SUMMARY OF 1998 ATLANTIC TROPICAL CYCLONE ACTIVITY, VERIFICATION OF AUTHORS' SEASONAL ACTIVITY PREDICTION

A year of above average hurricane activity (which was underforecast) and of unprecedented tropical cyclone-spawned destruction in the Caribbean and seven named storms impacting the US

(as of 25 November 1998)

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

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SUMMARY OF 1998 SEASONAL FORECASTS AND VERIFICATION

Tropical Cyclone Seasonal Parameters (1950-90 Ave.)	Forecasts 5 Dec 97 Forecast	7 Apr 98 Forecast	5 Jun 98 Forecast	6 Aug 98 Forecast	Observed Totals
Named Storms (NS) (9.3)	9	10	10	10	14
Named Storm Days (NSD) (46.9)	40	50	50	50	80
Hurricanes (H)(5.8)	5	6	6	6	9
Hurricane Days (HD)(23.7)	20	20	25	25	47
Intense Hurricanes (IH) (2.2)	2	2	2	2	3
Intense Hurricane Days (IHD)(4.7)	4	4	4	5	9
Hurricane Destruction Potential (HDP) (70.6)	50	65	70	75	142
Maximum Potential Destruction (MPD) (61.7)	55	65	65	65	110
Net Tropical Cyclone Activity (NTC)(100%)	90	95	100	110	172

Colorado State University Hurricane Forecast Team

Front Row - left to right: John Knaff, Bill Gray, Paul Mielke, Rick Taft. Back Row - left to right: Bill Thorson, Chris Landsea, John Sheaffer and Ken Berry and Todd Kimberlain (missing from photo).

DEFINITIONS

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

ABSTRACT

This report summarizes tropical cyclone (TC) activity occurring in the Atlantic Basin during 1998 and verifies the authors' seasonal TC activity forecasts initially issued on 5 December 1997, with updates on 7 April, 5 June and 6 August of this year. The 1998 hurricane season was characterized by enhanced levels of tropical cyclone activity and extensive destruction in the Caribbean basin by Hurricanes Georges and Mitch. A total of 14 named storms (average is 9.3) and 9 hurricanes (average is 5.8) persisted for a total of 47 days (average is 24). There were 3 major hurricanes of Saffir/Simpson intensity category 3-4-5 (average is 2.3 intense hurricanes) with 9.25 intense storm days (average is 4.7). The seasonal total of named storm days was 80 which is 171 percent of the long-term average. Net tropical cyclone (NTC) activity was 172 percent of the 1950–1990 average.

1 Introduction

The Atlantic basin (including the Atlantic Ocean, Caribbean Sea, and Gulf of Mexico) experiences greater season-to-season hurricane variability than occurs in any of the other global tropical cyclone basins. 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 1955, 1980, 1996), and as low as 2 (as in 1982) and 3 (1997, 1994, 1987, 1983, 1972, 1962, 1957). Until the mid 1980s there were no objective methods for advanced assessments of 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 led us to issue extended-range forecasts of Atlantic Basin hurricane activity in early December with updates in early April, early June, and early August of each year. The purpose of this paper is to verify the results of these forecasts for the 1998 hurricane season.

2 Factors Known to be Associated With Atlantic Seasonal Hurricane Variability

Forecasts at several lead times are based on the current values of indices derived from various global and regional scale predictive factors which the authors have shown to be related to subsequent seasonal variations of Atlantic Basin hurricane activity. Figures 1-3 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 information in these forecast parameters. The predictors include the following:

(a) El Niño-Southern Oscillation (ENSO): El Niño is characterized by warm sea surface temperature anomalies in the eastern equatorial Pacific areas of Nino 1-2, 3, 3.4 and 4 (Fig. 2), a negative value of Tahiti minus Darwin surface pressure gradient, and an increased amount of equatorial deep convection near the Dateline. These conditions cause disruptions of the global atmospheric circulation fields, particularly to create anomalous upper-level westerly winds over the Atlantic basin. The effects of a moderate or strong El Niño event are, typically, to reduce Atlantic basin hurricane activity. Conversely, during La Niña seasons with anomalously cold sea surface temperatures, high values of Tahiti minus Darwin surface pressure difference and reduced deep equatorial convection near the Dateline, an enhancement of Atlantic basin hurricane activity typically occurs.

(b) The stratospheric Quasi-Biennial Oscillation (QBO). The QBO refers to the variable east–west oscillating stratospheric winds which encircle the globe near the equator. Other factors being the same, there is 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) are from a westerly versus an easterly direction.

