SUMMARY OF 1989 ATLANTIC TROPICAL CYCLONE ACTIVITY

AND SEASONAL FORECAST VERIFICATION

By

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DEFINITIONS

Atlantic Basin - The ocean area of the entire Atlantic including 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 65 knots) or greater.

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

Tropical Storm - a tropical cyclone with maximum sustained winds between 39 (17 ms^{-1} or 35 knots) and 73 (32 ms^{-1} or 65 knots) miles per hour.

Named Storm - a hurricane or a tropical storm.

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 each hurricanes' maximum wind for each 6-hour period of its existence.

Hurricane Day - any part of a day in which a tropical cyclone is observed or estimated to have hurricane intensity winds.

Named Storm Day - any part of a day in which a tropical cyclone is observed or estimated to have tropical storm or hurricane intensity winds.

Millibar - (abbreviated mb). A measure of atmospheric pressure. Often used as a vertical height designator. 200 mb is at a level of about 12 kilometers, 50 mb at about 20 kilometers altitude. Monthly averages of surface pressure in the tropics show maximum seasonal summer variations of about $\pm$ 2 mb. These small pressure variations are associated with variations in seasonal hurricane activity. Average surface pressure is slightly over 1000 mb.

El Nino - (EN) - a 12-18 month period in which anomalously warm sea surface temperatures occur in the eastern half of the equatorial Pacific. Moderate or strong El Nino events occur irregularly. Their average frequency is about once every 5-6 years or so.

QBO - Quasi-Biennial Oscillation. These letters refer to stratospheric (16 to 35 km altitude) equatorial east to west or west to east zonal winds which have a period of about 26 to 30 months or roughly 2 years. They typically blow for 12-16 months from the east and then reverse themselves and blow 12-16 months from the west and then back to the east again.

SLPA - Sea Level Pressure Anomaly. Caribbean and Gulf of Mexico sea level pressure difference from long term average conditions. SLPA in the spring and early summer has an inverse correlation with late summer and early autumn hurricane activity. The lower the pressure the more likely there will be hurricane activity.

ZWA - Zonal Wind Anomaly. A measure of upper level (~ 200 mb or 12 km altitude) 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 summarizes the tropical cyclone (TC) activity which occurred in the Atlantic Basin during 1989, and verifies the author's seasonal forecast of TC activity that was issued in late May, and updated in late July. This forecast was based on the author's previous research (Gray, 1983, 1984a, 1984b) and new research which relates seasonal Atlantic hurricane activity to: 1) the El Nino (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; and 4) lower latitude Caribbean Basin 200 mb (12 km altitude) zonal wind anomaly in June and July in non-El Nino seasons.

Information received by the author as of 26 May 1988 indicated that the 1989 hurricane season should have been a below average season with about 4 hurricanes, 7 named storms of hurricane and tropical storm intensity, 15 hurricane days and 30 named storms days. An updated forecast was issued on 28 July 1989 with the number of named storms increased to 9 and named storm days to 35 and other forecast parameters the same.

The actual number of hurricanes which occurred in 1989 was 7 (three above the forecast); the number of named storms was 10 (one above forecast); number of hurricane days was 35 and number of named storm days was 66 - both much higher than forecast. For the second season the author issued a forecast of Hurricane Destruction Potential (HDP), which is a measure of the sum of all hurricane intensity wind speeds squared. The HDP forecast for 1989 was 40. The actual HDP number was 108 - again much higher than forecast. Most of the 1989 hurricane activity was in the central and eastern Atlantic. The Atlantic basin west of 68°W longitude experienced only 4 named storms with but 6 hurricane days and an HDP of 13.

The author's forecast did not verify well this season. This was due to the very high amounts of West African August to mid-September rainfall which fell and which caused the development of so many east and central Atlantic systems. Such heavy amounts of West African rainfall were not anticipated. West African (Sahel) rainfall has not yet been explicitly included in the author's forecast scheme. There had not been such a similar change from dry to wet conditions since 1948-50. We are now working to incorporate African rainfall into future seasonal forecasts. The long multi-decadal West Africa Sahel drought now appears to be broken.

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1. 1989 Atlantic Tropical Cyclone Activity

The 1989 Atlantic hurricane season officially ends on 30 November. There were seven hurricanes (maximum sustained wind >73 mph) and 35 hurricane days during 1989. Total named storms (or the sum of the number of hurricanes and tropical storms) was 10. In terms of tropical cyclone (TC) intensity, this was an active hurricane season because of intense hurricanes Gabrielle and Hugo. These intense Saffir/Simpson category 4 and category 5 hurricanes formed despite 1989 being in the easterly phase of the Quasi-Biennial Oscillation (QBO).

The 1989 season was distinguished primarily by the large number of named storms which formed and tracked in the eastern and central Atlantic. Only Hurricane Hugo and three weaker systems in the northwestern Gulf of Mexico were ever located west of 68°W. The large number of eastern Atlantic systems is attributed to the general strength of easterly waves which tracked out of West Africa. This strong wave activity was a consequence of a very active West African monsoon trough which produced unusually large amounts of August to mid-September rainfall in the western Sahel region of West Africa.

Table 1 and Fig. 1 give summaries of all 1989 Atlantic named storms. Note the very high intensity of hurricanes Gabrielle and Hugo. Perhaps the best measure of seasonal hurricane activity is given by the total potential for wind and storm surge damage. The author has proposed such a measure in the form of a parameter called Hurricane Destruction Potential or HDP. HDP is the sum of the square for each hurricane's maximum wind

TABLE 1

Summary of named storms occurring during the 1989 Atlantic tropical cyclone season. Hurricane (HUR) and Tropical Storm (TS) information has been supplied by the National Hurricane Center.

1989 ATLANTIC BASIN TROPICAL STORMS AND HURRICANES

	Storm Name	Dates-TS	Dates of Hurricane Intensity	Maximum Sustained Wind (kt/mph)	Minimum Central Pressure (mb)	Saffir/ Simpson Maximum Category	Storm Days	Hur. Days	HDP	Cape Verde African Origin
1.	TS Allison	Jun 26-27	---------	45/50	999	0	2	0	0.0	No
2.	TS Barry	Jul 11-13	---------	45/50	1005	0	3	0	0.0	Yes
3.	HUR Chantal	Jul 31-Aug 2	Aug 1	70/80	984	1	2	1	1.4	No
4.	HUR Dean	Aug 1-8	Aug 2-8	90/105	968	2	8	7	14.0	Yes
5.	HUR Erin	Aug 19-27	Aug 22-26	90/105	968	2	8	5	11.6	Yes
6.	HUR Felix	Aug 26-29 Sep 3-9	Sep 5-7	75/85	979	1	11	2	4.0	Yes
7.	HUR Gabrielle	Aug 31-Sep 12	Sep 1-10	125/145	937	4	13	9	35.5	Yes
8.	HUR Hugo	Sep 11-22	Sep 13-22	140/160	918	5	12	10	40.3	Yes
9.	TS Iris	Sep 18-20	---------	60/70	1000	0	3	0	0.0	Yes
10.	HUR Jerry	Oct 13-16	Oct 15-16	75/85	982	1	4	1	1.0	Not Directly
	10 Named Storms	7 Hurricanes					66 Storm Days	35 Hur. Days	107.8 HDP	7 of Cape Verde African Origin

