SUMMARY OF 1991 ATLANTIC TROPICAL CYCLONE ACTIVITY AND SEASONAL FORECAST VERIFICATION

(A Year of no hurricanes in the tropics but an unusually large number of higher latitude baroclinically influenced tropical cyclone systems)

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DEFINITIONS

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

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

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

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

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

Named Storm - A hurricane or a tropical storm.

Named Storm Day - Four 6-hour periods during which a tropical cyclone is observed or estimated to have attained tropical storm or hurricane intensity winds.

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

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

Intense Hurricane Day - Four 6-hour periods (hence, 24 hours) during which a hurricane has intensity of Saffir/Simpson category 3 or higher.

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

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

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 (1 to 5) of a hurricane's wind and ocean surge intensity. One is the weakest hurricane, 5 the most intense hurricane.

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

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

ZWA - Zonal Wind Anomaly. A measure of upper level ($\sim$ 200 mb) west to east wind strength. Positive 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 summarized the tropical cyclone (TC) activity which occurred in the Atlantic Basin during 1991, and verifies the author's seasonal forecast of such activity that was issued in early June, and updated on 2 August before the start of the active part of the hurricane season.

Information received by the author as of 5 June 1991 indicated that the Atlantic should experience a below average season with about 4 hurricanes, 8 named storms of hurricane and tropical storm intensity, 15 hurricane days, 35 named storm days and one intense hurricane of Saffir/Simpson category 3-4-5. The 2 August updated forecast, utilizing information of below average amounts of June-July Western Sahel rainfall, positive June–July Caribbean basin surface pressure and upper level zonal wind anomalies led me to reduce the forecast number of hurricanes to 3, named storms to 7 and of hurricane days to 10. The updated 2 August forecast also predicted no intense hurricanes.

The actual number of hurricanes in 1991 was 4; the number of named storms was 8. There were two intense or category 3 hurricanes (Bob and Claudette) which formed at high latitude and were short lived as intense systems. There were no hurricanes in the tropics, and except for the very weak Tropical Storm Fabian there was no tropical cyclone activity in the Caribbean or in the Gulf of Mexico. There were only 8.25 hurricane days (35% of the most recent 42-year average) and 22 1/4 named storm days (47% of average). The Hurricane Destruction Potential (HDP) was only 23; 30% of the long term average. All seasonal categories of tropical cyclone activity were below normal. The key to this very inactive season was the lack of developing African wave systems. Except for the two high latitude intense hurricanes which formed the author's forecast verified quite well as did the forecast of the parameters from which this prediction was made.

Besides the lack of low latitude hurricanes, the 1991 was characterized by the unusually large number (4) of high latitude forming hurricanes whose development was influenced by middle-latitude baroclinic processes. African waves were as frequent (68) in 1991 as in other years but these waves directly produced no hurricanes and only two tropical storms (Danny and Erika).

1 1991 Atlantic Tropical Cyclone Activity

The 1991 Atlantic hurricane season officially ends on 30 November. There were four hurricanes (maximum sustained wind >73 mph) and 8.25 hurricane days during 1991. Total named storms (or the sum of the number of hurricanes and tropical storms) was 8 and there were 22 1/4 named storm days. Figure 1 and Table 1 give the tracks and statistical summaries of all 1991 Atlantic named storms. Table 2 contrasts the tropical cyclone statistics for this season plus the recent past seasons and climatology. Note how the last three years of 1988, 1989 and 1990 had much more tropical cyclone activity than occurred this year.

In terms of all seasonal tropical cyclone parameters (except number of intense hurricanes), 1991 was a very inactive hurricane season. The two intense (Saffir/Simpson Category 3-4-5) hurricanes that developed (Bob and Claudette) formed at high latitudes and existed as intense or category 3 ($V_{max} \geq 100 knots$) hurricanes for a total of only 1.25 days. This season contrasted sharply with the recent seasons of 1988 and 1989 when there were five category