(c) African Rainfall (AR): The incidence of intense Atlantic hurricane activity is enhanced during those years or season when June-September Western Sahel region and August-November

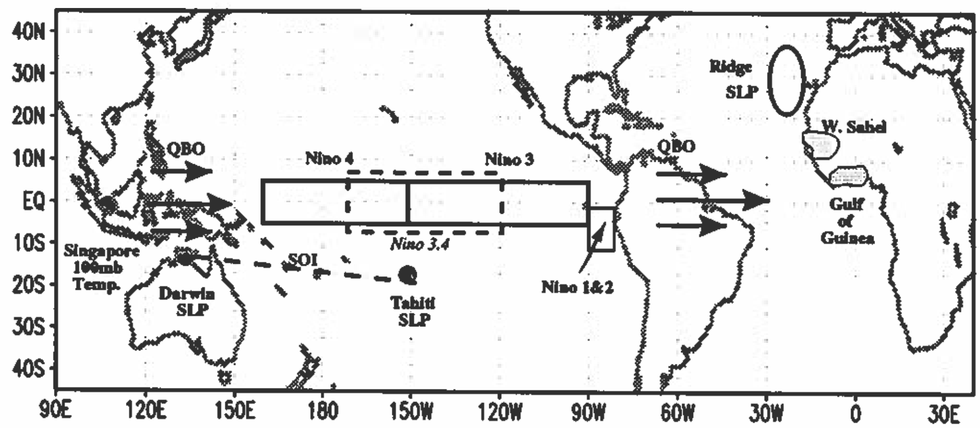

Figure 1: Meteorological parameters used in our various seasonal forecasts.

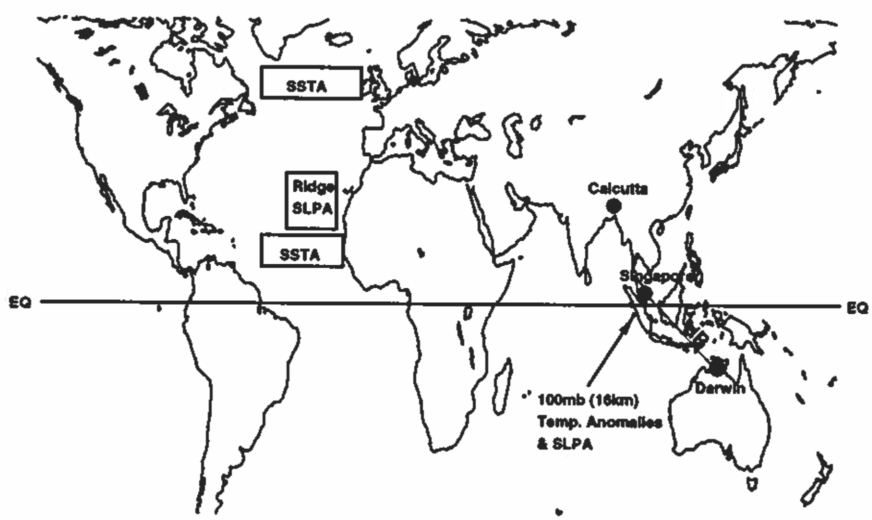

Figure 2: Additional predictors which relate to our Atlantic season hurricane forecasts.

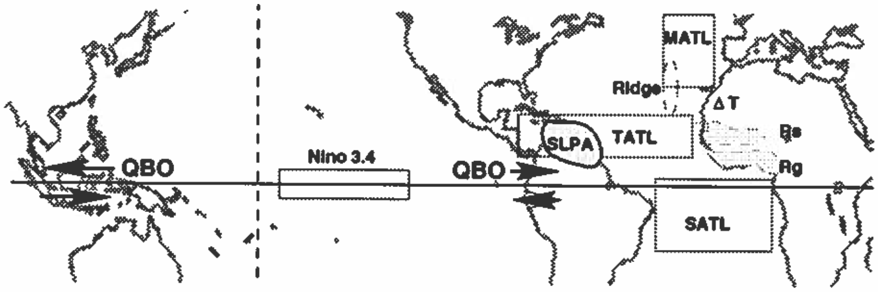

Figure 3: Some additional meteorological parameters which are now used in our reformulated early June and early August forecast.

Gulf of Guinea region rainfall during the prior year was above average. Other factors being the same, hurricane activity is typically suppressed if the rainfall in the prior year (or season) in these two regions is below average.

(d) Prior Year October-November and March northeast Atlantic Subtropical Ridge Strength (ONR). When this pressure ridge is anomalously weak during the prior autumn and spring periods, eastern Atlantic trade winds are weaker. This weak ridge condition is related to decreased mid-latitude cold water upwelling and advection 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 persist into the following summer period and contribute (other factors being constant) to greater seasonal hurricane activity. Less hurricane activity occurs when the October-November and spring pressure ridge is anomalously strong.