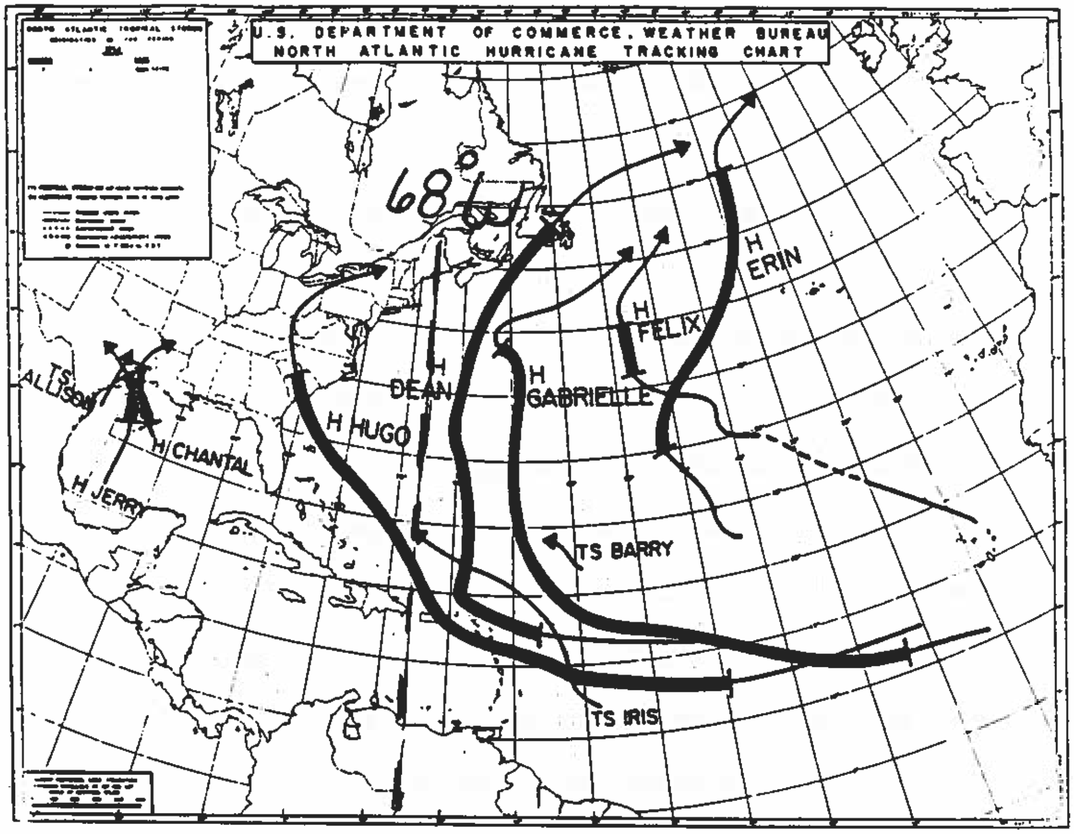

Fig. 1. Tracks of tropical cyclones for 1989. Dashed lines show periods of disturbance, solid lines indicate the periods of tropical storm intensity (maximum sustained winds with 39-72 mph), and thick lines show the periods of hurricane intensity (maximum sustained winds greater than 73 mph). Vertical dashed line at 68°W indicates dividing line between the more numerous tropical cyclone activity to the east.

(V_{max}) equal or greater than 65 knots (75 mph) for each 6-hour period of its existence.* The total HDP for 1989 was 108. Last year (1988) the HDP value was 81 and the Sahel was well watered. By contrast, during the drought years of 1982-1987 HDP values were only 18 (1982), 8 (1983), 42 (1984), 61 (1985), 23 (1986) and 11 (1987).

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

The 1989 hurricane season was notable for:

1. A large proportion of hurricanes and named storms forming in the Atlantic were far to the east. The seven Cape Verde or African spawned systems first made depression status at an average longitude of 30°W and acquired named storms status at the far eastern longitude of 37°W. Hurricane status for the five African spawned storms that became hurricanes was accomplished at an average longitude of 45°W. These formation statistics are significantly further to the east than those of the usual hurricane season. These unusual eastern Atlantic formations at low latitudes (usually south of 20°) dictated that 1989 systems have very long tracks. For instance, Hurricanes Dean, Erin, Felix, Gabrielle, and Hugo existed as named storm for 8, 8, 11, 13, and 12 days, respectively.

2. Although there were seven hurricanes in 1989 (one above average), five of the seven hurricanes were not strong hurricanes. Three of the seven hurricanes (Chantal, Felix, and Jerry) were of Saffir/Simpson Category 1, Hurricane Dean and Erin were of category 2. Early season Tropical Storms Allison and Barry were minimal tropical storms.

3. Although the early part of the hurricane season was quite active with seven of the 10 name storms forming by the end of August (the average number of named storms to the end of August is four), the latter part of the season was quite inactive. Only one relatively weak and short lived named storm (Hurricane Jerry) formed after September 18 (the average number of named storms for this later period is nearly four).

4. Hurricane Hugo was the most intense hurricane to strike the US coastline since Hurricane Camille in 1969. The property loss from Hurricane Hugo has been reported to be the largest of any previous storm

in the US history.

5. Although 1989 was an above average hurricane season, the amount of hurricane and tropical cyclone activity west of 68°W longitude was not very large. Figure 2 contrasts named storm tracks west of 68°W in the active hurricane seasons of 1985, 1988 and 1989. The 1989 season had fewer named storm tracks in the western part of the Atlantic basin than the two previous active hurricane seasons. Except for Hurricane Hugo there were no long westward moving named storm tracks through the western Atlantic basin.

As inspection of Fig. 1 show that most of the 1989 tropical cyclone activity occurred to the east of 68°W, a line running from eastern Maine to just west of Bermuda to just west of Caracas, Venezuela. Most people affected by hurricanes live west of this line. Table 2 gives tropical cyclone statistics for the Atlantic basin west of 68°W. This western region experience 14 named storm days, 6 hurricane days and an HDP of 13. This represented but 21, 13, and 12 percent of the total Atlantic basin activities. Few hurricane seasons such as 1989 have such a concentration of storm activity in the central and eastern part of the Atlantic basin. Those seasons that do (1980 for instance) usually have higher values of West African rainfall.

6. It was the formation of two category 4-5 Hurricanes (Gabrielle and Hugo) which made 1989 such an active hurricane season. Gabrielle was in hurricane status for 9 days and obtained a maximum sustained wind of 125 knots (145 mph) and a minimum central pressure of 937 mb (27.67" of mercury) while Hugo was in hurricane status for 10 days and obtained a maximum sustained wind of 140 knots (160 mph) and a minimum surface

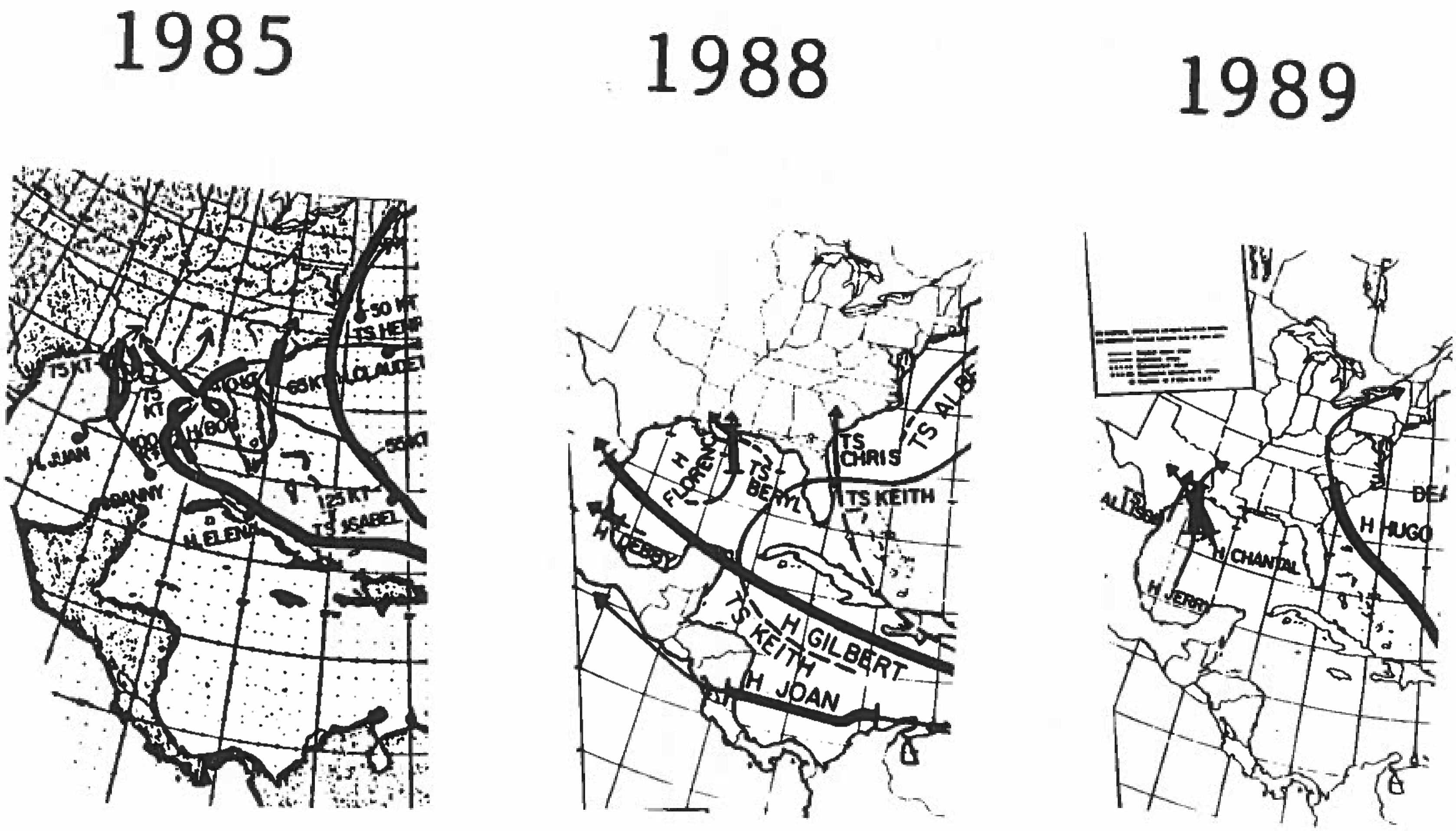

Fig. 2. Hurricanes (thick lines) and Tropical Storms (thin lines) in the vicinity of US and west Caribbean during the last three active hurricane seasons of 1985, 1988, and 1989.

