SUMMARY OF 1996 ATLANTIC TROPICAL CYCLONE ACTIVITY AND VERIFICATION OF AUTHORS' SEASONAL PREDICTION

(A year of extensive hurricane activity associated with the combined effects of cool ENSO conditions, low values of Atlantic basin tropospheric wind shear and the apparent onset of a multi-decadal shift in Atlantic Ocean north to south sea surface temperature conditions. Large forecast underestimation.

(as of 26 November 1996)

(1997 Hurricane Forecast Will Be Issued on 6 December 1996)

By
William M. Gray,[1]
Christopher W. Landsea,[2]
John A. Knaff,[3]
Paul W. Mielke, Jr. and Kenneth J. Berry,[4]

(The forecast verified within is based on ongoing research by the authors, together with meteorological information through November 25, 1996)

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

Thomas Milligan, Media Representative for Colorado State University, (970-491-6432) is available to answer questions concerning this forecast

Department of Atmospheric Science
Colorado State University
Fort Collins, CO 80523

[1] Professor of Atmospheric Science
[2] NOAA/HRD Lab. Scientist, Miami, FL
[3] Advanced Ph.D. Student
[4] Professors of Statistics

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

MPD - Maximum Potential Destruction - A measure of the net maximum destruction potential during the season compiled as the sum of the square of the maximum wind observed 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.

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

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

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

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

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

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

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

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

SSTA(s) - Sea Surface Temperature(s) Anomaly(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 (ΔP) and west to east surface temperature (ΔT) gradients across West Africa.

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

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

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

ABSTRACT

This paper summarizes the tropical cyclone (TC) activity which occurred in the Atlantic Basin during 1996 and verifies the authors' seasonal forecast of this activity which was initially issued on 30 November of last year, with updates on 5 April, 6 June and 7 August of this year. The 1996 hurricane season was characterized by very high hurricane activity, particularly that activity associated with major hurricanes. There was a total of 13 named storms (average 9.3) and 9 hurricanes (average 5.8) which persisted for a total of 45 days (average is 24). There were 6 major (intense) hurricanes of Saffir/Simpson category 3-4-5 (average is 2.3 intense hurricanes) with 13 intense or major storm days (average is 4.7). The seasonal total of named storm days was 78 or, 167 percent of the long-term average. Net tropical cyclone (NTC) activity was 198 percent, twice the average of the last 45 years.

We underforecast this very active hurricane season. We had called for only an average or slightly above average activity based on prior season predictors which had worked in most past situations. But, 1996 was a special year. Factors favoring an active hurricane season include low values of Atlantic Basin tropospheric vertical wind shear, cool ENSO conditions, a late season change to lower surface pressure conditions and a continuing (since late 1994) long period basic shift in Northern and Southern Atlantic sea surface temperature conditions. This last condition has yet to be included in our forecast scheme. The broad Atlantic SST arrangement appears to be an important component in seasonal hurricane variability.

1 Introduction

The Atlantic basin, including the Atlantic Ocean, Caribbean Sea, and Gulf of Mexico, experience more season-to-season hurricane variability than any of the other global tropical cyclone basin. The number of Atlantic Basin 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 recent years there has been no objective methods 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. This research has lead us to the issuance of extended range forecasts of Atlantic Basin hurricane activity on 30 November 1995, with updates in early April, early June, and early August of each year.

2 Factors Known to be Associated With Atlantic Seasonal Hurricane Variability

Our various lead time forecasts are based on the current values of indices derived from various global and regional scale predictive factors which the authors have previously shown to be statistically related to seasonal variations of Atlantic Basin hurricane activity. Figure 1 provides a summary of the locations of the various forecast parameters which go into our different lead time forecasts. Our methodology statistically optimizes the predictive signals from these various forecast parameters. Predictors include:

(a) The stratospheric Quasi-Biennial Oscillation (QBO). The QBO refers to the variable east-west oscillating stratospheric winds which circle the globe near the equator. On average, there is