(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 of these areas). Warmer SSTAs in these areas 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 (Fig. 3). Negative anomalies (i.e., low pressure and easterly zonal wind anomalies) imply enhanced seasonal hurricane activity (easterly 200 mb) while positive values imply suppressed hurricane activity (westerly 200 mb shear).

(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 between February and 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 from the period 1950–1997.

3 Statistical Summary of 1998 Atlantic Tropical Cyclone Activity

The 1998 Atlantic hurricane season officially ends on 30 November. There were nine hurricanes and 47 hurricane days during the 1998 season. The total named storms (i.e., the number of hurricanes plus tropical storms) was 14, yielding 80 named storm days. There were 3 major (or intense) hurricanes this season. All designated tropical cyclone activity parameters exceeded the long-term average. Figure 4 and Table 1 show the tracks and give statistical summaries, respectively, for the 1998 season. Table 2 characterizes 1998 seasonal tropical cyclone activity in terms of percentages of the 1950-1990 climatology.

By all measure, the 1998 season was an active one though not as active as the recent 1995 and 1996 hurricane seasons. Ranking seasons by the measure of Net Tropical Cyclone (NTC)[5] since 1950, only the hurricane seasons of 1950, 1955, 1961, 1995 and 1996 were more active than 1998. This high level of activity occurred despite the hurricane suppressing influence of an easterly QBO, dry conditions in western Africa before 1 August, and lagging El Niño conditions in the eastern equatorial Pacific.

4 Special Characteristics of the 1998 Hurricane Season:

1. The severe destruction wrought by Hurricanes Georges and Mitch in the Caribbean with over

[5]Average of the percentage of the long term mean of the six seasonal number of Named Storms (NS), Named Storm Days (NSD), Hurricanes (H), Hurricane Days (HD), Intense (category 3-4-5) Hurricanes (IH), and Intense Hurricane Days (IHD).

Figure 4: Tracks of the 14 named tropical cyclones of 1998. Dashed lines indicate the tropical storm intensity stage, thin solid lines indicate the Saffir/Simpson hurricane category 1-2 stage, and the thick lines show the intense (or major) hurricane category 3-4-5 hurricane stage.

Table 1: Summary of information for named tropical cyclones occurring during the 1998 Atlantic season. Information on Tropical Storm (TS), Hurricanes (H) and Intense Hurricanes (IH) with highest Saffir/Simpson category is shown. Information was supplied courtesy of the National Hurricane Center.

Highest Category	Name	Dates of Named Storms	Peak Sustained Winds (kts)/ lowest SLP in mb	NSD	HD	IHD	HDP
TS	Alex	Jul 27-Aug 2	45 kt/1000 mb	4.75	—		
IH-3	Bonnie	Aug 19-30	100/954	10.25	6.50	3.50	21.5
TS	Charley	Aug 21-24	60/1001	1.00	—		
H-2	Danielle	Aug 24-Sep 3	90/965	10.25	9.50		22.1
H-2	Earl	Aug 31-Sep 3	85/986	3.00	1.00		2.3
TS	Frances	Sep 8-13	55/990	2.00	—		
IH-4	Georges	Sep 15-29	130/938	13.00	11.00	1.75	35.2
TS	Hermine	Sep 17-20	40/999	1.00	—		
H-1	Ivan	Sep 19-27	80/975	6.50	3.25		6.7
H-2	Jeanne	Sep 21-Oct 1	90/970	9.00	7.00		16.6
H-2	Karl	Sep 23-28	90/970	4.25	2.50		6.0
H-1	Lisa	Oct 5-9	65/987	4.25	0.50		0.8
H-5	Mitch	Oct 22-Nov 1	155/906	8.75	5.50	4.00	30.4
TS	Nicole	Nov 23-24	60/1005	2.00			

Table 2: Summary of the 1998 seasonal hurricane in comparison with long-term average conditions.

Forecast Parameter	1950–1990 Mean	1998	1998 in percent of 1950-1990 Ave.
Named Storms (NS)	9.3	14	150
Named Storm Days (NSD)	46.6	80	172
Hurricanes (H)	5.8	9	155
Hurricane Days (HD)	23.9	47	197
Intense Hurricanes (IH)	2.3	3	130
Intense Hurricane Days (IHD)	4.7	9.25	197
Hurricane Destruction Potential (HDP)	71.2	142	199
Maximum Potential Destruction (MPD)	66.0	107	162
Net Tropical Cyclone Activity (NTC)	100	168	172

15 thousand deaths and years of economic and social recovery to be faced.