TABLE 2

Summary of 1989 tropical cyclone activity west of 68°W and percentage to total basic activity.

Named Storm	Named Storm Days	Hurricane Days	HDP
TS Allison	2	0	0
HUR Chantal	2	1	11.0
HUR Hugo	6	4	1.4
HUR Jerry	4	1	1.0
TOTAL	14	6	13.4
Percent of Total	21%	17%	12%

pressure of 918 mb (27.11" of mercury). These two hurricanes had a combined total of 19 hurricane days and an HDP of 76. Had these two hurricanes not formed, 1989 would have been classified as a comparatively inactive season. By contrast, each of the seasons of 1982-83-86-87 has seasonal HDP values less than 23.

A brief summary of each Atlantic TC which occurred in 1989 is as follows:

1) Tropical Storm Allison. This minimal tropical storm formed in the northwestern part of the Gulf of Mexico from the remnants of an east Pacific hurricane and a westward moving wave disturbance. Although it only existed as a named storm for 36 hours and its maximum sustained winds only reached 45 knots, its remnants persisted as a very weak circulation over western Louisiana for more than a week and produced extensive flood damage.

2) Tropical Storm Barry. This minimal tropical storm formed in the central Atlantic from a wave that had moved off of the West Africa coast. Barry lasted for only 2 1/2 days before it gradually dissipated to the east of the Bahamas due to vertical wind shearing. Its maximum sustained

winds were 45 knots and minimum central pressure was 1005 mb.

3) Hurricane Chantal. This short lived and minimal hurricane formed from a cloud cluster that could be traced backward to near Trinidad. The pre-storm cloud cluster moved westward as a tropical wave into the Gulf of Mexico and then turned towards Galveston. Chantal then began a rapid intensification one day from making landfall near Galveston. Chantal existed as a hurricane for only 18 hours. The main effects from Chantal were flooding from torrential rains, primarily in northeastern Texas.

4) Hurricane Dean. Hurricane Dean formed from a westward moving African wave and followed a typically long recurving track. It passed over Bermuda and then moved northwards to Newfoundland where it dissipated. It had a very slow but steady intensification over six days while moving westwards in the trades. Maximum winds were 90 knots and minimum estimated central pressure was 968 mb.

5) Hurricane Erin. This system formed from an African spawned westward moving easterly wave. It interacted with another mid-Atlantic wave system and then took a track NNW and gradually intensified to hurricane status far to the east of Bermuda. Erin then moved NNE to 50°N before taking an extra-tropical characteristics in the mid-Atlantic. Erin never reached as far west as 50° longitude.

6) Hurricane Felix. This short lived hurricane also formed from a westward moving African wave. After forming, Felix followed a NNW track similar to that of Erin a week before. Felix then weakened to a tropical depression before reintensifying, moving northward and dissipated far to the east of Newfoundland. Felix was a hurricane for less than 48 hours and had maximum sustained winds of 90 knots. It also never reached 50°W

longitude. The pre-storm waves from which Erin and Felix formed left the African coast at relatively high latitudes which inhibited their westward passage to the western Atlantic.

7) Hurricane Gabrielle. This was a major category 4 hurricane. It had a very broad circulation and lasted in named storm status for 13 days. It developed from an African wave near the Cape Verde Islands then tracked westward across the tropical Atlantic and followed a typical recurvature track. This was fortunate for the residents of the US east coast. Gabrielle nevertheless brought strong sea swells to the US Northeast Coast. Maximum sustained winds were 125 knots and minimum central pressure was 937 mb. Gabrielle took on extra tropical characteristics and weakened south of Newfoundland.

8) Hurricane Hugo. This most damaging of all hurricanes formed from an easterly wave that moved off the west African coast on the 9th of September. Hugo had a long and continuous west to WNW track, crossing the NE Caribbean before moving northwest and making landfall at Charleston, SC. Hugo attained a maximum wind of 140 knots (160 mph) and a minimum central pressure of 918 mb on the 15th of September when it was located to the east of the Leeward Islands. At this time it was a minimal class 5-hurricane on the Saffir/Simpson scale. It weakened somewhat near the Virgin Islands but then reintensified to a class-4 hurricane as it moved ashore at Charleston. Hugo caused extensive coastal and inland damage to the US. There was a very strong storm surge with Hugo.

9) Tropical Storm Iris. The tropical wave that spawned Iris moved off the west coast of Africa just a few days behind the African wave that had spawned Hugo. Iris moved westward across the Atlantic following

Hugo's path. But Iris's intensification was inhibited by Hugo's upper level outflow and it dissipated over the tropical Atlantic north of Puerto Rico. Iris existed as a tropical storm for only 3 days. Its maximum central pressure did not go below 1000mb

10) Hurricane Jerry. This weak and short lived October hurricane formed from a wave that moved across the Caribbean into the Bay of Campeche without much intensification. This system then made a turn to the north and underwent rapid intensification to hurricane status just before making landfall at Galveston. Jerry was of hurricane intensity for about 18 hours. Its maximum sustained winds were 75 knots and minimum central pressure was 982 mb.

Comparison of 1989 With Other Hurricane Seasons of the Last 40 Years. In terms of average hurricane days and HDP during the 40-year period of 1950-89 1989 was an active season. 1989 ranked 11th and 10th in activity (see Table 3). There were 14 of 40 other seasons during 1950-89 with as many or more hurricanes as 1989. There were 20 of 40 other seasons with as many or more named storms as 1989.

TABLE 3

Ranking of 1950-1989 seasons by highest number of hurricane days and Hurricane Destruction Potential (HDP).

Hurricane Days	Hurricane Destruction Potential
57 (1950)	213 (1959)
46 (1955)	183 (1961)
46 (1961)	171 (1955)
43 (1964)	149 (1964)
41 (1966)	126 (1966)
39 (1969)	126 (1980)
38 (1980)	120 (1951)
37 (1951)	114 (1969)
36 (1963)	111 (1963)
35 (1967)	108 (1989)
35 (1989)	

2. Associations Between Intense Hurricanes and West African Rainfall

Most intense hurricanes originate as wave systems emanating from Africa (or Cape Verde). A much higher percentage of these wave systems develop into intense hurricanes during wet as opposed to dry Sahel summers. It appears that it is not necessarily the number of systems emanating out of Africa each summer which is the crucial factor to the formation of intense hurricanes. Rather it is the organizational and intensity character of the individual system moving off Africa in combination with the properties of the tropical Atlantic environment into which the organized system moves for 4-5 days. Avila and Clark (1989) have recently discussed yearly variability in West African wave frequency.

When abundant Sahel rainfall occurs, wave disturbances coming off Africa are typically better organized and thus better able to take advantage of the generally more favorable equatorial Atlantic environment into which they move. Moist conditions in the Sahel act to reduce the regional lower tropospheric south-to-north West African temperature gradient and the strength of the 600-700 mb easterly jet. The mode of convection is thus one of producing more organized, slower, and deeper tropospheric weather systems as opposed to the more rapidly moving and less conservative squall line systems which are characteristic of dry years. Squall systems typically dissipate as they move across the eastern Atlantic and do not produce the steadily moving, vertically stacked and better organized weather system of the usual pre-hurricane cloud cluster.