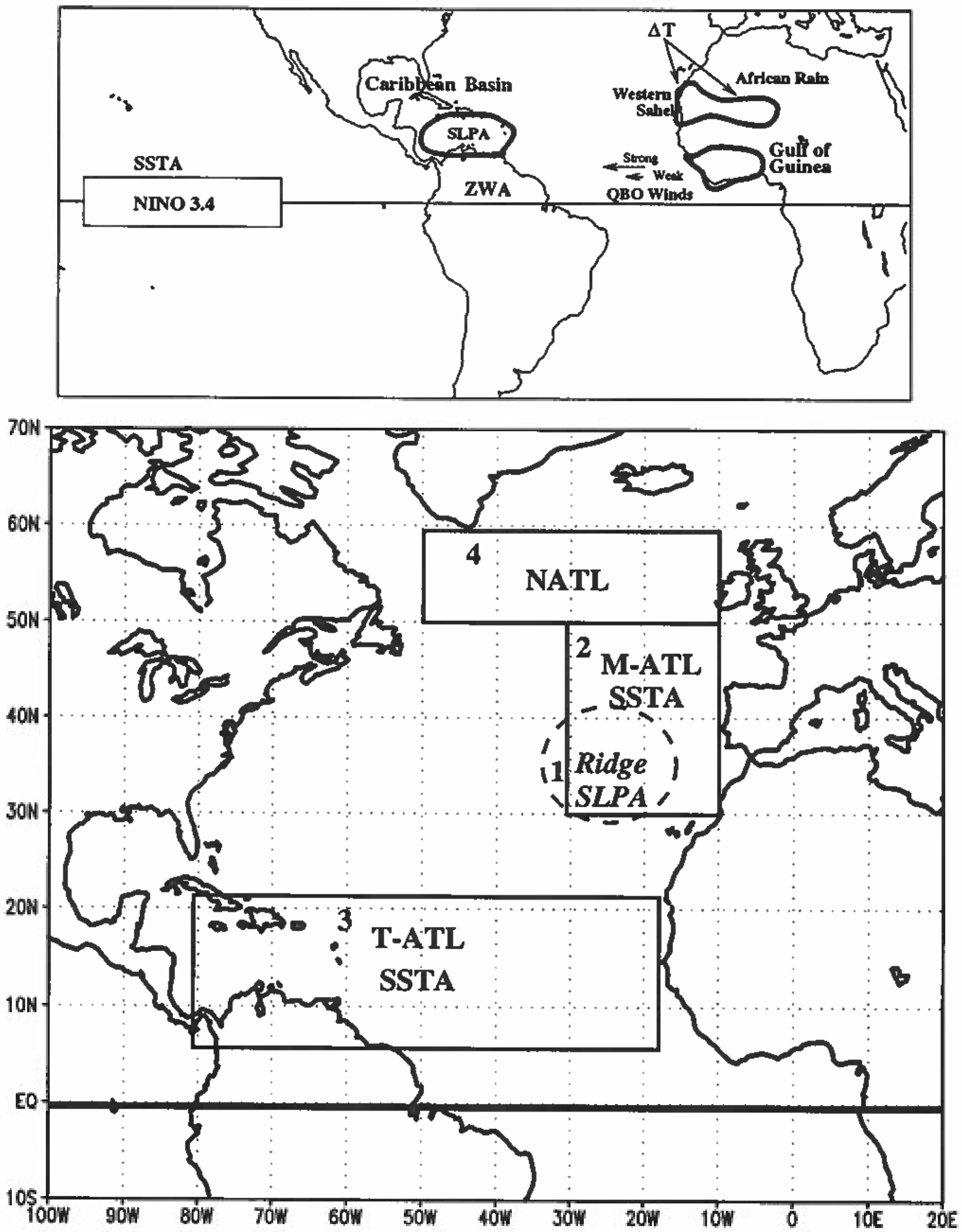

Figure 1: Source locations of meteorological parameters used in the seasonal forecasts. Symbols are defined on pages 3-5. The top diagram shows the locations of the global predictors. The bottom diagram shows the source locations for predictors in the Atlantic Ocean region.

nearly twice as much intense (category 3-4-5) Atlantic basin hurricane activity during those 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), the value of Tahiti minus Darwin surface pressure gradient, and the amount of equatorial deep convection near the Dateline. The effects of a moderate or strong El Niño event are to reduce Atlantic basin hurricane activity. By contrast, in those seasons with cold sea surface temperatures, high values of Tahiti minus Darwin surface pressure occur (La Niña years), and reduced deep equatorial convection near the Dateline is present, there is typically an enhancement of Atlantic basin hurricane activity.

(c) African Rainfall (AR): The incidence of intense Atlantic hurricane activity is enhanced during those prior years or season when June-September Western Sahel rainfall and previous year August-November Gulf of Guinea region have above average precipitation. Hurricane activity is typically suppressed if the rainfall of the prior year or season in these two regions is below average.

(d) Previous Year October-November and March northeast Atlantic Subtropical Ridge Strength (ONR). When this pressure ridge is anomously weak during the previous autumn and spring periods, the eastern Atlantic trade winds are weaker. This condition (weak ridge) which is related to a decrease in mid-latitude cold water advection and upwhelling off the northwest African coast as well as decreased evaporative cooling rates in this area of the Atlantic. A weak ridge 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 and spring ridge are anomalously high.

(e) Atlantic Sea Surface Temperature Anomalies (SSTA) in the three regions (MATL; 30-50°N, 10-30°N and TATL; 6-22°N, 18-82°W) during April through June and NATL; 50-60°N, 10-50°W and TATL during January through March: See Fig. 1 (bottom) for the location source 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): Spring and early summer 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): Anomalous west-to-east surface pressure and temperature gradients across West Africa from February through May are typically correlated with the hurricane activity which follows later in the year.

Our varying lead time forecast schemes are created by maximizing the pre-season forecast skill from a variety of the above predictors in combination.

3 Statistical Summary of 1996 Atlantic Tropical Cyclone Activity

The 1996 Atlantic hurricane season officially ends on 30 November. There were 9 hurricanes and 45 hurricane days during the 1996 season. The total named storms (or, the number of hurricanes plus tropical storms) was 13, yielding 78 named storm days. There were 6 major (or intense) hurricanes this season. All designated tropical cyclone activity parameters were much above the long term average. Figure 2 and Table 1 show the tracks and give statistical summaries, respectively, of the 1996 season. Table 2 characterizes 1996 seasonal tropical cyclone activity in terms of percentages of the 1950-1990 climatology. Note that all measures of seasonal hurricane activity were much above average. Table 3 shows a comparison of the 1996 hurricane season with 1995 and the average amount of hurricane activity for the seasons of 1991-1994. The hurricane seasons of 1995 and 1996 were much more active than the average 1991 through 1994 activity. Clearly, 1995 and 1996 represent a remarkable upsurge in hurricane activity.