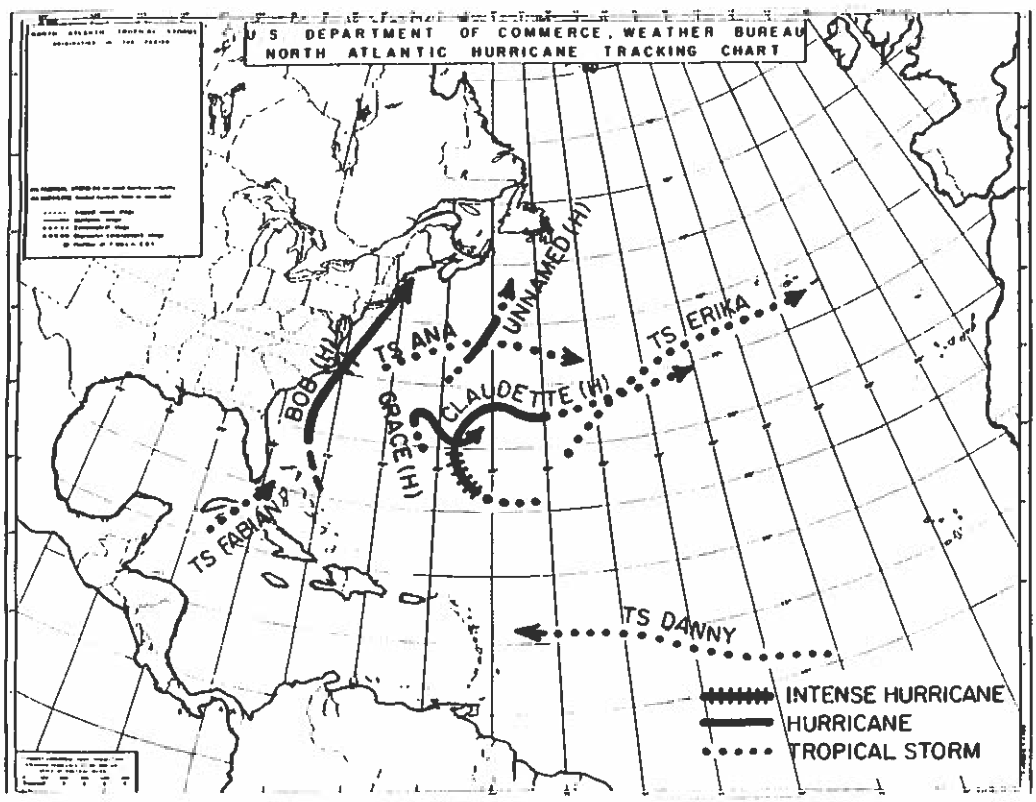

Figure 1: Tracks of tropical cyclones for 1991. Dotted lines indicate periods of tropical storm intensity (maximum sustained winds with 39-73 mph), and thick lines show the periods of hurricane intensity (maximum sustained winds greater than 73 mph) and railroad track lines indicate periods of intense hurricane activity.

Table 1: Summary of information on named tropical cyclones occurring during the 1991 Atlantic tropical cyclone season. Hurricane (H) and Tropical Storm (TS) information has been supplied by courtesy of the National Hurricane Center.

No.	Storm Name	Dates of Name Storm Intensity	Named Storm Days	H Days	Hurr. Dest. Pot. (HDP)	Cat. 3-4-5 Days	Max Wind kts	Minimum Central Pressure (mb)	Max. Saffir Simpson Cat.	From Cape Verde Wave
1.	TS Ana	Jul 4-5	1.75	0	0	0	45	1000	—	No
2.	H Bob	Aug. 16-20	4.00	2.25	6.36	.25	100	950	3	No
3.	H. Claudette	Sept 5-11	6.25	3.75	11.81	1.00	115	946	3	No
4.	TS Danny	Sept 8-11	3.00	0	0	0	45	998	—	Yes
5.	TS Erika	Sept 9-11	2.50	0	0	0	50	997	—	Yes
6.	TS Fabian	Oct 15-16	1.25	0	0	0	40	1002	—	No
7.	H Grace	Oct. 27-29	2.00	1.75	3.46	0	85	980	2	No
8.	H Unnamed	Nov. 1-2	1.50	0.5	0.94	0	65	980	1	No
		Seasonal Total	22.25	8.25	22.57	1.25				2

Table 2: Comparison of 1991 hurricane activity forecast with previous years' activity.

	1991	As % of the long term Average	Last three seasons 1990	1989	1988	Average Season 1982-87	Average Season 1970-87	1950-69	Long Term 1950-90 Ave.
Hurricanes	4	68	8	7	5	4.0	4.9	6.5	5.9
Named Storms	8	81	14	11	12	7.5	8.3	9.8	9.9
Hurricane Day	8.25	35	27.5	32	24	10.7	15.5	30.7	23.8
Named Storm Days	22.25	47	68	66	47	32.0	37.3	53.4	47.2
Hurr. Dest. Pot. (HDP)	23	30	57	108	81	27.0	42.7	100.0	74.5
Major Hurricanes (Cat. 3-4-5)	2	80	1	2	3	1.2	1.6	3.4	2.5
Major Hurricane Days	1.25	23	1	10.75	8.0	1.1	2.1	8.8	5.5

4-5 hurricanes (Gilbert, Helene, Joan, Gabrielle, Hugo) and a total of 18.75 intense hurricane days. Only two minimal intensity name storms (Danny, maximum sustained wind of 45 knots and Fabian, $V_{max} = 40$ kt,) occurred at latitudes equatorwards of 25°N. The tropical Atlantic was completely devoid of any significant tropical cyclone activity in 1991. This was largely a consequence of the unfavorable stratospheric QBO, an ENSO warming event in progress, and Western Sahel rainfall conditions, and high values of Caribbean basin surface pressure and 200 mb wind anomalies. All five of these factors had an inhibiting influence upon the formation of low latitude named storms and hurricanes. This unfavorable tropical environment was in contrast with conditions at higher latitudes which saw 6 named storms and 4 hurricanes develop in association with middle latitude baroclinic systems. The author's forecast scheme is most skillful at predicting lower latitude (< 25°) cyclone activity. Little skill exists for the seasonal forecast of higher latitude cyclones development.