Figure 3 illustrates the direct association between Lamb's (1985) Sahel rainfall index and Hurricane Destruction Potential (HDP) and hurricane days. Figure 4 is similar to Fig. 3 but for the comparison of

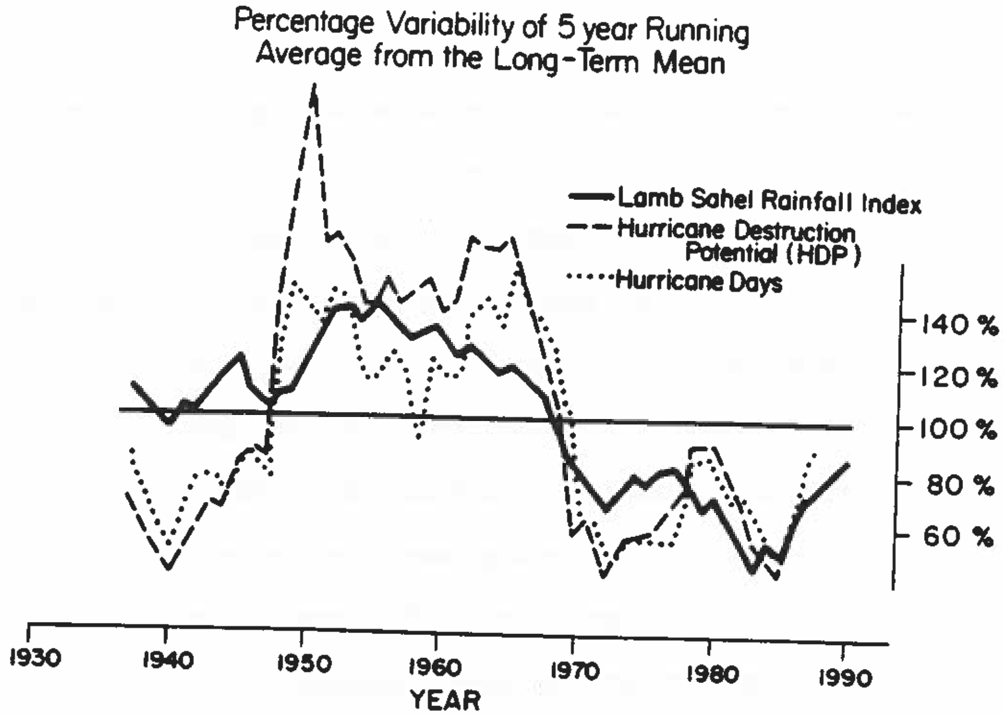

Fig. 3. Comparison of variability of the Lamb Sahel rainfall index with Hurricane Destruction Potential (HDP) and number of hurricane days.

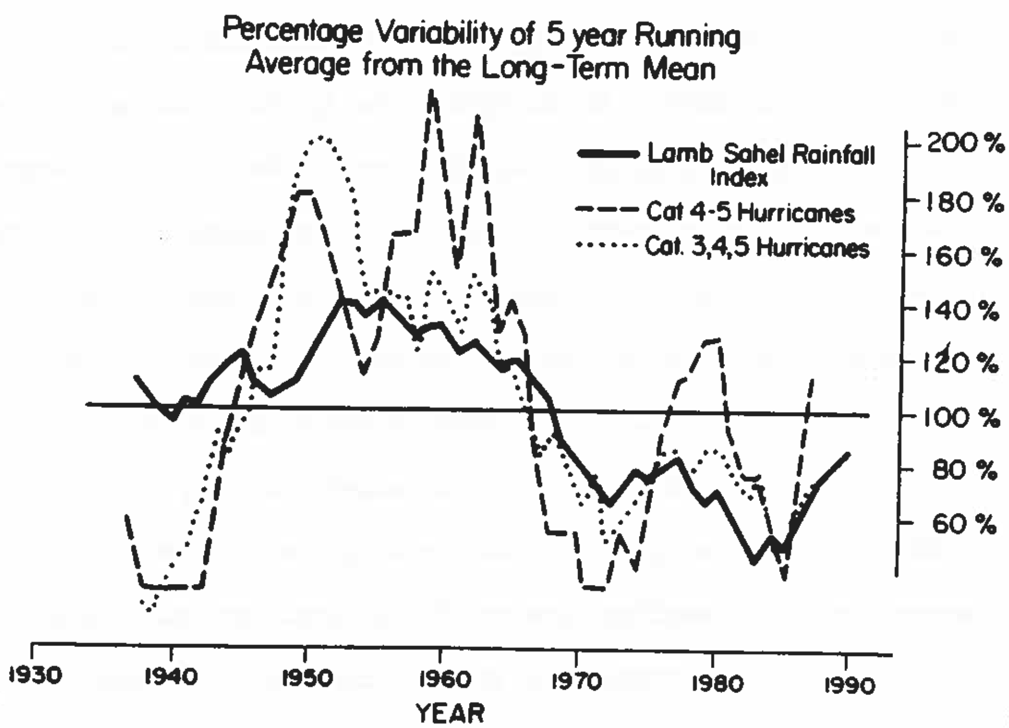

Fig. 4. Comparison of variability of the Lamb Sahel rainfall index with Saffir/Simpson category 4-5 and category 3-4-5 hurricanes.

the frequencies of Saffir/Simpson category 4-5 and category 3-4-5 hurricanes with Sahel rainfall. Note the high association of these 5-year overlapping values with Sahel multi-decadal rainfall variations.

The character of the systems coming off of Africa which are strongly modulated by West African rainfall conditions. This rainfall modulation of hurricane activity is strikingly illustrated by the number of Atlantic hurricane tracks during periods when the stations of the northern two-thirds of Senegal had more than 120% of their May to October long-term rainfall (Fig. 5) in contrast to when these same Senegal stations had rainfall which was less than 80% of their long-term average values (Fig. 6). Note the striking contrast in the hurricane track frequency of African spawned systems. It is these African spawned systems which produce the most intense and destructive hurricanes.

3. Rainfall in the Western Sahel in 1989

Very large amounts of rainfall occurred in the western Sahel region in July through September 1989. August rainfall was substantially higher than that which occurred during August of the drought years of 1970-87. Figure 7 shows ratios of August 1989 rainfall at each station to the average August rainfall at each for the period of 1970-87. Western Sahel August 1989 rainfall was nearly double that of the 1970-87 drought period and averaged 142% of the long-term mean August rainfall (Fig. 8). August 1989 was 116% of the average August rainfall experienced during the wet period of 1951-69. Figure 9 graphically compares the average August 1989 West Sahel rainfall for all stations with similar August rainfall for the 1970-87 (dry) and 1951-69 (wet) periods. This heavy 1989 August rainfall trend continued through mid-September and is consistent with the

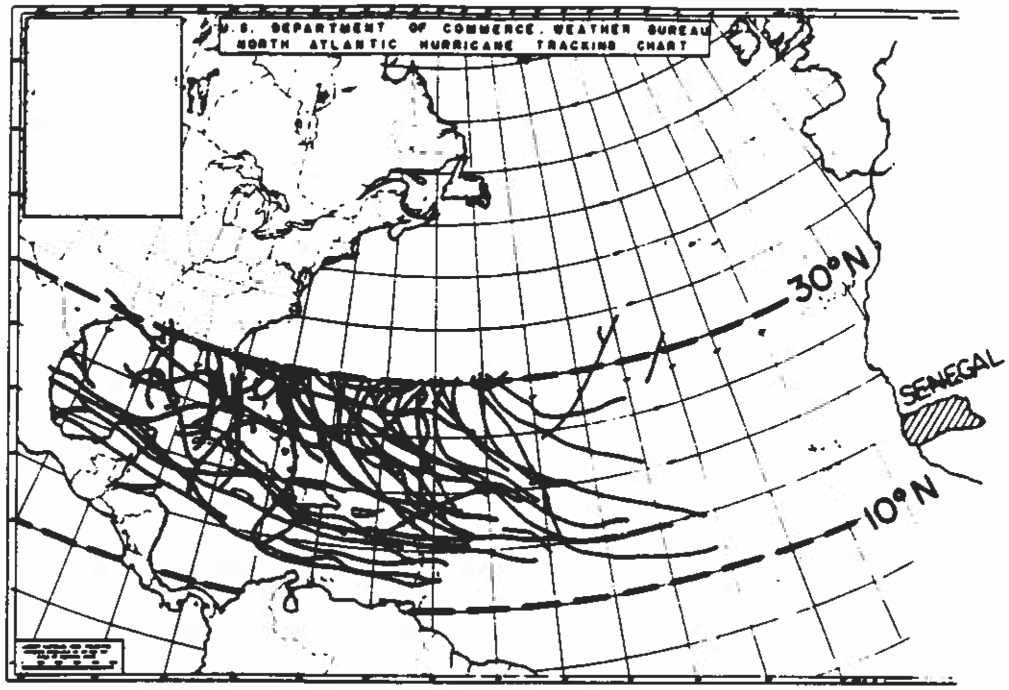

Fig. 5. Ten years of hurricane tracks equatorwards of 30°N when northern two-thirds of Senegal May-October precipitation was greater than 120% of the long term average. Years 1950-51-52-54-55-64-66-67-69-88.