2. Tropical Storm Alex formed in late July but did not intensity further. The second named storm (Bonnie) did not occur until 20 August . From the initial naming of Bonnie as a tropical storm on 20 August to the naming of Tropical Storm Karl on 23 September, 10 named storms formed in the intervening 34-day period (20 August-23 September). This constitutes an average formation rate of one named storm every 3.4 days; very unusual for an easterly QBO year. Few Atlantic hurricane seasons have seen as large a number of tropical cyclones in such a concentrated period. A close second to this degree of storm concentration occurred during 1984 when nine named storms formed in 28 days (28 August to 25 September). Curiously, 1984 season was also an easterly QBO year.

3. The late start of the season for such an active hurricane year. This is much like the active hurricane season of 1961 when a late July hurricane formed (Anna) and then nothing else until 2 September. The 1961 season was also very active.

4. All but four (Charley, Hermine, Karl and Nicole) of the 14 named storms in 1998 formed equatorward of 25°N. This was also somewhat unusual in an easterly QBO year and indicative of very favorable warm SSTA and low SLPA conditions in the tropical regions of the Atlantic basin.

5. The unprecedented development of a category 5 hurricane as intense as Mitch (with maximum wind 155 knots and 906 mb central pressure) to form so late in season (26 October).

6. The very large number of hurricanes (Bonnie (strong category 2); Earl (category 1), and Georges (strong category 2) and Tropical Storms (Charley, Frances, Hermine and Mitch) which impacted the US coast (see Fig. 5): All seven of these named systems impacted the US. Only 1916 (9) and 1985 (8) had more US named storm impacts while the 1901, 1936, 1947 and 1953 seasons also had seven. No major hurricanes made landfall in the US, although Hurricane Bonnie was close to category 3 at landfall. The US was fortunate in regard to major hurricane impacts which, in a statistical sense, cause about 80-90 percent of the normalized hurricane damage (Pielke and Landsea 1998).

7. The large number of landfalling systems (5) along the US Gulf Coast.

8. The number of weaker hurricanes (Jeanne and Karl) and tropical storms (Alex, Lisa, Ivan, Nicole) which never made it west of 60° longitude with six of these systems not progressing west of 50° longitude.

9. The most unusual far east high latitude and late season formation of tropical cyclone Nicole.

10. Since 1950 we have never experienced such an active hurricane season with easterly stratospheric QBO winds and with June and July western Sahel rainfall (–0.89 SD) being so dry.

Figure 5: Tracks of the US landfalling named storms. Line designations are the same as in Fig. 4.

5 Variation of 1998 Forecast Parameters – Factors Known to be Associated with Seasonal Variation of Hurricane Activity

Factors known to be associated with seasonal variation of hurricane activity that were present during 1998 include the following:

a) The dissipation of the 1997–98 El Niño and development of La Niña conditions, Equatorial Pacific SSTAs (in °C) in Niño-1-2, 3, 3.4 and 4 (see Fig. 1 for locations) are shown in Table 3. Cold water (or La Niña) conditions developed rapidly in the central Pacific in late spring, but weak warm anomalies persisted in some areas of the eastern Pacific throughout the season. In addition, the Tahiti minus Darwin surface pressure difference or Southern Oscillation Index (SOI) rose rapidly in the early summer and Outgoing Longwave Radiation (OLR) values near the Dateline were much increased, indicating a precipitous decrease of deep convection which had been present on and east of the Dateline during the previous 12 months. The rapid onset of cold water conditions in the east-central Pacific (Niño-3 and Niño-3.4) and in the Central Pacific (Niño-4) is one of the important causes of increased Atlantic basin hurricane activity after 20 August.

Table 3: Values for April through October various Niño sea surface temperature anomaly indices (in °C) and for Tahiti minus Darwin (SOI) surface pressure differences (in SD).

	April	May	June	July	August	September	October
Niño-1-2	3.3	3.8	2.6	2.0	1.2	0.7	0.6
Niño-3	1.8	1.4	–0.2	–0.1	–0.2	–0.4	–0.6
Niño-3.4	1.0	0.9	–0.7	–1.0	–1.2	–0.8	–1.1
Niño-4	–0.2	0.1	0.1	–0.4	–0.6	–0.4	–1.0
Normalized SOI in S.D.	–1.9	–0.1	0.7	1.3	1.0	1.2	1.0

b) Stratospheric QBO Winds

Tables 4 and 5 show both the absolute and relative (i.e., anomaly) values of 30 mb (23 km) and 50 mb (20 km) stratospheric QBO zonal winds near 12°N during the period of March through October 1998. During the height of the 1998 hurricane season, QBO winds were from an easterly direction and thus were likely an inhibiting influence for the hurricane activity that did occur.

c) Sea-Level Pressure Anomaly (SLPA)

Table 4: Observed March through October 1998 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)	−13	−18	−25	−29	−29	−27	−23	−20
50 mb (20 km)	+2	+2	−15	−21	−23	−22	−19	−18

Table 5: As in Table 4, but for the 1998 "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)	−6	−5	−8	−9	−11	−11	−10	−10
50 mb (20 km)	+12	+14	−5	−7	−10	−12	−13	−15

Table 6 gives information on regional Caribbean basin and Gulf of Mexico SLPA during the 1998 season. Note that Caribbean basin pressures were below average during August and September. This contributed to the increased hurricane activity in these months. Knaff's (1997) Atlantic SLPA forecast scheme for 1998 was correct in predicting slightly below average pressure conditions during the height of the hurricane season.