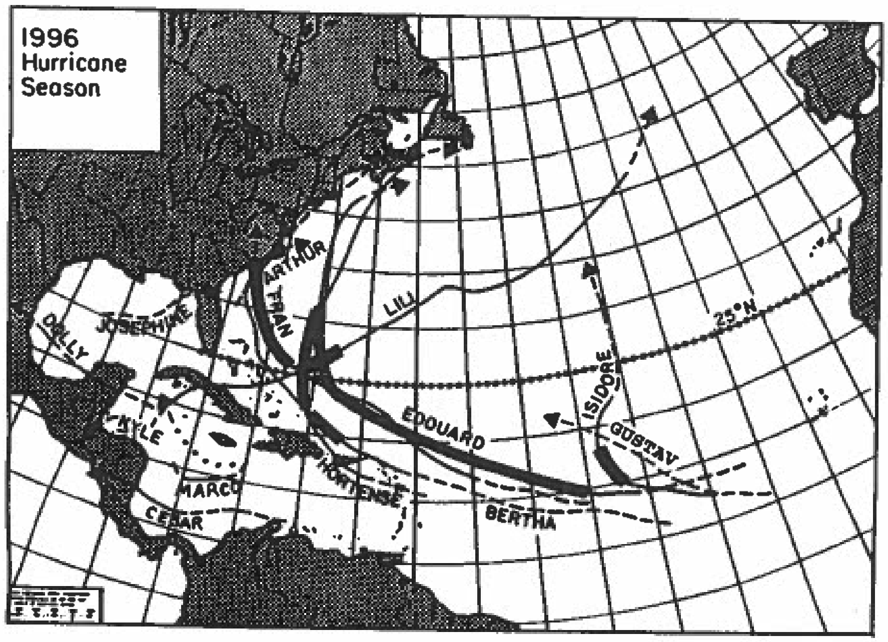

Figure 2: Tracks of the thirteen 1996 named tropical cyclones. Dashed lines indicate the tropical storm intensity stage, thin solid lines indicate the Saffir/Simpson hurricane category 1-2 stage, and thick lines show the intense hurricane category 3-4-5 hurricane stage. Note dots indicate depression stage in the case of Marco.

By all measures, the 1996 season was an active one. In the 47 years since 1950 there have been only:

- Five years (1950, 53, 69, 90, 95) with more named storms,
- Four years (1950, 55, 49, 95) with more named storm days,
- Three years (1950, 69, 95) with more hurricanes,
- Three years (1950, 61, 95) with more hurricane days,
- One year (1950) with more intense hurricanes,
- Two years (1950, 61) with more intense hurricane days,
- Three years (1950, 61, 95) with a higher HDP, and
- Three years (1950, 61, 95) with a higher NTC.

Although the hurricane activity numbers for 1996 are very high, the numbers of hurricanes and major hurricanes would have been less but if not for the intensity of a number of systems being only marginally included in a higher intensity category. Note in Table 1 that:

Table 1: Summary of information on named tropical cyclones occurring during the 1996 Atlantic tropical cyclone season. Information on Tropical Storm (TS), Hurricanes (H) and Intense Hurricanes (IH) with highest Saffir/Simpson category is shown. Information was supplied by courtesy of the National Hurricane Center.

	Named Storm	Peak Category	Dates of > = TD	Peak Sustained Wind	NSD	HD	IHD	HDP
1.	Arthur	TS	Jun 17-21	40kt	1.50	0	0	0
2.	Bertha	IH-3	Jul 5-14	100	9.00	5.50	0.50	13.9
3.	Cesar	H-1	Jul 24-28	75	3.50	1.00	0	1.9
4.	Dolly	H-1	Aug 19-25	70	3.75	0.50	0	0.9
5.	Edouard	IH-4	Aug 21-Sep 2	125	12.00	10.25	7.75	45.8
6.	Fran	IH-3	Aug 23-Sep 8	105	10.25	7.75	2.00	20.2
7.	Gustav	TS	Aug 27-Sep 2	40	4.50	0	0	0
8.	Hortense	IH-4	Sep 3-15	120	9.25	6.25	2.00	19.4
9.	Isidore	IH-3	Sep 24-Oct 2	100	6.25	3.75	0.50	10.5
10.	Josephine	TS	Oct 4-8	60	1.50	0	0	0
11.	Kyle	TS	Oct 11-12	45	0.75	0	0	0
12.	Lili	IH-3	Oct 15-27	100	11.00	9.50	0.25	21.6
13.	Marco	H-1	Nov 18-22;24-25	65	5.50	0.5	0	0
	Totals				78.75	45.0	13.00	135.0

Table 2: Summary of the 1996 seasonal hurricane in comparison with long term average conditions.

Forecast Parameter	1950–1990 Mean	1996	1996 in % of 1950-1990 Ave.
Named Storms (NS)	9.3	13	140
Named Storm Days (NSD)	46.6	78	167
Hurricanes (H)	5.8	9	155
Hurricane Days (HD)	23.9	45	188
Intense Hurricanes (IH)	2.3	6	261
Intense Hurricane Days (IHD)	4.7	13	277
Hurricane Destruction Potential (HDP)	71.2	135	190
Maximum Potential Destruction (MPD)	66.0	92	139
Net Tropical Cyclone Activity (NTC)	100	198	198

Table 3: Comparison of 1995 and 1996 seasonal hurricane activity with means for the recent 1991-1994 seasons.