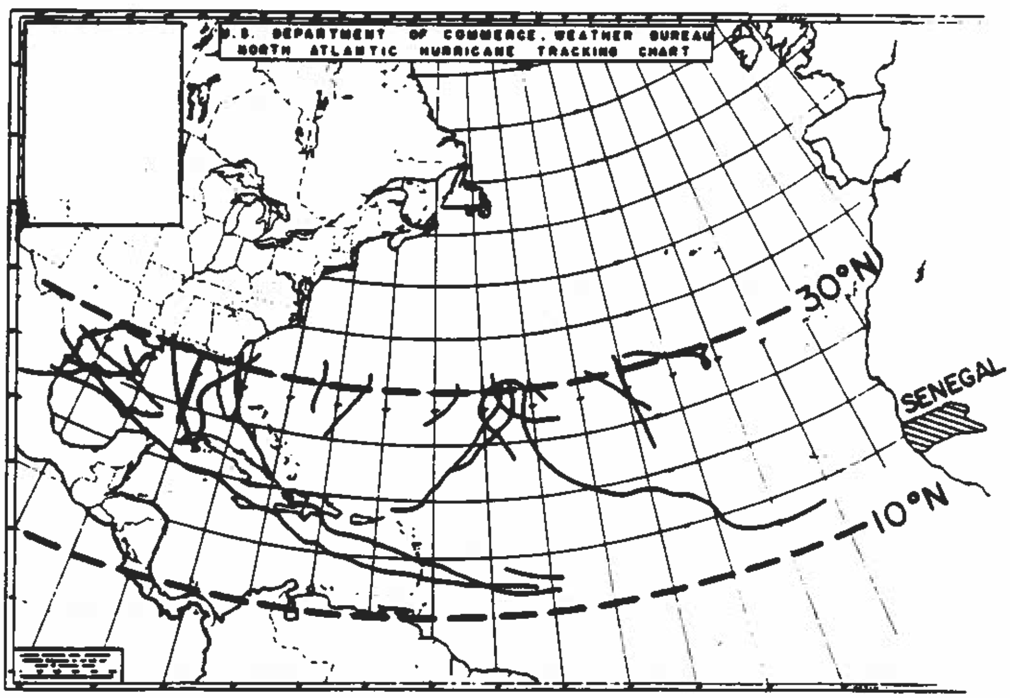

Fig. 6. Eleven years of hurricane tracks when northern two-thirds of Senegal May-October precipitation was less than 80% of the long term average. Years 1968-70-72-73-77-79-80-82-83-84-86.

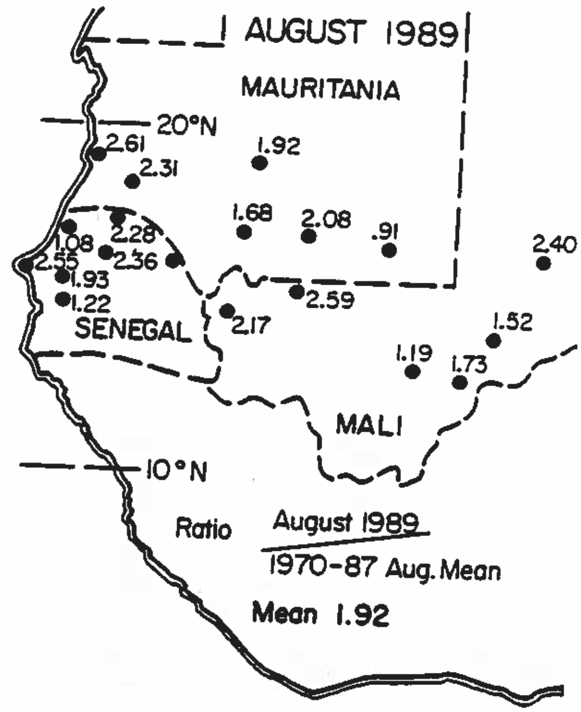

Fig. 7. Ratio of August 1989 rainfall in the western Sahel to mean August rainfall for the period of 1970-87.

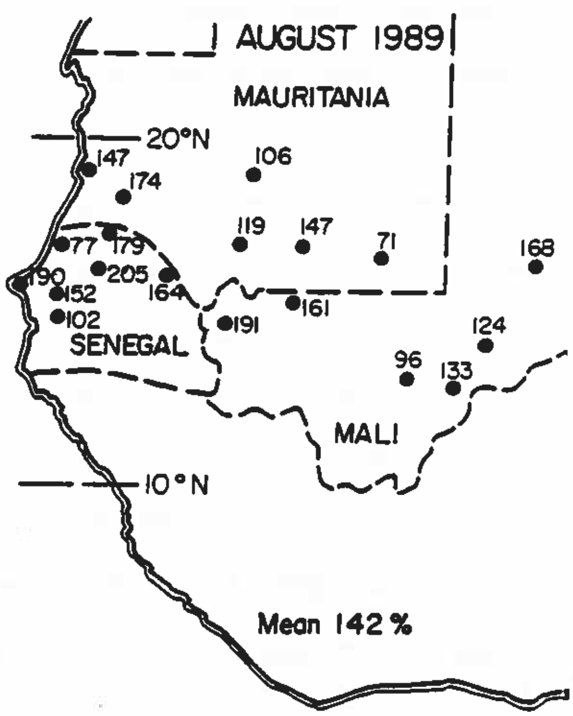

Fig. 8. August 1989 rainfall in the western Sahel expressed as a percentage of the average August rainfall for the period of 1951-87.

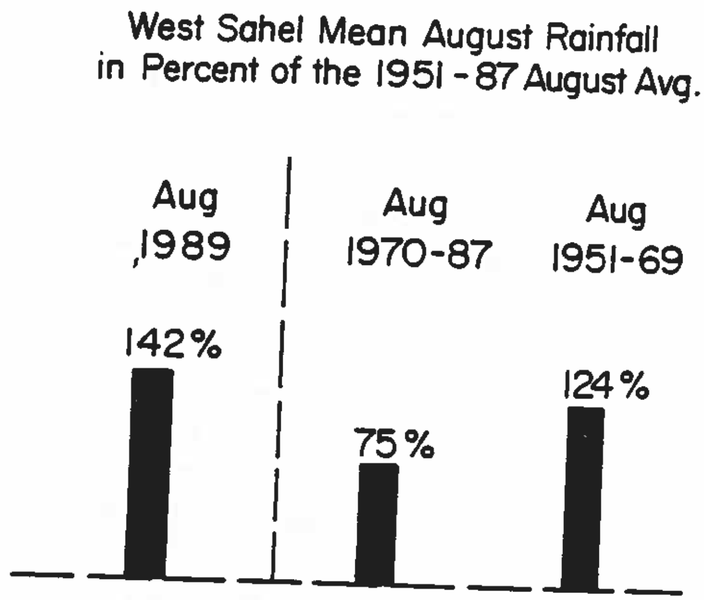

Fig. 9. Comparison of 1989 August western Sahel rainfall with August rainfall for earlier dry (1970-87) and west (1951-69) periods.

propagation of the five 1989 hurricanes (Dean, Erin, Felix, Gabrielle, Hugo) and one Tropical Storm (Iris) which formed from wave disturbances when left the west African coast between late July and the middle of September.

After mid-September western Sahel rainfall decreased substantially and at the same time, no further named storm developments occurred in the Atlantic. West African wave activity also appreciably decreased. West African rainfall from mid-September through October 1989 has been below normal and except for weak Hurricane Jerry which formed in the Gulf of Mexico in mid-October, no named storms formed in the Atlantic Basin after the western Sahel rains abated in mid-September.