One of the best measures of seasonal hurricane activity is given by the potential for wind and storm surge damage. The author has proposed such a measure in the form of a parameter called HDP [1] The total HDP for 1991 was only 23. This is much lower than values for the last three seasons of 1990 (57), 1989 (108) and 1988 (81). The last 42 year average is 74. The low 1991 value for HDP this year is well associated with the below normal value of Western Sahel rainfall that occurred this year. During the drought years of 1982-1987 HDP values were only 18 (1982), 8 (1983), 42 (1984), 61 (1985), 23 (1986) and 11 (1987).

In terms of HDP or the number of hurricane days (8.25) or intense (category 3-4-5) hurricane days (1.25) 1991 was a very inactive season. There have not been many seasons where the tropical cyclone activity in the tropics (latitude less than 25°N) has been as low as 1991. The lowest latitude of a hurricane intensity cyclone in 1991 was 26.2°N (with Claudette). There were a total of only 2.5 hurricane days at latitudes below 30° latitude. Intense Hurricane Bob existed as a category 3 hurricane for only one 6-hour period and Claudette for 1 day. Hurricanes which develop into named storms at latitude greater than 26°N usually do not become intense hurricanes. This year saw two such category 3 hurricanes develop and two other lesser intensity hurricanes. This is quite unusual.

2 Brief Summary of Individual Named Storm Characteristics

1. **TS Ana**. This weak tropical storm developed downward from an upper level trough in early July off the southeast US East Coast near 36°N. It formed as it was moving ENE ahead of a middle latitude baroclinic system to its north. Ana existed as a named storm for only 1 3/4 days and reached a maximum intensity of 45 knots and minimum pressure of 1000 mb. It then moved rapidly eastward and dissipated over colder water.

2. **H Bob**. This system originated at higher latitudes from the remnants of a frontal trough 200 miles to the east of Florida. It then had a long track to the NNE. Bob experienced steady development into a named storm the 16th of August, at 26°N to a hurricane late on the 17th at 29°N and to a minimal category 3 intense hurricane on the 19th of August at 36.5°N. It existed as a category 3 hurricane ($V_{max} = 100$ knots) or only one 6-hour period. It then weakened and moved rapidly NNE across eastern Long Island and eastern New England states. Bob was a strong category 2 cyclone as it made landfall in the Northeast. A number of locations

[1] Hurricane Destruction Potential (HDP) = $\Sigma(V_{max})^2$ for each V_{max} equal or greater 65 knots for each 6-hour period which the hurricane is in existence. HDP is expressed in units of $10^4 knots^2$. For instance, a hurricane of 100 knots existing for 1 full day (or four 6-hr time periods) would accrue 4 HDP units.

experienced high surge conditions with this cyclone. Bob caused an estimated 1.5 billion dollars in the northeast. Bob was unusual in that it first reached an intensity hurricane stage poleward of 35°N.

3. **H Claudette**. This most intense of the Atlantic basin hurricane of 1991 was also of non-tropical origin. It became a named storm in early September over the subtropical Atlantic at 26°N. It rapidly intensified and developed a small eye as it moved west under a deep tropospheric easterly current. It was during this period that Claudette became a category 3 hurricane for 1 day. All strong winds were concentrated near the center. Claudette recurved near 30°N as a result of a westerly trough moving across its poleward fringe. It then moved eastward along the 34th parallel and gradually dissipated as a named storm southwest of the Azores.

4. **TS Danny**. This was the first (of only two) named storms that formed in 1991 that was of purely tropical origin. It moved steadily WNW during its lifetime as a named storm between 8-10 September. Danny developed from an African wave near 10°N. 35°W and dissipated due to negative vertical shearing influences near 16°N, 56°W. Maximum winds were never greater than 45 knots of central pressure less than 998 mb.

5. **TS Erika**. This second (and last) named storm to be of tropical wave origin developed from an African spawned wave on 9 September as it was recurving to the northeast from the influence of a middle level trough. Erika then tracked steadily NE towards the Azores. It existed as a named storm for 2 1/2 days and obtained a maximum wind of 50 knots.

6. **TS Fabian**. This minimal named storm had a typical October origin in the western Caribbean. It became a tropical storm SW of Cuba on 15 October and tracked steadily NE across western Cuba to the Bahamas where it dissipated due to shearing influences from a middle latitude baroclinic system. It existed as a named storm for only 1 1/4 days and did not develop winds greater than 40 knots or a central pressure less than 1002 mb.

7. **H Grace**. This late October high latitude forming hybrid hurricane developed within a strong middle latitude low pressure system to the east of Florida. It developed convection near its center and was classified as a warm core system for 2 days. It became a named storm north of 30° latitude, then very soon recurved and moved rapidly eastward along the 32° parallel. It's hurricane force winds were south of the center and were primarily a result of its eastward translation. Grace had hurricane force winds for 1 3/4 days. It's formation and structural characteristics were not those of the typical hurricane.