Table 6: Lower Caribbean basin SLPA for 1998 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). Values in millibars (mb).

	Apr	May	Jun	Jul	Aug	Sep	Oct
5-station Lower Caribbean Ave. SLPA	−0.2	+0.3	+0.5	+0.2	−0.5	−0.1	+0.8
6-station Caribbean plus Gulf of Mexico Ave. SLPA	−0.4	−0.6	+0.4	+0.1	−0.5	−1.5	+0.5

d) Zonal Wind Anomalies (ZWA)

Table 7 shows that the upper tropospheric (12 km or 200 mb) Zonal Wind Anomalies (ZWA) were negative (easterly) in all months except June and October. These negative ZWA values reduce tropospheric vertical wind shear and are a primary factor in explaining why the 1998 season was so active. Negative easterly wind anomalies allowed the westward moving easterly waves from Africa to become better organized. Such negative ZWA values are typical of La Niña years which this season turned out to be.

Table 7: 1998 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	−1.8	−0.9	+1.5	−0.6	−5.4	−3.5	+0.5

e) <u>African Western Sahel Rainfall in 1998</u>

The Western Sahel region of Africa turned out to be near normal for the rain season of June through September (−0.23 SD) despite the fact that June and July were very dry (−0.89 SD). The early dryness was made up by above average August and September rainfall. There was a large shift in Atlantic basin circulation patterns between July and August of this year.

6 Verification of 1998 Individual Lead Time Forecasts

Table 8 compares various lead time forecasts for 1998 with the forecast verification while Table 9 provides a more detailed verification of our after 1 August forecast. As is evident, all our forecasts underestimated the seasonal amounts of 1998 hurricane activity. Our 6 December 1997 forecast was an obvious failure. Our 4 April 1998 forecast was close to climatology, our 6 June 1998 was slightly superior to climatology and our after 1 August forecast (issued on 5 August 1998) was a definite improvement over climatology (Table 9). Note that our actual forecasts did not deviate very much from our statistical forecasts; Table 10 shows that all statistical forecasts underestimated actual hurricane activity. Note that our statistical forecasts from 1 December to 1 August show an appreciable upward prediction of NTC from 78 to 87, to 110, to 133. Our actual forecasts of NTC increased from 90 (1 December) to 95, 100 and to 110 (1 August). Our statistical forecast proved superior to our actual forecasts. Table 11 compares our statistical forecasts to our actual forecasts.

Table 8: Verification of our 1998 total seasonal hurricane predictions.

Forecast Parameter	1950-1990 Mean	6 Dec 1997 Fcst.	Apr 4 1998 Fcst.	Jun 6 1998 Fcst.	Aug 5 1998 Fcst.	1998 Observed Activity
Named Storms (NS)	9.3	9	10	10	10	14
Named Storm Days (NSD)	46.9	40	50	50	50	80
Hurricanes (H)	5.8	5	6	6	6	9
Hurricane Days (HD)	23.7	20	20	25	25	47
Intense Hurricanes (IH)	2.2	2	2	2	2	3
Intense Hurricane Days (IHD)	4.7	4	4	5	5	9.2
Hurricane Destruction Potential (HDP)	70.6	50	65	70	75	142
Maximum Potential Destruction (MPD)	66.0	55	65	65	65	110
Net Tropical Cyclone Activity (NTC) in percent	100	90	95	100	110	172

7 Causes of the 1998 Underforecast of Atlantic TC Activity

We did not predict nearly as active a 1998 hurricane season as occurred. During the pre-season, our perception of the important climate controls which prevented us from predicting an overly active hurricane season were:

Table 9: Verification of 6 August 1998 forecast for hurricane activity after 1 August.

Forecast Parameter	Climatology After 1 Aug	Forecast 1998 Activity After 1 Aug	Forecast after 1 Aug in percent of after 1 Aug Climatology	1998 After 1 Aug Verification
Named Storms (NS)	7.8	9	115	13
Named Storm Days (NSD)	41	47	115	77
Hurricanes (H)	5.1	6	118	9
Hurricane Days (HD)	21.4	25	117	47
Intense Hurricanes (IH)	2.0	2	100	3
Intense Hurricane Days (IHD)	4.4	5	114	9.2
Hurricane Destruction Potential (HDP)	64.4	75	116	142
Maximum Potential Destruction (MPD)	57.1	67	117	107
Net Tropical Cyclone Activity (NTC) in percent	86	107	124	172

Table 10: Summary of our best statistical forecasts for 1998 from different time periods.