4. Other Primary Factors Associated with Atlantic Seasonal Hurricane Variability

The author's Atlantic seasonal hurricane forecast has been based on the characteristics of two global and two regional environmental factors which the author has previously shown to be statistically related to variations in seasonal hurricane frequency. These factors are:

a) The presence or absence of a moderate or strong El Nino (warm water event) in the eastern tropical Pacific off of Peru. Seasons during which an El Nino event is present are usually experience suppressed hurricane activity.

b) The direction of the 30 mb (23 km altitude) and 50 mb (20 km altitude) stratospheric or Quasi-Biennial Oscillation (QBO) winds which circle the globe over the equator. On average, there is nearly twice as much Atlantic hurricane activity (as reflected by the number of hurricane days) in seasons when QBO winds are from a relatively westerly direction as compared to seasons when QBO zonal winds are from a relatively easterly direction.

c) The Caribbean Basin-Gulf of Mexico Sea Level Pressure Anomaly (SLPA). Other factors aside, a negative spring-early summer sea surface pressure anomaly generally precedes greater the Atlantic seasonal hurricane activity. Higher pressures are associated with reduced hurricane activity.

d) Low latitude Caribbean Basin upper tropospheric (~ 200 mb or 12 km altitude) west to east Zonal Wind Anomaly (ZWA) in non-El Nino seasons. The stronger the 200 mb zonal winds are from the west the generally greater the suppression of hurricane activity and vice-versa.

5. Characteristics of Seasonal Hurricane Predictors During 1989

a) El Nino. No El Nino event was present in the Pacific during the 1989 season. In fact somewhat cool water was present during the whole of the 1989 hurricane season. The lack of an El Nino event during 1989 is further verified by the presence of 200 mb (12 km altitude) easterly wind anomalies in the lower Caribbean Basin during August and September. In El Nino seasons Caribbean Basin 200 mb zonal winds are typically anomalously from the west rather than from the east as was observed this year.

b) <u>Stratospheric QBO in 1989</u>. Table 4 shows the actual QBO zonal wind speeds as measured by upper air stations near 12°N in the Atlantic region for April-October 1989. It is at these latitudes where African spawned hurricanes form. These winds are an average of the low latitude eastern Caribbean stations of <u>Curacoa</u> (12°N), <u>Trinidad</u> (11°N), and <u>Barbados</u> (13°N). Table 5 shows the generally easterly QBO wind anomalies which extended through the entire layer by August. Wind at 30 mb (23 km), 50 mb (20 km), and 70 mb (18.5 km) were strongly from the east during the height of the hurricane season. Although easterly QBO winds are normally a suppressing influence on low latitude African origin tropical cyclones, two intense hurricanes did form. Had QBO winds been from a relative easterly direction, we might have, because of the unusually large amounts of western Sahel rainfall, had 3 or 4 intense hurricanes in 1989.

c) Sea Level Pressure Anomalies (SLPA) were above normal for the period of April through most of July and then fell abruptly to negative values for August and then to very large negative values in September (see Table 6). In normal years, higher than average April through July SLPA is indicative of higher SLPA values for the crucial August-September period. This was not the case in 1989 although pressure rose in late September and October SLPA was also positive.

TABLE 4

April through October 1989 observed average stratospheric zonal wind (u) for the lower latitude and eastern Caribbean Basin stations of Curacoa (12°N), Trinidad (11°N), and Barbados (13°N). Values in m/s. (Courtesy of Colin McAdie of NHC).

	Observed						
Level	Apr	May	Jun	Jul	Aug	Sept	Oct
30 mb (23 km)	-18	-23	-25	-33	-29	-29	-25
50 mb (20 km)	- 1	- 4	-11	-17	-19	-18	-14
70 mb (18.5 km)	- 1	+ 4	- 6	-11	-12	-13	- 6
100 mb (16.5 km)	0	+11	+ 3	- 4	- 5	- 8	+ 4

d) Upper-tropospheric Zonal Wind Anomaly (ZWA). Table 7 shows lower Caribbean 200 mb (12 km altitude) west to east zonal wind anomalies for the period of June through October, expressed as departures from mean values for the period of 1970-1986. As with the SLPA, the 200 mb lower Caribbean Zonal Wind Anomaly (ZWA) was positive from April through June, slightly negative in July and August but quite negative (-6.8 m/s) in September. Given the positive average of 1.1 m/s for April through July, the rapid swing to such large negative values in September was not anticipated.

Discussion. It was unusual for both the 1989 SLPA and ZWA patterns to swing sharply from positive values in the spring and early summer to large negative values in the late summer. These exceptional trends were likely a result of a strengthening of the monsoon trough off of West Africa and the more northward penetration of the Intertropical Convergence

TABLE 5

April through October 1989 relative zonal wind (u) where the annual wind cycle has been removed. Values represent an average of the eastern Caribbean Basin stations of Curacao (12°N), Trinidad (11°N), and Barbados (13°N). Values in m/s.

Level	Apr	May	Jun	Jul	Aug	Sept	Oct
30 mb (23 km)	-10	- 9	- 8	- 8	- 9	- 7	- 6
50 mb (20 km)	+ 1	+ 3	0	- 3	- 5	- 8	- 5
70 mb (18.5 km)	- 1	+ 5	0	- 1	- 2	- 4	- 1
100 mb (16.5 km)	- 3	+ 6	- 1	+ 1	0	- 9	- 1

TABLE 6

1989 Sea Level Pressure Anomaly (SLPA) for Six Key Caribbean Basin-Gulf of Mexico Stations and five low latitude stations (in mb). (1 mb = .0295 inches of mercury). Courtesy of Colin McAdie of NHC.

6 Gulf of Mexico-Caribbean Basin Stations

	April-May	Jun	Jul	Aug	Sept	Oct
Brownsville (26°N)	+0.5	-1.4	+0.7	-0.3	+1.1	+1.7
Merida (21°N)	+1.8	+1.0	+0.6	+0.5	-0.8	+2.1
Miami (25.5°N)	+0.7	+2.1	+0.9	-0.6	-1.0	+2.1
San Juan (18.5°N)	+0.5	+0.6	-0.1	-1.5	-2.7	+0.5
Curacao (12°N)	+0.8	+1.3	+0.6	-0.2	-1.1	+1.3
Barbados (13.5°N)	+1.1	+0.5	-0.2	-0.7	-2.1	+0.4
6-Station Average	+0.9	+0.7	+0.4	-0.5	-1.1	+1.3

5 Low Latitude Stations

	April-May	Jun	Jul	Aug	Sept	Oct
San Juan (18.5°N)	+0.5	+0.6	-0.1	-1.5	-2.7	+0.5
Curacao (12°N)	+0.8	+1.3	+0.6	-0.2	-1.1	+1.3
Barbados (13.5°N)	+1.1	+0.5	-0.2	-0.7	-2.1	+0.4
Trinidad (12°N)	+1.5	+1.0	+0.8	-0.5	-1.2	+1.1
Cayenne (5°N)	+0.6	+1.0	+0.2	0	-0.9	+0.6
5-Station Average	+0.9	+0.9	+0.3	-0.6	-1.6	+0.8

TABLE 7

Lower Caribbean Basin 1989 200 mb (12 km) Zonal Wind Anomaly from 1970-1986 average conditions - in m/s.

Station	Apr-May	Jun	Jul	Aug	Sept	Oct
Trinidad (11°N)	+ 2	+ 3	- 3	- 2	-11	+ 7
Curacao (12°N)	+ 2	+ 4	- 3	- 2	- 7	+ 2
Barbados (13.5°N)	+ 1	+ 4	- 1	- 2	-10	+ 4
Kingston (18°N)	+ 1	+ 3	- 4	- 1	- 1	+ 3
Balboa (9°N)	+ 2	0	+ 2	+ 2	- 4	+ 2
Average	+1.6	+2.8	-1.8	-1.0	-6.8	+3.6

Zone (ITCZ) over the central Atlantic and northern portions of South America. This more poleward penetration of the ITCZ caused a lowering of surface pressure and 200 mb zonal winds in central Atlantic and Caribbean basins and lead to the establishment of very favorable conditions for low latitude hurricane formation from African spawned wave disturbances. The very heavy rainfall in the Sahel throughout August and the first part of September was a consequence of the broad Western Hemisphere and African large-scale region circulation changes which brought about a sharp enhancement of the West African monsoon trough. Positive SST anomalies were observed to form off of West Africa, the mid-Atlantic equatorial trades weakened and the 600-700 West African jet weakened. All these factors have previously been associated with wet conditions in the western Sahel (see Hastenrath, 1984; Newell and Kidson, 1974; and Reed, 1986).