	'96	'95	Four-year Ave. for 1991-1994
Hurricanes (H)	9	11	3.8
Named Storms (NS)	13	19	7.3
Hurricane Days (HD)	45	62	10
Named Storm Days (NSD)	78	121	29
Hurr. Dest. Pot. (HDP)	135	172	28
Intense Hurricanes (Cat. 3-4-5) (IH)	6	5	1.0
Intense Hurricane Days (IHD)	13	12	1.3
Net Tropical Cyclone Activity (NTC)	198%	237%	53%

- Cesar, Dolly and Marco just made hurricane intensity and were classified as hurricanes for only four, two and two six-hour time periods, respectively.
- Bertha, Isidore and Lili just attained the intensity of a category 3 hurricane. None of these three hurricanes ever became stronger than 100 kts (minimum speed to be classified as a major hurricane). Bertha and Isidore existed as intense hurricanes for only two and one 6-hour periods, respectively..

4 Contrast of 1993-1994 and 1995-1996 Hurricane Seasons

It is difficult to envisage hurricane seasons more different than 1993-1994 and 1995-1996. These contrasts are portrayed in Table 4. In terms of intense hurricanes and intense hurricane days the 1995-96 seasons had more than ten times the activity of 1993-94. This constitutes a remarkable upswing in hurricane activity. The overall combined hurricane activity for 1995 and 1996 was more than in any previous two consecutive years on record. Global and ocean circulation conditions in 1993-94 were very different from conditions during 1995-96. Table 5 shows some of these atmospheric and oceanic differences.

Table 4: Contrast of average hurricane activity during the seasons of 1993-94 and 1995-96.

	NS	NSD	H	HD	IH	IHD	HDP	MPD	NTC
1993-1994 Ave.	7.5	29	3.5	8.5	0.5	.37	19	32	49
1995-1996 Ave.	16	87	10	53.5	5.5	12.5	151	100	218
Ratio 1995-1996 to 1993-1994	2.1	3.0	2.9	6.3	11.0	33.8	7.9	3.1	4.4

5 Details and Specific Values for Predictors of the 1996 Hurricane Season

a) ENSO

An El Niño like warm water event began forming in the tropical Pacific in late 1989 and El Niño-like conditions persisted in a complicated and somewhat variable mode until the spring of 1995

Table 5: Comparison of environmental conditions during August-September 1995 and 1996 expressed as differences between the mean for 1993-1994.

Δ Caribbean Basin ZWA (m/s)	−7.2 m/s
Δ SLPA in Caribbean Basin	−1.37 mb
Δ Western Sahel Rainfall	0.24 S.D.
Niño-3 SSTA	−0.6°C
N. Atlantic minus S. Atlantic SST	0.8°C

at which time, an ongoing cooling finally began to emerge. This cooling has persisted during 1995 and 1996 and has been a primary contributing factor to the increased hurricane activity during this period. Table 6 provides a tabular summary of Niño-3 sea surface temperature anomaly (SSTA) conditions for the last four years.

Table 6: SSTAs (°C) in the equatorial Pacific of Niño-3 during the years of 1993-1996 and anticipated SSTA conditions through November 1997. Note cooling has been present since April 1995.

Niño3 (5°N to 5°S, 90-150°W)

Year	J	F	M	A	M	J	J	A	S	O	N	D
1993	0.1	0.3	0.8	1.2	1.7	0.8	0.3	0.0	0.3	0.4	0.3	0.3
1994	0.4	0.0	0.1	0.2	0.4	0.4	−0.2	−0.1	0.2	0.7	1.1	1.2
1995	1.0	0.7	0.2	−0.2	−0.4	−0.1	0.0	−0.5	−0.5	−0.6	−0.8	−0.7
1996	−0.4	−0.5	−0.1	−0.5	−0.4	−0.3	0.0	−0.2	−0.3	−0.2	−0.2	est.
1997	⟵		Expected to continue on the cool (La Niña) side								⟶	

Sea surface temperature anomaly conditions (in °C) in Niño-1-2, 3, 3.4 and 4 (see Fig. 3 for locations) as well as the SOI values since April 1996 are shown in Table 7. Weak cold water conditions were present. Even though the SSTs in the Niño-3 and Niño-4 region were not very cold, the Outgoing Longwave Radiation (OLR) values near the Dateline were quite low. This is also an important ENSO designator. The variety of cool ENSO conditions are judged to be an important enhancing influence on this year's hurricane activity.

Table 7: April through October 1996 Niño area sea surface temperature anomalies in °C along with the SOI in S.D.