8. **H Unnamed**. This unusual early November and high latitude ($\approx 36 - 37°$N) system developed from a strong mid-latitude low pressure or "bomb" system that had weakened. This weakening bomb system then experienced an unusual southwest motion over the Gulf stream and developed a central core of deep convection. It may not have been classified as a minimal hurricane ($V_{max} = 65$ kts) for two 6-hour periods if a reconnaissance aircraft had not penetrated its center and measured a warm core and minimal hurricane force winds. This system existed as a named storm for 1 1/2 days. It's minimal pressure was 980 mb. It then moved into higher latitudes and dissipated. There have likely only been a few such similar type of systems over the Atlantic in the last 40 years. The New England coastal damage which this system spawned was a result of the storm's stronger outer radius winds which were associated with the earlier baroclinic 'bomb' stage of its development.

3 Verification of Author's 1991 Forecast

Table 3 gives information on the author's seasonal forecast. The number of hurricanes, named storms, hurricane days, and Hurricane Destruction Potential (HDP) were well forecast. The 2 August updated forecast missed the number of intense hurricanes however. Most intense hurricanes form from Cape Verde waves. But that was not the case this year. The two intense hurricanes that occurred (Bob and Claudette) developed at high latitudes in association with middle latitude baroclinic activity. It is unusual that two such high latitude baroclinically associated intense hurricanes would form in one year.

Table 3: Comparison of 1991 Hurricane Activity Forecast With Activity in Previous Years.

	1991 Verification	2 Aug Updated Forecast	5 June Forecast 1991	Observed 1990	Observed 1989	Observed 1988	Average Season 1970-87	Average Season 1950-69	42–Year Ave.
Hurricanes	4	3	4	8	7	5	4.9	6.5	5.9
Named Storms	8	7	8	14	11	12	8.3	9.8	9.9
Hurricane Days	8.25	10	15	28	32	24	15.5	30.7	23.8
Named Storm Days	20.25	30	35	68	66	47	37.3	53.4	47.2
Hurr. Dest. Pot.(HDP)	23	25	40	57	108	81	42.7	100.0	74.5
Major Hurricanes (Cat. 3-4-5)	2	0	1	1	2	3	1.6	3.4	2.5
Major Hurricane Days	1.25	0	2	1	10.75	8	2.1	8.8	5.5

The author's forecast of El Niño, QBO, SLPA, ZWA and West African rainfall conditions went quite well. Inspection of Table 3 show that, except for the number of intense hurricanes, this year's overall forecast worked out very well.

4 Discussion

From Bob's dissipation as a hurricane on the 19th of August until Grace reached hurricane intensity on the 28th of October, or 70 days during the height of the hurricane season, there was only 3 3/4 days of hurricane activity associated with Hurricane Claudette. This is an unusually long period at the height of the hurricane season to have only one hurricane.

In those years when African waves produce only a few named storms as 1991 was, we typically observe more high latitude tropical cyclone developments. The 1991 season was more typical of the years of 1968, 1972, 1977, 1982, 1983 and 1986 when very few African waves developed into named storms. Conversely, when African waves spawned a lot of named storms, sub-tropical development is typically reduced. There is a degree of latitude compensation.

The author's forecast scheme is primarily designed to predict the seasonal variation of the majority of hurricane activity which develops at lower latitudes. Little skill exists for the type of high latitude formation which occurred this year. The forecast scheme works because in most years, the majority of tropical cyclone activity is associated with those systems which form at low latitudes.

Continuation of African Sahel Drought Conditions. The above average rainfall which fell in the Western Sahel in 1988 and 1989 led the author to speculate that the long running multi-decadal Sahelian drought might finally be coming to an end. We now believe that this 2-year drought interruption was a response to the unusually cold ENSO event that occurred during the 1988-89 period. East Pacific SSTA conditions are, statistically, inversely related to Western Sahel rainfall conditions. Once this cold 1988-89 ENSO event dissipated, drought conditions again returned to the Western Sahel in 1990 and 1991. And our new research leads us to predict a continuation of Western Sahel drought conditions for 1992. It appears that a true break off of these over 20-year drought conditions is still at least two or more years away. This means that intense hurricane activity should remain below average and that the probability of intense landfalling hurricanes along the US East Coast and in the Caribbean will be below average.

5 Factors Known to be Associated With Atlantic Seasonal Hurricane Variability

This forecast was based on the author and his colleagues' past research (Gray, 1983, 1984a, 1984b; Gray, 1990; Landsea, 1991) which relates seasonal Atlantic hurricane activity to: 1) the El Niño (EN); 2) the Quasi-Biennial Oscillation (QBO) of equatorial 30 mb and 50 mb stratospheric winds; 3) Caribbean Basin-Gulf of Mexico Sea-Level Pressure Anomaly (SLPA) in spring and early summer; 4) lower latitude Caribbean Basin 200 mb (12 km altitude) zonal wind anomaly in early summer, and 5) the new and very important parameter of Western Sahel rainfall. These five factors have been shown to be strongly related to seasonal variations in Atlantic tropical cyclone activity.

The author's seasonal forecast scheme has the following form:

$$\begin{pmatrix} \textit{Predicted Amount} \\ \textit{of TC} \\ \textit{Per Season} \end{pmatrix} = \textit{Ave. Season} + \overbrace{(EN + QBO + SLPA + ZWA + AR)}^{\textit{Adjustment Terms}}$$

where

[EN] = El Niño influence. Warm East Pacific water reduces hurricane activity, cold water enhances it.