The author's global predictors, the El Nino and QBO, are not observed to be related to western Sahel rainfall whereas SLPA and ZWA are statistically related to Sahel rain conditions. In any individual year the SLPA-ZWA and Sahel rainfall relationship may not hold, however. 1989 was one of these years. The author's 1989 seasonal forecast was largely insensitive to the abnormally amounts of Sahel rainfall that would fall this year, leading to the sizable underforecast.

6. Verification of Author's Seasonal Prediction

Table 8 gives a summary of the author's end of May 1989 forecast for the hurricane season, the end of July updated forecast and their verification. Except for the number of named storms this year's forecast was very poor for all other forecast parameters. This lack of accuracy is attributed to the apparent breaking of the African Sahel drought which was not explicitly included in the author's forecast scheme and which the author did not properly account for. A study of the last 40 years of hurricane seasons had shown that those seasons of easterly QBO wind and above average SLPA in April through July were usually suppressed hurricane seasons. I had to follow my already developed forecast scheme. The British Meteorological Office statistical forecast had indicated dry conditions for the Sahel. Their global numerical model somewhat wet conditions. It was impossible to know if the relatively heavy Sahel rains of 1988 were a one year occurrence or whether 1988 represented the start of a longer term break in the Sahel drought. It has been 40 years since the last Sahel transition from wet to dry conditions. Western Sahel rainfall in 1988-89 has been greater than any two consecutive years since 1966-67.

The most intense hurricanes are usually African spawned hurricanes that typically have the longest lifetimes. Underforecasting just one or two of these strong African systems may render HDP and hurricane day

TABLE 8

Forecast and Verification of 1989 Seasonal TC Forecast

	Original 26 May Forecast	Updated 27 July Forecast	Observed Verification
No. of Hurricanes	4	4	7
No. of Named Storms (Hurricanes and Tropical Storms)	7	9	10
No. of Hurricane Days	15	15	35
No. of Hurricane and Tropical Storm Days	30	35	66
Hurricane Destruction Potential (HDP)*	40	40	108

*The seasonal sum of the square of each hurricane's maximum sustained winds at each 6-hour period of its existence (units 10^4 $knots^2$). A hurricane with 100 kt (115 mph) maximum winds which exists for 1 day (or four 6-hour time period) has a HDP of 4.

forecast off by a large margin. Hurricane Hugo alone had a total HDP of over 40 units and Gabrielle and Hugo together had a total of 19 hurricane days and 25 named storm days, and an HDP of 76.

It is now clear that any Atlantic seasonal forecast scheme which fails to account for western Sahel rainfall will fail, especially in those seasons in which a basic change from drought to wet or from wet to drought occurs. The associations between intense hurricanes and Sahel rainfall are too strong to be neglected.

African rainfall influences were partially contained in the forecast through the Caribbean Basin Sea Level Pressure Anomaly (SLPA) and Upper Tropospheric Zonal Wind Anomaly (ZWA). When African rainfall is above average, Caribbean Basin SLPA and ZWA are typically below average;

conditions which act to enhance hurricane activity. Conversely, when African rainfall is below average, lower Caribbean Basin SLPA and ZWA is typically higher than normal and hurricane activity is reduced. Unfortunately, these African rainfall and Caribbean Basin pressure-wind associations are not strong and hence not as reliable for individual years as one would desire. There are some seasons wherein low Caribbean SLPA and ZWA in late spring-early summer is not a good predictive signal of late summer (August-September) SLPA-ZWA or of West African rainfall. Although Caribbean basin SLPA was high for April through July 1989, a rapid lowering of Caribbean Basin SLPA and ZWA occurred from late July to early August. This trend led to established very favorable conditions for low latitude hurricane formation from African spawned systems. These late July early August changes would likely not have occurred if western Sahel rainfall conditions had remained as they were from 1970-87. Seven named storms originating from Africa formed during the 48 day period of 31 July through 17 September during which time western Sahel precipitation was nearly double the average values for 1970-87.

The author has constantly stated that his forecast scheme:

> "although showing quite promising statistical skill in the standard meteorological sense, can only predict about half of the total variability in Atlantic seasonal hurricane activity. This forecast scheme will likely fail in some years when other currently unknown factors (besides the QBO, EN, SLPA and ZWA) which affect hurricane variability are more dominant. It is impossible to determine beforehand those years in which the author's forecast scheme will work best or worst." (Stated in all previous forecasts).

The poor verification of this year's forecast is almost certainly related to the as yet unassimilated effects of western Sahel rainfall conditions. The poor 1989 forecast may in the long run prove to be beneficial in the sense that the author and his project personnel have recently embarked on a major new study of the variability and causes of seasonal West African rainfall and its relationship to hurricane variability.

We are now engaged in new research to assess the extent to which we may be able to make advanced predictions of western Sahel August-September rainfall. Given the association of Sahel rainfall with Atlantic SST, wind, and pressure patterns as discussed by Newell and Kidson (1974), Hastenrath (1984), and Reed (1986), it is very likely that an explicit and skillful seasonal Sahel rainfall forecast scheme will eventually be devised. Such a forecast would have added a significant improvement to this year's predictions and I am very confident that this new research will add to the improvement of future forecasts.

Verification of the Author's Previous Five Seasons of Forecasts. Table 9 gives verification data for the five previous seasonal forecasts of Atlantic hurricane activity by the author. The late July forecasts have been superior to the late May forecasts and the forecasts of named storm activity have been the most successful. Forecasts for 1984-1988 had been a significant improvement over climatology, the only objective seasonal prediction that had previously been available.

7. Outlook for 1990

Assuming that the Sahel drought is now broken, it is expected that the western Sahel will likely have above average rainfall in 1990. Because it is not very long since the moderate El Nino event of 1986-87, or the unusually strong El Nino of 1982-83, the odds do not favor the development of an El Nino in 1990. If the suppressing influence of a

TABLE 9
Verification of the author's previous seasonal predictions of Atlantic tropical cyclone activity for 1984-1988.

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		21
No. of Named Storm Days	45		61

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	29
No. of Named Storm Days	55	50	60

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	13
No. of Named Storm Days	35	25	27

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	7
No. of Named Storm Days	40	35	36

1988	Prediction of 26 May and 28 July Update	Climatology	Observed
No. of Hurricanes	7	(6)	5
No. of Named Storms	11	(9)	12
No. of Hurricane Days	30	(24)	26
No. of Named Storm Days	50	(45)	56
Hurr. Destruction Potential (HDP)	75	(73)	81

moderate or strong El Nino event does not occur next year then it is to be expected that 1990 will be an above average hurricane season. This is especially the case as regards the hurricane statistics for the last 20 years.

By next season the QBO winds will likely have shifted or be in the process of shifting from a relatively easterly to a westerly direction. A QBO shift to westerly anomalies should be a factor in enhancing next year's hurricane activity.

Because of the breaking of the Sahel drought, we have likely entered into a new multi-decadal period of intense West African spawned hurricanes that will be similar to the more frequent intense hurricanes of the mid-1930s and of the 1950s and 1960s. It appears likely that next season may see 2 or 3 hurricanes with intensities similar to Gilbert, Helene, Joan, Gabrielle, and Hugo of 1988-1989.

8. Possibilities for More Intense Atlantic Hurricanes in the 1990s.

Because of the heavier western Sahel rainfall and more intense hurricanes of 1988 and 1989, it appears that the long 18-year Sahel drought is now broken. We have to go back to 1966-67 before we find two consecutive seasons when western Sahel rainfall or HDP as large or greater than the seasons of 1988-89.

We might compare how intense Atlantic hurricanes were during the last Sahel wet period of the 1950s and 1960s to the recent dry period. Figure 10 compares the wet period of 1947-69 and dry period of 1970-87 by the annual average of Saffir/Simpson category 4-5, 3, and 1-2 hurricanes per season. Note the more than two-to-one differences in category 4-5 and 3 hurricanes between these two contrasting wet and dry periods and the lack of any period differences between category 1-2 hurricanes. It is only the intense hurricanes which have shown these multi-decadal differences associated with Sahel rainfall conditions.