	Apr	May	Jun	Jul	Aug	Sept	Oct
Niño-1-2	−1.6	−0.9	−1.1	−1.4	−1.0	−0.9	−0.8
Niño-3	−0.5	−0.4	−0.3	0.0	−0.2	−0.3	−0.2
Niño-3.4	−0.2	−0.2	−0.1	0.1	−0.1	−0.1	−0.2
Niño-4	−0.3	−0.2	0.0	0.0	0.1	0.1	0.1
SOI	0.6	0,1	1.0	0.6	0.4	0.6	0.4

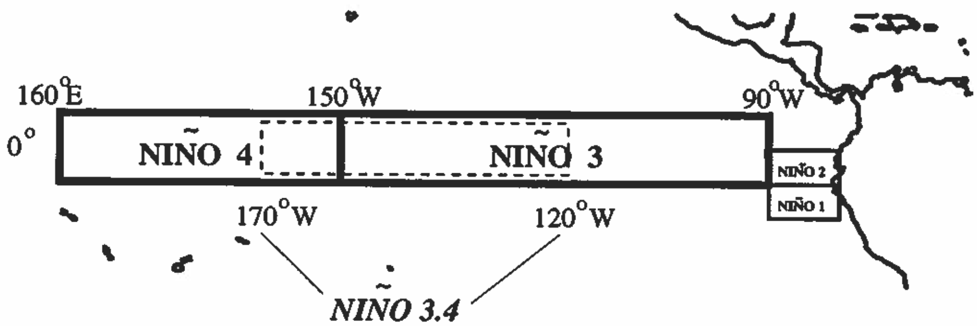

Figure 3: Equatorial Pacific sea surface temperature anomaly indices (°C) for the areas indicated. Note that Niño 3.4 is comprised of portions of Niño-4 and Niño-3.

b) Stratospheric QBO Winds

Tables 8 and 9 show both the absolute and relative (i.e., anomaly) values for 30 mb (23 km) and 50 mb (20 km) stratospheric QBO zonal winds near 12°N during March through October 1996. During the height of the 1996 hurricane season, QBO winds were from a relatively easterly direction. These QBO wind conditions should have been a suppressing influence on this year's hurricane activity. But they were not.

Table 8: Observed March through October 1996 observed 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} (as supplied by James Angell and Colin McAdie).

	Observed							
Level	March	April	May	Jun	Jul	Aug	Sept	Oct
30 mb (23 km)	–16	–21	–27	–31	–31	–26	–25	–22
50 mb (20 km)	+8	+4	–6	–12	–15	–20	–17	–15

Table 9: As in Table 8, but for the 1996 "relative" (or anomalous) zonal wind values wherein the annual wind cycle has been removed. Values are in ms^{-1}.

	Observed							
Level	March	April	May	Jun	Jul	Aug	Sept	Oct
30 mb (23 km)	–12	–13	–14	–14	–13	–8	–9	–8
50 mb (20 km)	+8	+5	0	+2	–3	–6	–7	–8

c) Sea-Level Pressure Anomaly (SLPA)

Table 10 gives information on regional Caribbean basin and Gulf of Mexico SLPA during the 1996 season. Note that all stations had above average SLPA during the months of April through August with a sharp and latter than expected change to lower SLPA conditions during September and October. Such mid-season changes usually do not occur.

d) Zonal Wind Anomalies (ZWA)

Table 10: Lower Caribbean basin SLPA for 1996 in mb (for San Juan, Barbados, Trinidad, Curacao and Cayenne) - top row and for the Caribbean-Gulf of Mexico. Brownsville, Miami, Merida (Mexico), San Juan, Curacao and Barbados - bottom row (as kindly supplied by Colin McAdie of NHC in combination with our CSU analysis).

	Apr	May	Jun	Jul	Aug	Sep	Oct
5-station Lower Caribbean Ave. SLPA	0.9	1.3	0.6	0.6	0.5	–0.2	0.1
6-station Caribbean plus Gulf of Mexico Ave. SLPA	0.8	1.2	0.1	0.5	0.5	–0.4	–0.5

Table 11 shows that the upper tropospheric (12 km or 200 mb) Zonal Wind Anomalies (ZWA) were negative in all months but June. These negative ZWA conditions were very important in explaining why the 1996 season was so active.

Table 11: 1996 Caribbean basin 200 mb (12 km) Zonal Wind Anomaly (ZWA) in ms^{-1} (as supplied by Colin McAdie of NHC and in combination with CSU data) for the four stations including Kingston (18°N), Curacao (12°N), Barbados (13.5°N), and Trinidad (11°N).

	April	May	June	July	August	September	October
Average ZWA	–0.7	–0.7	1.8	–4.6	–2.9	–0.4	–3.6

e) African Western Sahel Rainfall in 1996

African Western Sahel rainfall is a strong modulator of intense or category 3-4-5 hurricane activity. Typically, when many category 3-4-5 hurricanes form the Western Sahel is wet. This was not the case this year. Our measurements indicate that June through September 1996 Western Sahel rainfall was near average (–0.07 SD).

This Western Sahel and intense hurricane relationship has not shown a strong association in 1995 and 1996. We attribute this trend-like change in association to positive values of SSTA that have developed over the Equator south of the Gulf of Guinea area. Higher equatorial SSTA south of the Guinea Coast typically cause more rainfall over the Guinea area and less in the Sahel. We believe that this is the cause for the short term lack of close agreement between the Western Sahel rainfall and intense hurricane activity during 1995-1996.

6 Verification of Individual Lead Time Forecasts

Table 12 compares our various lead time forecasts for 1996 with their verification, while Table 13 provides a more detailed verification of our after 1 August forecast. All our forecasts underestimated the seasonal amounts of 1996 hurricane activity. We were particularly in error in our forecast on the number of intense hurricanes, of hurricane and intense hurricane days.

Table 12: Verification of our 1996 total seasonal hurricane predictions.