Forecast Parameter	From 1 Dec 97	From 1 Apr 98	From 1 Jun 98	From 1 Aug 98	Observed
NS	9.36	8.71	10.0	9.73	14
NSD	35.13	49.95	53.7	47.58	80
H	4.57	6.10	3.4	7.89	9
HD	15.88	21.14	26.8	31.8	47
IH	1.67	2.88	2.8	1.98	3
IHD	0.91	3.61	4.5	8.18	9.2
HDP	43.59	64.22	79.0	87.76	142
MPD		49.96	63.1	82.44	107
NTC	78.32	86.78	109.5	133.48	168

Table 11: Comparison of statistical and actual forecasts for four lead time periods.

Forecast Parameter	1 Dec 97 Statistical Scheme	1 Dec 97 Fcst	1 Apr 98 Statistical Scheme	7 Apr 98 Fcst
Named Storms (NS)	9.36	9	8.71	10
Named Storm Days (NSD)	35.13	40	49.95	50
Hurricanes (H)	4.57	5	6.10	6
Hurricane Days (HD)	15.88	20	21.14	20
Intense Hurricanes (IH)	1.67	2	2.88	2
Intense Hurricane Days (IHD)	0.91	4	3.61	4
Hurricane Destruction Potential (HDP)	43.59	50	64.22	65
Maximum Potential Destruction (MPD)	49.96	55	63.98	65
Net Tropical Cyclone Activity (NTC)	78.32	90	86.78	95
Forecast Parameter	1 Jun 98 Statistical Scheme	5 Jun Fcst	1 Aug 98 Statistical Scheme	6 Aug 98 Fcst
Named Storms (NS)	10	10	9.73	10
Named Storm Days (NSD)	53.7	50	47.58	50
Hurricanes (H)	3.4	6	7.89	6
Hurricane Days (HD)	26.8	25	31.8	25
Intense Hurricanes (IH)	2.8	2	1.98	2
Intense Hurricane Days (IHD)	4.5	4	8.18	5
Hurricane Destruction Potential (HDP)	79	70	87.76	75
Maximum Potential Destruction (MPD)	63.1	65	82.44	65
Net Tropical Cyclone Activity (NTC)	109.5	100	133.48	110

1. an easterly QBO winds,
2. dry Gulf of Guinea conditions during August-November 1997 (–0.43 SD) and in the western Sahel in June-July 1998 (–0.89),
3. (unspecified) residual El Niño influences present in the eastern equatorial Pacific throughout the season, and
4. near neutral April through July Caribbean basin SLPA and ZWA conditions.

Using these factors of our statistical schemes based on 48 years of hindcast data indicated an average to only slightly above average hurricane season. Our forecasts are based on the assumption that the observed global and ocean circulation features preceding active hurricane seasons in past years will also be present for future seasons and that circulation features which have preceded average and below average seasons will be representative of coming average and below average seasons.

We find that in a 48-year sample of past (i.e., hindcast) studies (1950-97) that atmosphere and ocean precursor parameters typically explain about 45-60 percent of past year variance. A smaller amount of variation is explained when our forecast schemes are applied to independent data sets. Hindcast skill shows only a small improvement as the lead time of our forecasts go from 1 December to 1 April to 1 June, and 1 August; our 1 August hindcast skill being only about 10-15 percent higher than our 1 December hindcast in a 48-year sample.

Although precursor signals can statistically explain a substantial amount (45 to 60 percent) of the net 48-year hindcast hurricane variance, there is a sizeable portion of variance (40-55 percent) that our hindcast schemes still cannot explain. There are individual seasons representing about 15-25 percent of the cases, when the global precursor signals fail to give meaningful (improvement on climatology) prior information for the coming season. But there is skill above climatology in the majority of years. We believe that it is desirable to have objective techniques for specifying how active the coming hurricane season is likely to be, even if these objective techniques will fail in a minority of seasons. There is, unfortunately, no way to tell beforehand in which season our forecast will do well or poorly. Nevertheless, our research and attempts at seasonal prediction is teaching us much about those global atmosphere and ocean features which cause such large variations in Atlantic hurricane seasons.

Our 1998 forecast, as in last year's (1997) forecast did not perform well because the forecast variables which have shown to be successful in prior years have just not worked well during the last two years. We attributed last year's forecast bust to the strongest El Niño on record which neither we nor anyone else was able to well forecast. This year's substantial underforecast is more difficult to assess. It is rare in a stratospheric easterly QBO regime with low prior 1 August western Sahel rainfall values and a lingering easterly Pacific El Niño (as were present this year) to have as much hurricane activity as we did. But progress is being made. If we used our 1992 schemes our forecast underestimate would have been much larger.

