is able to sink to great depth, thereby causing increased equatorward flow of deep water and engendering a northward flow of warm near surface replacement water; hence - the Atlantic Ocean conveyor. A strong conveyor increases North Atlantic water temperatures and thus transports more heat to high latitudes.

The salinity values in the North Atlantic have been steadily rising over the last 15 years and recent deep water observations in the North Atlantic reveal that fairly stagnant water has been present for a decade or more. The surface salinity increases that are now being measured in the North Atlantic will likely lead to greater Atlantic Ocean thermohaline circulation in the next few years. Presuming this occurs, we anticipate a concurrent general increase in West African Sahel rainfall, a decrease in Atlantic summertime upper tropospheric westerly winds over the tropical Atlantic and, regarding the issue at hand, a likely multi-decadal long increase of Atlantic basin intense hurricane activity. These new regional North Atlantic measurements may thereby be an ominous sign of future increases of US and Caribbean basin hurricane landfalling activity.

Outlook for 1997. Barring the development of an El Niño event during the second half of next year (which we do not expect), it is likely 1997 will be an active hurricane activity. The QBO will be from the westerly direction (favorable) next year and the severe drought conditions in the Western Sahel (which have occurred over most of the last 25 years) appear to be dissipating. These trends enhance the prospects for increased levels of intense hurricane activity during 1997. Also, Atlantic SST and salinity patterns indicate the possibility of increased Atlantic Ocean thermohaline circulation which may also enhance 1997 hurricane activity over that expected for 1996.

9 Forthcoming Early December Forecasts of 1997 Hurricane, West African Sahel and ENSO Variability

We will be issuing 1997 seasonal forecasts of Atlantic basin hurricane activity, West African rainfall and the ENSO on 6 December 1996. These forecasts will be based on data through November 1996. Recent research has shown that we have almost as much extended range hurricane seasonal forecast skill by early December as we do for our later forecasts.

10 Cautionary Note

It is important that the reader appreciate that these seasonal forecasts are based on statistical schemes which, owing to their intrinsically probabilisetic nature, must fail in some years. Moreover, these forecasts do not specifically predict where within the Atlantic basin storms will strike. Regardless of whether 1996 should prove to be an average hurricane season or not, the probability exists that one or more hurricanes may strike along the US or Caribbean Basin coastline and do much damage.

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APPENDIX A - YEARLY LISTINGS OF NTC and MPD

Measures of seasonal tropical cyclone activity include seasonal totals for 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 activity indices are given at the beginning of this report. More detailed information is contained in Gray et al. (1992, 1994) and in Landsea (1993). In view of this complexity, 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:

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

where each of six of the percentage departure values from the long term means are used as component measures of seasonal activity. The resulting NTC value is useful as a measure of seasonal tropical cyclone activity because it combines most of the other tropical cyclone parameters of interest into a single index. There are many seasons during which a single parameter, as for example, the number of hurricanes, is not well representative of the actual character of the overall tropical cyclone activity for that year. This single NTC index has the highest forecast skill. Table 17 lists the values of NTC for 1950-1994.

Table 17: Listing of Seasonal Net Tropical Cyclone activity (NTC) values between 1950-1995.

Year	NTC (%)	MPD	Year	NTC (%)	MPD	Year	NTC (%)	MPD
1950	237	130	1965	85	38	1980	134	86
1951	119	80	1966	138	65	1981	112	70
1952	96	59	1967	96	54	1982	36	29
1953	119	81	1968	40	28	1983	31	22
1954	128	66	1969	154	120	1984	77	53
1955	195	103	1970	63	57	1985	109	73
1956	68	46	1971	94	72	1986	38	29
1957	84	46	1972	28	22	1987	47	28
1958	137	82	1973	51	39	1988	122	82
1959	97	59	1974	75	50	1989	135	78
1960	96	53	1975	91	65	1990	101	65
1961	218	106	1976	83	51	1991	59	43
1962	33	30	1977	46	44	1992	66	48
1963	115	61	1978	85	60	1993	53	33
1964	165	88	1979	94	59	1994	36	31
						1995	229	108

MAXIMUM POTENTIAL DESTRUCTION (MPD)

Maximum Potential Destruction (MPD) is computed as the seasonal total of the squared values of each cyclone's peak maximum wind. Squared wind velocities better indicate the amount of damage that tropical cyclones can inflict upon property than do the winds themselves (Landsea 1993). The previously utilized HDP includes a component of duration into a similar calculation, while this new MPD parameter is confined to the sum of the squared peak wind velocities and has no duration linked component. Values of NTC and MPD are given in Table 16.

APPENDIX B: Verification of All Past Seasonal Forecasts

The first author has now issued seasonal hurricane forecasts for the last 12 years. In most of the prior forecasts, predictions have been superior to climatology, which was previously the only way to estimate seasonal hurricane activity in advance (see Table 18). The eight late May and early June seasonal forecasts for 1985, 1986, 1987, 1988, 1991, 1992, 1994 and 1995 were more accurate than climatology. 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 processes associated with 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 incorporated Western Sahel rainfall estimates and we have developed a new Sahel rainfall prediction scheme. The failure of the 1993 seasonal forecast is attributed to our failure to anticipate the resurgence of El Niño conditions. In particular, the first 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 so long as the recent 1991-94 event. This failure motivated us to develop a new extended range ENSO prediction scheme, which is used as a quantitative first approximation of upcoming El Niño conditions.

Table 18: Verification of the authors' previous seasonal predictions of Atlantic tropical cyclone activity for 1984-1995.

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	11
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		21
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 of 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	66
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 of 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	22
Major Hurricanes (Cat. 3-4-5)		1	0	2
Major Hurr. Days		2	0	1.25

1992	Prediction of 26 Nov 1991	Updated Prediction of 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	39
Hurr. Destruction Potential(HDP)	35	35	35	51
Major Hurricanes (Cat. 3-4-5)	1	1	1	1
Major Hurr. Days	2	2	2	3.25

1993	Prediction of 24 Nov 1992	Updated Prediction of 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

1994	Prediction of 19 Nov 1993	Updated Prediction of 5 June	Updated Prediction of 4 August	Observed
No. of Hurricanes	6	5	4	3
No. of Named Storms	10	9	7	7
No. of Hurricane Days	25	15	12	7
No. of Named Storm Days	60	35	30	28
Hurr. Destruction Potential(HDP)	85	40	35	15
Major Hurricanes (Cat. 3-4-5)	2	1	1	0
Major Hurr. Days	7	1	1	0
Net Trop. Cyclone Activity	110	70	55	36

1995	Prediction of 30 Nov 1994	14 April Qualit. Adjust.	Updated Prediction of 7 June	Updated Prediction 4 August	Obs.
No. of Hurricanes	8	6	8	9	11
No. of Named Storms	12	10	12	16	19
No. of Hurricane Days	35	25	35	30	62
No. of Named Storm Days	65	50	65	65	121
Hurr. Destruction Potential(HDP)	100	75	110	90	173
Major Hurricanes (Cat. 3-4-5)	3	2	3	3	5
Major Hurr. Days	8	5	6	5	11.5
Net Trop. Cyclone Activity	140	100	140	130	229