Forecast Parameter	1950-1990 Mean	Nov 30 1995 Fcst.	Apr 5 1996 Fcst.	Jun 6 1996 Fcst.	Aug 7 1996 Fcst.	1996 Observed Activity
Named Storms (NS)	9.3	8	11	10	11	13
Named Storm Days (NSD)	46.6	40	55	45	50	78
Hurricanes (H)	5.8	5	7	6	7	9
Hurricane Days (HD)	23.9	20	25	20	25	45
Intense Hurricanes (IH)	2.3	2	2	2	3	6
Intense Hurricane Days (IHD)	4.7	5	5	5	4	13
Hurricane Destruction Potential (HDP)	71.2	50	75	60	70	135
Maximum Potential Destruction (MPD)	66.0	55	75	60	65	92
Net Tropical Cyclone Activity (NTC)	100%	85%	105%	95%	105%	198%

Table 13: Verification of 7 August 1996 forecast for hurricane activity after 1 August.

Forecast Parameter	Climatology After 1 Aug	Forecast 1996 Activity After 1 Aug	1996 After 1 Aug Verification
Named Storms (NS)	7.8	8	10
Named Storm Days (NSD)	41.4	37	65
Hurricanes (H)	5.1	5	7
Hurricane Days (HD)	21.4	19	39
Intense Hurricanes (IH)	2.0	2	5
Intense Hurricane Days (IHD)	4.4	3	12
Hurricane Destruction Potential (HDP)	64.4	54	119
Maximum Potential Destruction (MPD)	61.7	49	78
Net Tropical Cyclone Activity (NTC)	86.0%	74%	167%

7 Reasons for Our Underforecast of 1996 Hurricane Activity

Obviously, we did not expect such an active 1996 hurricane season. The following discussion provides some justification for our underforecast.

- Most years following very active hurricane years (such as 1995) are observed to have below average activity. This is due to the strong biennial nature of Atlantic Basin hurricane activity. Table 14 shows the average annual hurricane activity in those years following the ten most active hurricane seasons (1887, 1893, 1906, 1916, 1926, 1933, 1950, 1955, 1961, 1969) during the last 120 years excluding 1995. Note how low the hurricane activity was in those years following very active years. Compare the years following those years having active seasons with what occurred in 1996 – after the very active 1995 season. The 1996 season had much more activity in each seasonal tropical cyclone category than any of the other ten years (1888, 1894, 1907, 1917, 1927, 1934, 1951, 1956, 1962 1970) following these most active hurricane seasons. The 1996 season was indeed a unique year.
- The stratospheric QBO was from the east this year. Hurricane activity is usually reduced in easterly QBO year. Table 15 compares seasonal hurricane activity in annual percent for those 18 years when the 30 mb QBO zonal winds were strongest from the east versus the activity during 1996. (During 1996 QBO winds were from a relatively easterly direction — Table 9). By this measure 1996 should have been much less active than it was observed to be.
- April through July Lower Caribbean Basin Sea Level Pressure Anomaly (SLPA) was quite high (average +0.85 mb). It is unusual to have such high amounts of hurricane activity in a year in which April through July surface pressure was so high.

It is important that the reader to appreciate that these seasonal forecasts are based on statistical schemes which, owing to their intrinsically probabilistic nature, will fail in some years. 1996 was one of these years.

Table 14: Average seasonal totals of named storms (NS), named storm days (NSD), Hurricanes (H), Hurricane Days (HD), Intense Hurricanes (IH), Intense Hurricane Days (IHD), Hurricane Destruction Potential (HDP), and Net Tropical Cyclone (NTC) activity in the years following the ten previous seasons of 1887, 1893, 1906, 1916, 1926, 1933, 1950, 1955, 1961, 1969) versus the seasonal totals for 1996. The ratio of active year to subsequent year activity are on the third line.

	NS	NSD	H	HD	IH	IHD	HDP	NTC
Ave. of Ten years Following Ten Most Active Seasons	7.3	38	4.2	17	1.2	2.2	49	83
1996 Season	13	78	9	45	6	13	139	198
Ratio 1996/Ave. of 10 Following Years	1.8	2.0	2.1	2.6	5.0	5.9	2.8	2.4

8 Large Number of Intense Hurricanes

Since 1950 and before this year (1996) there have been 14 seasons in which three or more intense (or major) hurricane occurred; these were 1950, 52, 53, 55, 58, 61, 64, 66, 69, 75, 81, 85, 88, 95. In all but one of these seasons (1958) stratospheric QBO winds were from the west. And 1958 had excessive amounts of Western Sahel rainfall (+1.83 SD above average). Further, in only three of these years (1981, 85, 95) was West African rainfall below average and in each of these

Table 15: Percentage of average Atlantic Basin tropical cyclone activity occurring during 18 years between 1950-1996 when the September QBO 30 mb zonal winds were from a relative easterly direction.

	NS	NSD	H	HD	IH	IHD	HDP	NTC
18 Easterly 30 mb QBO Wind Years	85%	78%	84%	75%	71%	80%	73%	78%
1996 With Easterly 30 mb	140%	167%	155%	188%	261%	277%	190%	198%
Ratio 1996 to Other Easterly QBO Years	1.6	2.1	1.8	2.5	3.7	3.5	2.6	2.5

years only slightly below average: 1981 (-0.27 SD), 1985 (-0.35 SD), 1995 (-0.20 SD). During June through September 1996 West African rainfall was observed to be –0.07 SD.