[QBO] = 30 mb and 50 mb Quasi-Biennial Oscillation equatorial zonal wind correction. Increased hurricane activity for westerly or positive phase, reduced hurricane activity for easterly or negative zonal wind.

[SLPA] = Average SLPA for Spring and early Summer. Reduce hurricane activity if SLPA is significantly above average, add activity if significantly below average.

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

[AR] = Western Sahel rainfall, increase activity if wet, reduce it if dry.

6 Characteristics of Known Seasonal Hurricane Predictors During 1991

A) El Niño

A weak El Niño began forming early in 1991. This event very slowly intensified during the year and now (as of November) is close to moderate intensity. Like the onset of the 1982 and 1986 El Niños it has developed more along the Dateline than off of the South American coast which has, to date, shown only a small warming. We expect the current ENSO warming event to continue to strengthen and reach moderate intensity by the coming winter period. It should then begin to weaken.

Quite consistent with this ENSO warming event has been the strongly positive 200 mb zonal wind anomalies (ZWA) which have been observed all season long throughout the Caribbean basin (see Table 6). Note that all months from April through October had substantial above average 200 mb westerly winds. These winds acted as a strong suppressing influence on this season's low latitude tropical cyclone activity through their inhibiting vertical wind shear influences.

B) Stratospheric QBO

Tables 4 and 5 show the absolute and relative (anomaly) value of the 30 mb (23 km), 50 mb (20 km), and 70 mb (18.5 km) stratospheric QBO zonal winds in the lower Caribbean basin. Note that during the primary August through October hurricane season that 30 to 70 mb stratospheric winds were from a relative easterly phase. This resulted in the absolute values of the QBO winds being stronger than average from the east. This caused lower stratospheric vertical wind shear to be larger than average. This is typically an inhibiting influence on low latitude TC activity.

Table 4: April through October 1991 observed absolute value of stratospheric QBO zonal winds (U) in the critical latitude belts between 8-12°N as obtained from the lower Caribbean basin stations of Curacao, Barbados, and Trinidad. Values in ms^{-1} (as supplied by James Angell and Colin McAdie).

	Observed Actual Zonal Winds						
Level	April	May	Jun	Jul	Aug	Sept	Oct
30 mb (23 km)	+12	-3	-21	-25	-27	-25	-24
50 mb (20 km)	+15	+10	-17	-18	-20	-18	-12
70 mb (18.5 km)	+5	+2	-2	-12	-15	-11	-3

C) Sea-Level Pressure Anomaly (SLPA)

Table 6 gives information on SLPA during the 1991 season. It is the Caribbean SLPA's which are most important. Note that nearly all stations had quite high SLPA for the entire April through October period. These high pressure anomalies are consistent with the very low amount of tropical cyclone activity which occurred this year throughout the low latitude Atlantic.

D) Zonal Wind Anomaly (ZWA)

Table 5: Same as Table 1 but for the relative zonal wind where the annual wind cycle has been removed. Values in ms^{-1}.

Level	Observed Relative Zonal Winds						
	April	May	Jun	Jul	Aug	Sept	Oct
30 mb (23 km)	+12	+0	-4	-7	-9	-8	-12
50 mb (20 km)	+12	+7	+3	-2	-5	-5	-4
70 mb (18.5 km)	+6	+4	+2	-1	-4	-3	+1

Table 6: 1991 Average Eastern Caribbean Basin and Gulf of Mexico-E. Caribbean Basin Sea-Level Pressure Anomalies (SLPA) - in mb (as kindly supplied by Colin McAdie from NHC analysis in combination with CSU analysis).

Low Latitude SLPA	Apr-May	Jun-Jul	Aug	Sept	Oct	Aug-Sept-Oct Average
San Juan (19.5°N, 66°W)	+0.5	+0.1	+1.2	+0.6	+0.2	+0.7
Curacao (12°N, 69°W)	+0.4	+1.0	+2.2	+1.4	+1.0	+1.5
Barbados (13.5°N, 60°W)	+0.3	+0.1	+1.2	+2.2	-0.3	+1.0
Trinidad (11°N, 62°W)	+0.9	+0.6	+2.0	+1.2	+1.3	+1.5
Cayenne (5°N, 52.5°W)	+0.5	0	+1.1	+0.4	+1.2	+0.9
Average	+0.5	+0.4	+1.5	+1.2	+0.7	+1.1
Gulf of Mexico-Caribbean Basin	**Apr-May**	**Jun-Jul**	**Aug**	**Sept**	**Oct**	**Aug-Sept-Oct Average**
Brownsville (26°N)	-1.5	+0.2	+1.0	+2.5	+1.3	+1.6
Merida (Mex.) (21°N)	+0.1	+1.1	+2.1	+1.9	-0.1	+1.3
Miami (25.5°N)	+0.7	+0.3	+1.7	+1.7	+0.5	+1.3
San Juan (18.5°N)	+0.5	+0.1	+1.2	+0.6	+0.2	+0.7
Curacao (12°N)	+0.4	+1.0	+2.2	+1.4	+1.0	+1.5
Barbados (13.5°N)	+0.3	+0.1	+1.2	+2.2	-0.3	+1.0
Average	+0.1	+0.5	+1.6	+1.7	+0.4	+1.2

Table 7 shows that the upper tropospheric Zonal Wind Anomalies (ZWA) were consistently positive throughout the April through October, 1991 period. These strong and positive upper tropospheric zonal wind anomalies caused increased tropospheric vertical wind shear in the low latitude Atlantic. This was a strong inhibiting influence on this years lower latitude TC activity.