There appears to be a view among some meteorologists that it would have been easy to have predicted an inactive hurricane season last year (1997) and an active season this year (1998) based on the simple argument of there being a strong El Niño last year and a La Niña this year. Yes, they may have made superior forecasts to ours with this simple model that last two years. But, for most years this one parameter model would not render the best forecast. One should not expect to skillfully predict Atlantic hurricane activity over many years based on the ENSO signal alone. Many other global circulation and ocean signals need to be consulted and integrated into any skillful objective and quantitative multi-parameter predictive scheme. Long period skillful Atlantic seasonal prediction requires the commitment to many years of innovative research and is not a recommended area for those not well schooled in the basic physics and climatology of tropical cyclones.

8 Hurricane Enhancing Atlantic Surface Temperature Rearrangements

A major rearrangement of Atlantic Ocean SST features began in late 1994 and has continued through November 1998. We hypothesize that these strong, broadscale SST changes are due to a major change in the strength of some components of the Atlantic Ocean thermohaline or "conveyor belt" circulation. This interpretation is consistent with changes in various global circulation features during the last four years which also indicate a major shift towards a stronger Atlantic Ocean thermohaline circulation between 1994 and 1995. If this interpretation is correct, then increased intense (category 3-4-5) hurricane activity is to be expected during the coming decades in comparison with activity which occurred during the 1970s, 1980s and early 1990s.

For some years we have been suggesting that the era of greatly reduced Atlantic intense (category 3-4-5) hurricane activity, which occurred between 1970-1994, was likely ending and that Atlantic coastal residence should expect an eventual long-term increase in the probability of landfalling major hurricanes (Gray 1990). This outlook is ominous because, when normalized by increasing coastal population, inflation, and per capita wealth [see Pielke and Landsea (1998) and Gray (1998)] major hurricanes cause between 80-90 percent of all US tropical cyclone linked destruction.

It appears that this new era is now upon us, the major change occurring between 1994 and 1995. Despite the El Niño-linked reduced level of hurricane activity last year (1997), the last four years (1995–1998) are together the most active four (consecutive) year period on record. Table 12 lists the total number of named storms (53), hurricanes (32), major hurricanes (category 3-4-5) (15), major hurricane days (36) and Net Tropical Cyclone (649) which occurred during the last four years. Note in line No. 4 of Table 12, that despite the weak 1997 hurricane season, the annual average NS, H, IH, IHD and NTC during the last four years are 142, 138, 170, 191 and 162 percent of the average hurricane activity for 1950–1990. And, as shown in line 6, annual average NS, H, IH, IHD and NTC during the last four years have been 154, 160, 250, 419 and 216 percent of the average for the previous 25-year period 1970-1994. The greatest increase has occurred for IH and IHD activity. The three recent active hurricane seasons 1995, 1996, 1998 had 311 (IH) and 524 (IHD) percent of the average major hurricane activity respectively for the prior 25-year period 1970–1994. Hence, these trends of increased hurricane activity give strong support to the suggestion that we have indeed entered a new era of greatly increased major hurricane activity. Our preliminary projections for 1999 are for a continuation of this enhanced hurricane activity.

Table 12: Comparison of recent 1995–1998 hurricane activity to prior period annual activity.

Line No.	Year	Named Storms (NS)	Hurricanes (H)	Cat 3-4-5 Hurricanes (IH)	Cat 3-4-5 Hurricane Days (IHD)	Net Tropical Cyclone Activity (NTC)
	1995	19	11	5	11.50	229
	1996	13	9	6	13.00	198
	1997	7	3	1	2.25	54
	1998	14	9	3	9.25	168
1.	TOTAL	53	32	15	36.00	649
2.	4-Year Ave 1995-1998	13.2	8	3.75	9	162
3.	1950-1990 Ave.	9.3	5.8	2.2	4.7	100
4.	1995-1998 Ave/1950-1990 in percent	142	138	170	191	162
5.	1970-1994/1950-1990 in percent	92	86	68	46	75
6.	1995-1998/1970-1994 in percent	154	160	250	419	216
7.	Years 1995, 96, 98/1970-97 Ave in percent	174	194	311	524	248

9 Forthcoming Early December Forecasts for 1999 Hurricane Activity

We will be issuing seasonal forecasts for 1999 Atlantic basin hurricane activity and West African rainfall on 4 December 1998. These forecasts will be based on data available to us through November 1998. A new aspect of the forecast for 1999 will be inclusion of US hurricane landfall along all US coastal locations and an assessment of hurricane-spawned destruction potential in comparison with long-term averages. Forecasts will be disseminated on the World Wide Web.