In none of these 14 prior years between 1950-1995 in which three or more intense hurricane occurred were April through July Caribbean Basin SLPA as high as 1996 (+0.85 mb). Ten of these 14 prior years had below average April-July SLPA. Four years have above average SLPA but not as high as 1996. These were 1961 (0.50 SD), 1975 (0.45 SD), 1985 (0.45 SD) and 1988 (0.05 SD).

Having QBO easterly wind conditions, above average April through July Caribbean Basin surface pressure and Western Sahel rainfall only average (–0.07 SD) made the likelihood very remote that this season would see the formation of six major hurricanes. In the last 47 years there has never been a season with QBO easterly winds that has had more than two major hurricanes except for 1958. And, those years in which Western Sahel June through September rainfall has been less than average there have never been more than three intense hurricanes.

The six intense hurricanes of this year (although three were just intense enough to be so classified) are quite anomalous. Nothing in our historical records indicate a hurricane season in which so many intense hurricanes could form with the pre-season predictive factors which we observed in 1996.

Given the above pre-active season measurements and the past years of evidence that suggest such pre-season conditions would result in reduced hurricane activity, it was not unwise for us to forecast anything but an average to slightly above average season. We will always follow sour data and its indication of past season associations.

9 Atlantic Surface Temperature Rearrangements and Multi-decadal Climate Change

We view our 1996 forecast underestimate in part as a consequence of a large and basic shift in the broadscale Atlantic Ocean south to north sea surface temperature patterns which we believe are associated with alterations of the Atlantic Ocean thermohaline circulation. This information was not contained in our forecast data sets. The North Atlantic surface temperatures have warmed and the South Atlantic surface temperatures have cooled since 1994. This is indicative of an increase in the Atlantic's thermohaline or conveyor belt circulation from its typical diminished strength of the last 25-30 years.

Since late 1994 there has begun a major rearrangement of the Atlantic Ocean SST features. This is illustrated by Fig. 4 which shows the change in Atlantic August-September-October SST conditions between 1994 and 1996. The SST changes shown in Fig. 4 are broadscale and are substantial in magnitude in comparison with the typical changes which take place between two year periods. We can better quantify these changes. Figure 5 defines broad ocean areas of SST measurements. There has been a general warming of the North Atlantic and a cooling of the South Atlantic during the last two years. We hypothesize that this is due to a major shift in the Atlantic Ocean thermohaline or conveyor belt circulation. This hypothesis is also consistent with a number of other global circulation feature changes that have occurred in the last 1-2 years. Figure

6 more explicitly shows this abrupt increase in North Atlantic minus South Atlantic SST change between 1994 and 1996. Though similar changes occurred during 1988 and 1989, no changes of this magnitude, roughly twice as large as 1988-89, have occurred since 1950.

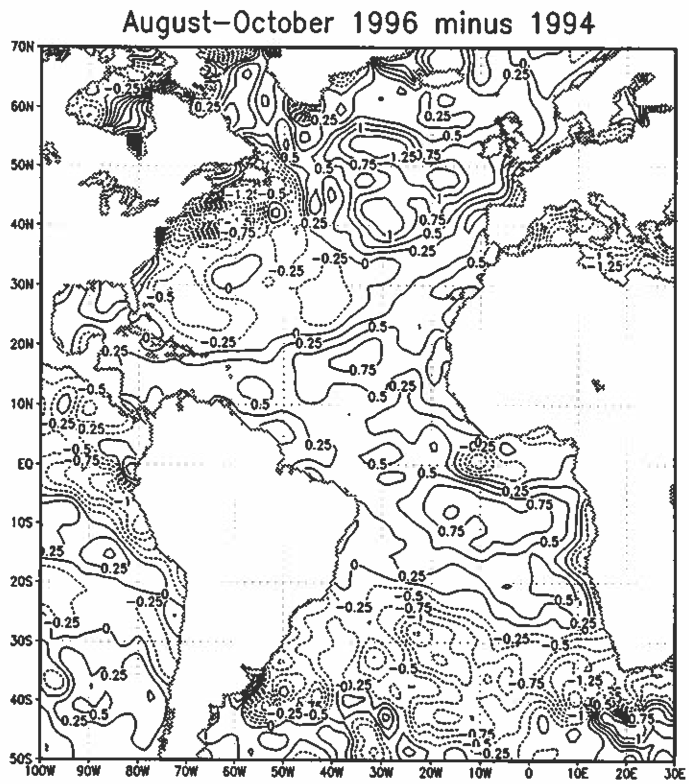

Figure 4: 1996 minus 1994 difference in sea surface temperature during the August through October period. Values in °C.

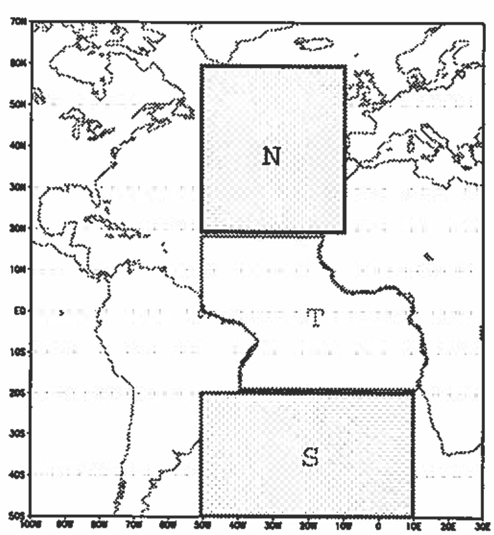

Figure 5: Areas of the Atlantic from which we average sea surface temperature anomalies.