Table 7: 1991 Caribbean Basin 200 mb (12 km) Zonal Wind Anomaly (ZWA) in ms^{-1} (as supplied by Colin McAdie of NHC analyses in combination with CSU data).

Station	April	May	June	July	Aug	Sept	Oct	Aug-Oct Ave.
Kingston (18°N, 77°W)	+1	+3	+8	+1	+3	+5	−1	+ 2
Curacao (12°N, 69°W)	+5	+ 3	+ 6	+3	+6	+5	+3	+ 5
Barbados (13.5°N, 60°W)	+7	+6	+5	+2	+4	+1	+3	+3
Trinidad (11°N, 62°W)	+4	+4	+8	+2	+5	+4	+4	+4
Average	+4	+4	+7	+2	+4	+4	+3	+3.5

High Caribbean basin SLPA and positive 200 mb ZWA are associated with the Intertropical Convergence Zone (ITCZ) in the Western Atlantic being displaced further south from its normal position. This was the situation this year.

E) African Rainfall (AR)

African Rainfall (AR) is a new forecast parameter that was included in this year's forecast only for the second time. In the last few years we have found (Gray, 1990; Landsea, 1991; Landsea and Gray, 1991) that Atlantic intense hurricane activity is much enhanced when the Western Sahel region of West Africa (see Fig. 2) has above average precipitation and much reduced in drought conditions. Intense hurricane activity shows special sensitivity to Western Sahel rainfall conditions. Recent analysis by Landsea (1991) are showing high correlations between the year-to-year variance in the number of intense (category 3-4-5) hurricane days with the year to year variations in Western Sahel rainfall. The rainfall which fell in the 38-station Western Sahel region (Fig. 2) between June and September was observed to be below average with a mean S.D. of -0.45. This was also an important contributing factor to the reduction of Atlantic tropical cyclone activity equatorwards of 25°N.

7 Synoptic Conditions Controlling 1991 Atlantic Tropical Cyclone Activity

During much of August and 1991 September the Atlantic upper level circulation was dominated by a mid-ocean semi-permanent Tropical Upper Tropospheric Trough (TUTT), as shown in an idealized rendering in the top diagram of Fig. 5. This was the dominant synoptic feature explaining much of this season's dearth of low latitude tropical cyclone activity. The vertical wind shear induced by this TUTT feature prevented nearly all of the 68 westerly moving African spawned wave systems from intensifying into named storms except for tropical storm Danny.

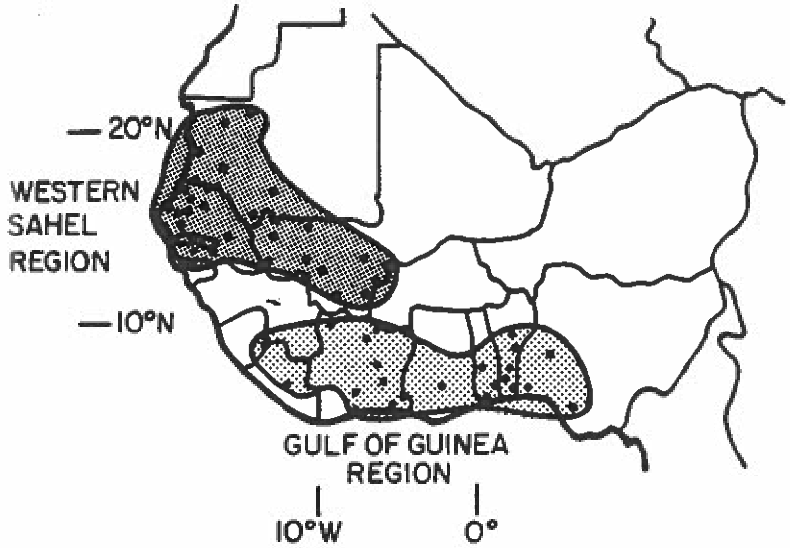

Figure 2: Location of rainfall stations which make up the Western Sahel precipitation index.