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APPENDIX A: Verification of Past Seasonal Forecasts

The first author has now issued seasonal hurricane forecasts for 15 consecutive years (1984–1998). In the majority of these prior forecasts, predictions have been superior to climatology (i.e., long-term averages), particularly for named storms. Figures 6.1 and 7.1 offer a comparison of our 1 August forecasts of named storms and hurricanes versus climatology and actual year-by-year variability. Overall there is skill above climatology.

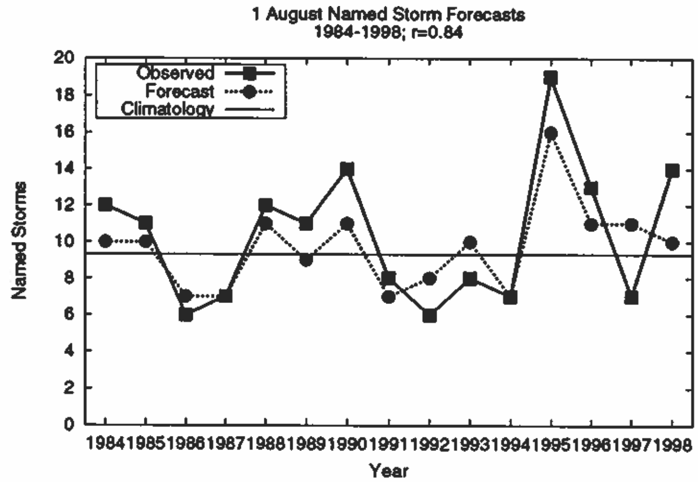

Figure 6: 1 August prediction of total named storms versus the number of actually observed versus long-term climatological mean (r = 0.85) for period 1984–1998.

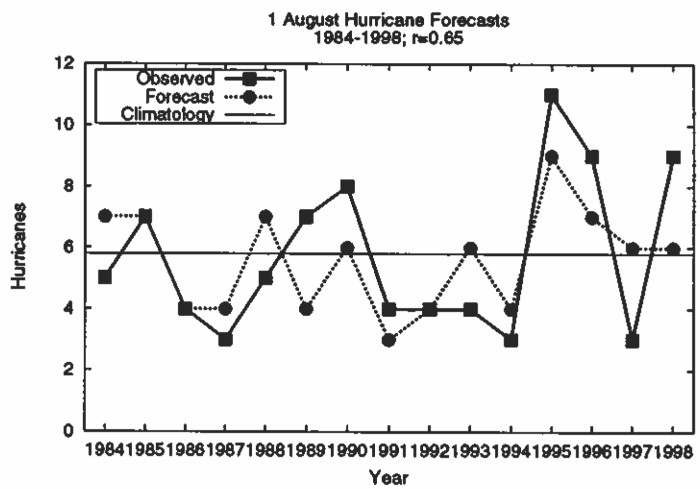

Figure 7: 1 August prediction of total hurricanes versus the number of actually observed versus climatological long-term mean (r = 0.65) for period 1984–1998.

Table 13: Verification of the author's previous seasonal predictions of Atlantic TC activity for 1984-1997.

1984	Prediction Dates 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	**of 28 May**	**Update 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	**29 May**	**Update 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	**26 May**	**Update 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	**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	**26 May**	**Update 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	**5 June**	**Update 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	**5 June**	**Update 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	26 Nov 1991	Update 5 June	Update 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	24 Nov 1992	Update 4 June	Update 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	19 Nov 1993	Update 5 June	Update 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	30 Nov 1994	Update 14 April	Update 7 June	Update 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

1996	30 Nov 1995	Update 4 April	Update 7 June	Update 4 August	Obs.
No. of Hurricanes	5	7	6	7	9
No. of Named Storms	8	11	10	11	13
No. of Hurricane Days	20	25	20	25	45
No. of Named Storm Days	40	55	45	50	78
Hurr. Destruction Potential(HDP)	50	75	60	70	135
Major Hurricanes (Cat. 3-4-5)	2	2	2	3	6
Major Hurr. Days	5	5	5	4	13
Net Trop. Cyclone Activity	85	105	95	105	198

1997	30 Nov 1996	Update 4 April	Update 6 June	Update 5 August	Obs.
No. of Hurricanes	7	7	7	6	3
No. of Named Storms	11	11	11	11	7
No. of Hurricane Days	25	25	25	20	10
No. of Named Storm Days	55	55	55	45	28
Hurr. Destruction Potential(HDP)	75	75	75	60	26
Major Hurricanes (Cat. 3-4-5)	3	3	3	2	1
Major Hurr. Days	5	5	5	4	2.2
Net Trop. Cyclone Activity	110	110	110	100	54