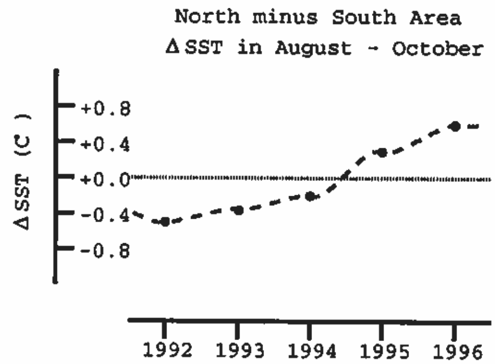

Figure 6: Difference in SST between north and south areas of Fig. 5 for the periods of August through October 1992 to 1996.

Apparently, we are now experiencing a major shift towards a stronger Atlantic Ocean thermohaline circulation. It has been nearly three decades since the SST anomaly patterns of the Atlantic Ocean were as strongly arranged with north to south SST differences as large as they now are. We expect that this changing Atlantic SST rearrangement patterns will lead to enhanced intense (or major) hurricane activity in coming years, somewhat similar to the conditions that we saw in the mid 1940s to mid-1960s. This will manifest itself in more low latitude forming hurricanes which will become more intense.

We attribute part of our underforecast of the 1995 and 1996 seasons to this basic shift towards a stronger thermohaline circulation. Such large ocean SST change features causing the North Atlantic warm and the South Atlantic cool were not contained in our predictive equations. Our seasonal forecast scheme is based on the premise that forthcoming hurricane seasons will be like those of past seasons with similar pre-season predictors. The developmental data set from which we established our forecast technique goes back to 1950. We have observed an opposite multi-decadal shift during which the North Atlantic cooled and the South Atlantic warmed during the late 1960s and early 1970s. Our forecast developmental data set has no record of an opposite multi-decadal shift back to a cool South Atlantic and warm North Atlantic. It appears that during 1995 and 1996 we are observing such a multi-decadal shift in thermohaline circulation. Historical and other inferential data have indicated that this sort of change has occurred many times prior to 1950.

We believe we are seeing the early stages of a transition to enhanced Atlantic thermohaline (Conveyor Belt) circulation from a three decade long slowing of circulation. There are reports of decreased ice flow through the Fram Strait (the North Atlantic passage between Greenland and Spitzbergen) which reduces the introduction of fresh water; thus 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. Rising salinity increases water density. Chilling of high salinity surface water then creates 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 appear to be leading to a stronger Atlantic Ocean thermohaline circulation

Our data sets of the last 46 years have shown a multi-decadal decrease in intense hurricane activity from the late 1960s to 1994. We believe that this is associated with a slow down of the North Atlantic thermohaline circulation during this period. This slow down resulted in the Northern Hemisphere Atlantic SSTs cooling and Southern Hemisphere Atlantic SSTs warming during these decades. Presuming that the opposite ocean circulation changes are now occurring, we anticipate a concurrent coming decade 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 North Atlantic SST change measurements may thereby be an ominous sign of future increases of US and Caribbean Basin intense hurricane frequency and landfalling. A new era of increased hurricane spawned destruction appears to be approaching.

10 The 1995-96 Hurricane Seasons and Global Warming

It is likely that some individuals will interpret the great upswing in 1995-96 hurricane activity as related in some way to increased man-induced greenhouse gases like carbon dioxide (CO_2). We do not agree with such an assessment. There is no reasonable way that such an interpretation can be made. Man-induced greenhouse gas warming, even if a physically valid hypothesis, is a very slow and gradual process that, at best would be expected to bring about only small changes in global circulation over periods of 50 to 100 years, not the abrupt and dramatic one to two year upturn in hurricane activity as has occurred between 1994 and 1995-1996. And, even if man induced greenhouse increases over the last 25 years were to be interpreted as causing global mean temperature increase during this period, there is no way to relate such small global temperature increases to intense Atlantic basin hurricane activity during this period. Atlantic intense (or category 3-4-5 hurricane activity) has shown a substantial decrease from the late 1960s to 1994 while the globe has apparently undergone a small mean temperature increase (Landsea et al. 1996). We interpret most of this global mean temperature increase as resulting from natural and not from man-induced influences. The large increase in 1995-96 Atlantic hurricane activity is no mystery. It was the result of natural variations in global atmospheric and oceanic circulations.

11 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 El Niño-Southern Oscillation (ENSO) on 6 December 1996. These forecasts will be based on data available to us 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. These forecasts will be disseminated on the World Wide Web.

12 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 also be an active hurricane season. The QBO will be from the westerly direction (favorable) next year and the severe drought conditions in the Western Sahel (which have occurred during most of the last 25 years) appears to have dissipated. And, as just discussed observations indicate the likelihood that the Atlantic Ocean SST patterns and the thermohaline circulation for next year will be more typical of conditions which occurred during the earlier period of the mid-1940s to the late 1960s. These trends enhance the prospects for continued high levels of hurricane activity during 1997. Should 1997 hurricane season prove to be only an average activity season, then the three years of 1995-96-97 will have been the most active three consecutive hurricane years on record.

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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 1950-1996. 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 previously was the only

Table 16: Listing of Seasonal Net Tropical Cyclone activity (NTC) values between 1950-1996.

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
						1996	198	92

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 17: 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