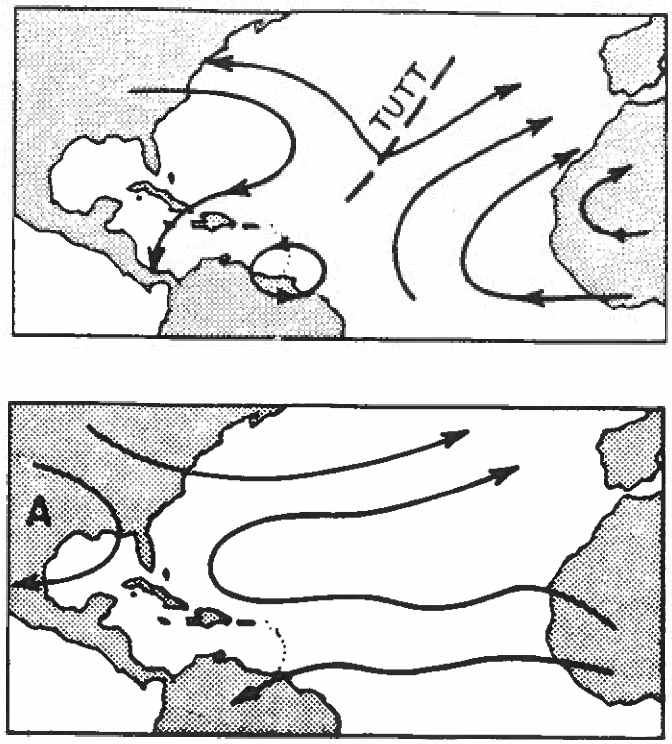

Figure 3: Illustration of the contrasting mean upper tropospheric flow conditions typically associated with August-September seasons when vertical shearing conditions prevent African waves develop into named storms (top—as occurred in 1991) versus those seasons when shear is weak and the African systems develop many named storms (bottom).

The existence of such mid-Atlantic TUTTs are much more common during seasons of Western Sahel drought as this year was and in seasons of warm ENSO, as this year was. By contrast, during those seasons when the Western Sahel experiences above average rainfall and a cold ENSO event is present, the mid-Atlantic upper level shearing conditions are typically reduced (see the idealized bottom diagram of Fig. 3) and African spawned westward traveling systems or Cape Verde easterly waves can more readily develop into named storms and then into intense hurricanes.

8 Forecast for 1992

New studies by the author and his research colleagues is showing that there are skillful seasonal prediction signals related to the QBO and West African rainfall that are available by late November of the prior year. The existence of these signals allows for statistically skillful predictions of next season's tropical cyclone activity. Using these prediction signals we project a below average Atlantic hurricane season for 1992. A separate report giving more background information on next year's seasonal hurricane activity has been prepared. A more detailed report of this extended range forecast scheme (Gray, *et al.*, 1991) has been sent off for publication.

9 Verification of Previous Year Forecasts

The author has now issued seasonal forecasts for 8 years. A record of these forecast verifications is given in Table 8. An evaluation of their skill in comparison with climatology, the only other previously available method of predicting future hurricane activity is presented below.

This author's forecast scheme has evolved over the last eight years with the following changes:

1) In the more recent forecasts I have added seasonal predictors of Hurricane Destruction Potential (HDP), the number of intense or Saffir/Simpson category 3-4-5 hurricanes and of the number of category 3-4-5 days. There has not been a long enough period for a meaningful evaluation of the forecasts of these parameters.

2) West African rainfall, now known to be a fundamental component in variations in Atlantic hurricane activity has only been explicitly included in the most recent two updated August forecasts. The first six forecasts were deficient in not including this very important but previously unknown parameter.

3) Until three years ago a hurricane day was accepted as a whole hurricane day if any 6-hour period of a day had hurricane intensity winds. This tended to inflate the number of hurricane days. We have now adopted the more desirable method of tabulating hurricane days by the number of 6-hour periods in which hurricane intensity conditions exist. A hurricane day now requires four 6-hour periods of hurricane intensity conditions. This has caused a downward alteration of the previous reported number of hurricane days per season by an average of 2.5.

It is impossible to give a really good assessment of the true potential of seasonal predictive skill from only the last eight (1984-1991) years of forecasts. This is too short a period for a very meaningful verification.

New statistical analysis of data for the 41 seasons of 1950-1990 by the author and colleagues (CSU Statistics Professors Paul Mielke and Kenneth Berry) show there is a very high predictive

Table 8: Verification of the author's previous seasonal predictions of Atlantic tropical cyclone activity for 1984-1989.

1984	Prediction of 24 May and 30 July Update		Observed
No. of Hurricanes	7		5
No. of Named Storms	10		12
No. of Hurricane Days	30		18
No. of Named Storm Days	45		51
1985	**Prediction of 28 May**	**Updated Prediction of 27 July**	**Observed**
No. of Hurricanes	8	7	7
No. of Named Storms	11	10	11
No. of Hurricane Days	35	30	21
No. of Named Storm Days	55	50	51
1986	**Prediction of 29 May**	**Updated Prediction of 28 July**	**Observed**
No. of Hurricanes	4	4	4
No. of Named Storms	8	7	6
No. of Hurricane Days	15	10	10
No. of Named Storm Days	35	25	23
1987	**Prediction of 26 May**	**Updated Prediction of 28 July**	**Observed**
No. of Hurricanes	5	4	3
No. of Named Storms	8	7	7
No. of Hurricane Days	20	15	5
No. of Named Storm Days	40	35	37
1988	**Prediction of 26 May and 28 July Update**		**Observed**
No. of Hurricanes	7		5
No. of Named Storms	11		12
No. of Hurricane Days	30		24
No. of Named Storm Days	50		47
Hurr. Destruction Potential(HDP)	75		81
1989	**Prediction of 26 May**	**Updated Prediction of 27 July**	**Observed**
No. of Hurricanes	4	4	7
No. of Named Storms	7	9	11
No. of Hurricane Days	15	15	32
No. of Named Storm Days	30	35	66
Hurr. Destruction Potential(HDP)	40	40	108
1990	**Prediction 5 June**	**Updated Prediction of 3 August**	**Observed**
No. of Hurricanes	7	6	8
No. of Named Storms	11	11	14
No. of Hurricane Days	30	25	27.5
No. of Named Storm Days	55	50	68
Hurr. Destruction Potential(HDP)	90	75	57
Major Hurricanes (Cat. 3-4-5)	3	2	1
Major Hurr. Days	Not fcst.	5	2

skill in the forecast of intense hurricane activity (Gray, et al., 1991). Using 41 years of newly acquired African rainfall data in combination with previously used parameters, we find that it is possible to independently hindcast between 45–50% of the seasonal variability of HDP, intense hurricanes (category 3-4-5) and intense hurricane days with the early June forecast. These hindcast analyses utilized the jackknife method whereby forecasts are made on developmental data sets not utilized by the year being forecast. In this sense each year's forecast is made with independent data.

Forecasts which are made with information through July show that it is possible to explain approximately 60 percent of the forthcoming season' variance of HDP, intense hurricanes and intense hurricane days. August 1 forecast skill for seasonal variations of the numbers of hurricanes, named storms, and hurricane days varies between 55-60%.

This 41-year longer running and independent or jackknife statistical analyses is believed to be the best evaluation of the potential forecasting skill. Verification of only eight of the author's forecasts is not nearly as reliable a sample, particularly in that 6 of these last 8 years did not utilize the new information we have recently uncovered concerning the substantial influence of West Africa rainfall on hurricane activity. I will nevertheless attempt to verify my last 8 years of forecasts.

Last Eight Year Forecast Skill. Only four parameters have been predicted during all of the last 8-year forecasts—number of hurricanes, number of named storms, number of named storm days, and number of hurricane days. Table 9 shows the ratios of the mean variance of the author's seasonal forecast from observations to the mean of the individual seasonal variances from climatology for the period of 1950-90. Values less than 1.00 show forecast skill over climatology. Values greater than 1.00 lack skill over climatology. For all four forecast parameters and for both forecast periods the variance of the errors of the author's predictions were considerably less than the average year to year variances from climatology.

Table 9: Eight Year (1984-91) forecast skill expressed as the ratio of variance of mean forecast error to the mean seasonal variance from climatology for the period 1949-90.

Forecast Parameter	1 June Forecast	1 August Forecast
Number of Named Storms	.49	.29
Number of Named Storm Days	.65	.45
Number of Hurricanes	.60	.60
Number of Hurricane Days	.64	.44
HDP (Last 4 years only)	.49	.38

Considerations of statistical independence suggests that the proper comparison of the last 8 years of forecast error should likely be made using only the average variances from climatology of the last eight rather than the last 41 seasons. Seasonal variances from climatology during the last 8 years were only 60% as large as were the seasonal variances from climatology of the data of the last 41 years. In other words, climatology has done a better job "forecasting" during the last 8 years in comparison to the previous 33 years. For instance, the yearly numbers of hurricanes during the period of 1984-91 has been 5, 7, 4, 3, 5, 7, 8, 4 and average variance from the long term mean has been 2.86. The 41 year mean variance of hurricanes has been 4.77, or

67% greater. Seasonal hurricane numbers between 1950-91 range from 2 to 12. The greater the variance from climatology, the greater is the potential forecast skill. It thus has been more difficult to demonstrate forecast skill over the last 8 years when the variance from the mean has been smaller than normal.

Table 10 shows the mean 8-year forecast skill using the mean variance from a climatology based only on the period 1984-91. This reduction in forecast skill has been primarily due to the very poor forecast of 1989 when a below average hurricane season was forecast but an above average season occurred. This bust is attributed to conditions accompanying the unusually heavy amounts of rainfall which fell during June to September in the Western Sahel in 1989 which were, at that time not anticipated and whose influence on Atlantic hurricane activity was not then well understood. Western Sahel 1989 rainfall was the highest than it has been in any year since 1967. It was this large forecast bust in 1989 that has stimulated the author's project to perform new research towards a better understanding of this strong relationship between Western Sahel rainfall and hurricane activity.

Table 10: Eight year (1984-91) forecast skill expressed as the ratio of variance of mean forecast error to the mean variance from climatology for the period 1984-91.

Forecast Parameter	1 June Forecast	1 August Forecast
Number of Named Storms	.60	.36
Number of Named Storm Days	.87	.66
Number of Hurricanes	.98	.98
Number of Hurricane Days	1.04	.71
HDP	1.17	.91

Regardless of how one might rate my forecast skill over the last 8 years, I am very confident that future forecasts will stand the test of time and will demonstrate an ever improving skill. Our 41-year jackknife statistical analyses well demonstrates that substantial potential predictive skill exists over a more representative period of 41 years

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