Figure 11 contrasts the number of landfalling US hurricanes by Saffir/Simpson intensity category. During 1947-69 there were 18 landfalling hurricanes of category 3-4-5 versus 8 during the period of 1970-87. There were six landfalling category 4-5 hurricanes in the earlier period but none in the later period. This trend amounts to close to a two to one difference in intense US hurricane strikes per year. A similar increase in intense US landfalling hurricanes should likely be expected. Hugo may be a precursor of a number of more intense hurricanes to strike the US and Caribbean in the next decade or two.

Previous African Multi-decadal Wet and Dry Periods. Multi-decadal climate changes are a pervasive feature of the global circulation. Multi-decadal rainfall and circulation changes have been observed back as far as meteorological measurements have been made. Although we do not understand the causes of multi-decadal circulation and rainfall changes, it is likely that they are related to multi-decadal variations of the ocean circulation and vertical mixing processes that are known to occur on time scales of decades to centuries.

Figure 12 shows Entekhabi and Nicholson's (1987) estimate of Sahel drought condition back to 1900. Note that a period of drought occurred in the early years of this century that was similar to the recent 1970-87 drought. There was also a period similar to 1950-69 when enhanced Sahel rain conditions occurred from the middle 1920s through to the late 1930s.

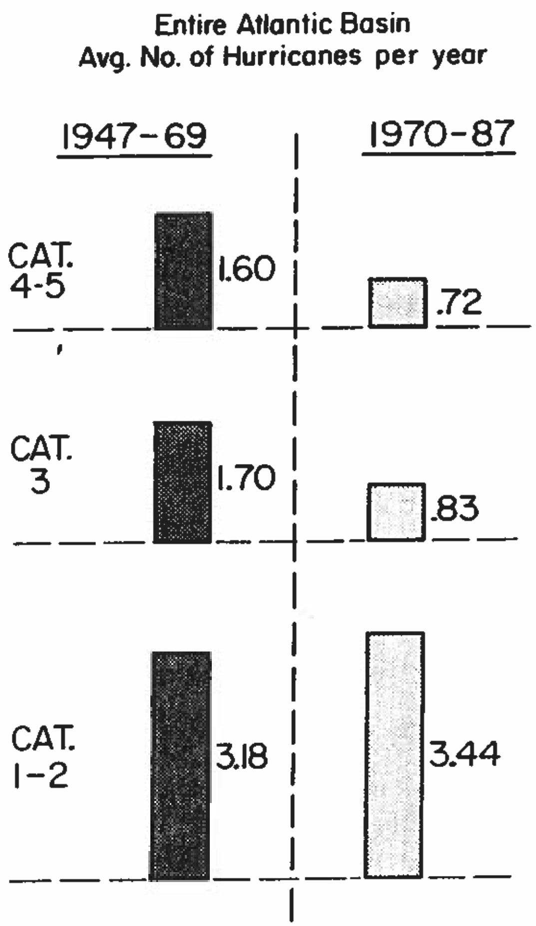

Fig. 10. Comparison of wet (1947-69) and dry (1970-87) West African periods with regards to annual number of Saffir/Simpson category 4-5, 3, and 1-2 hurricanes.

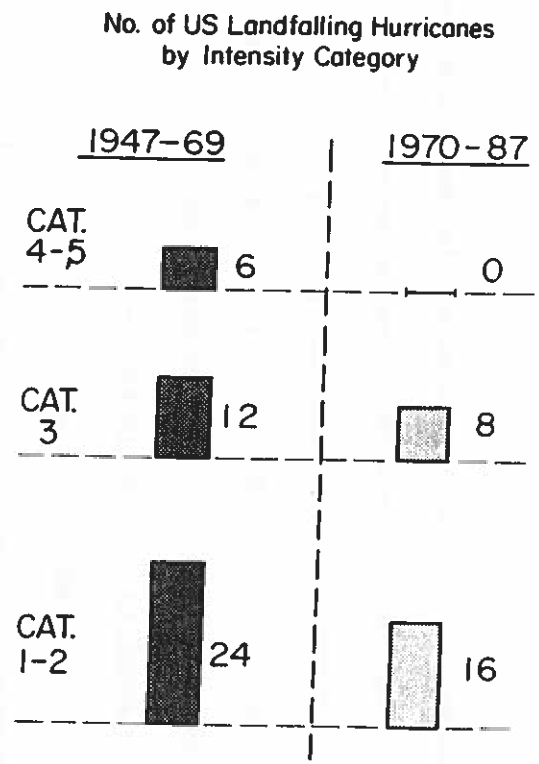

Fig. 11. Number of US landfalling hurricanes of various Saffir/Simpson Category by earlier West African wet (1947-69) versus later dry period (1970-87).

Records indicate that intense hurricane activity was reduced in the early years of this century and enhanced during the period of late 1920s to late 1930s.

Nicholson (1978) has also studied the available West African rainfall records or has inferred rainfall from existing accounts back to the 17th century. Her records and other indirect evidence is indicative of earlier periods of similar multi-decadal African wet and dry periods. Figure 13 presents evidence that the multi-decadal periods of 1820-1840 and 1895-1920 were generally dry, while the period 1870-1895 was judged to be relatively wet. Such multi-decadal rainfall changes are not unusual and should be expected. We should have anticipated that after 18 years of drought that the African Sahel would likely return to a new period of higher rainfall.

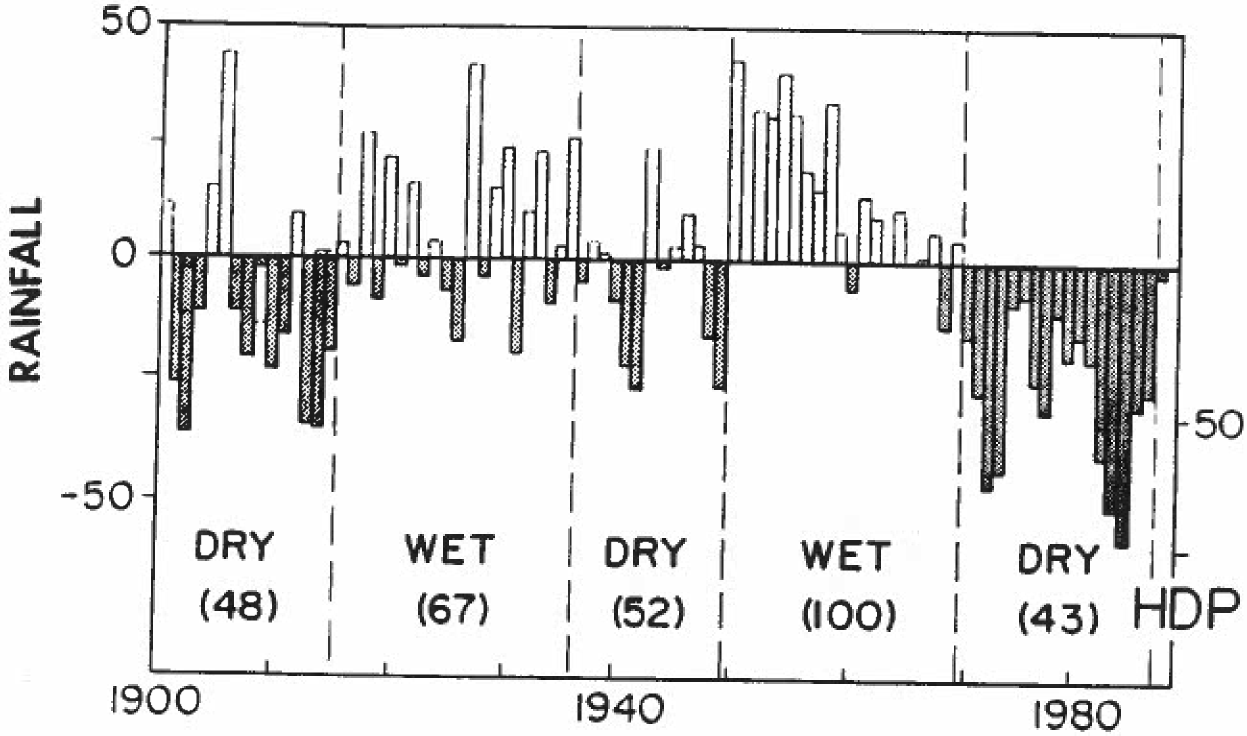

Fig. 12. Portrayal of normalized percentage Sahel region yearly rainfall anomaly for 1900-1987 and the association of these multi-decadal wet and dry periods with the mean annual Atlantic Hurricane Destruction Potential (HDP) during each period. Data adopted from Entekhabi and Nicholson (1987).

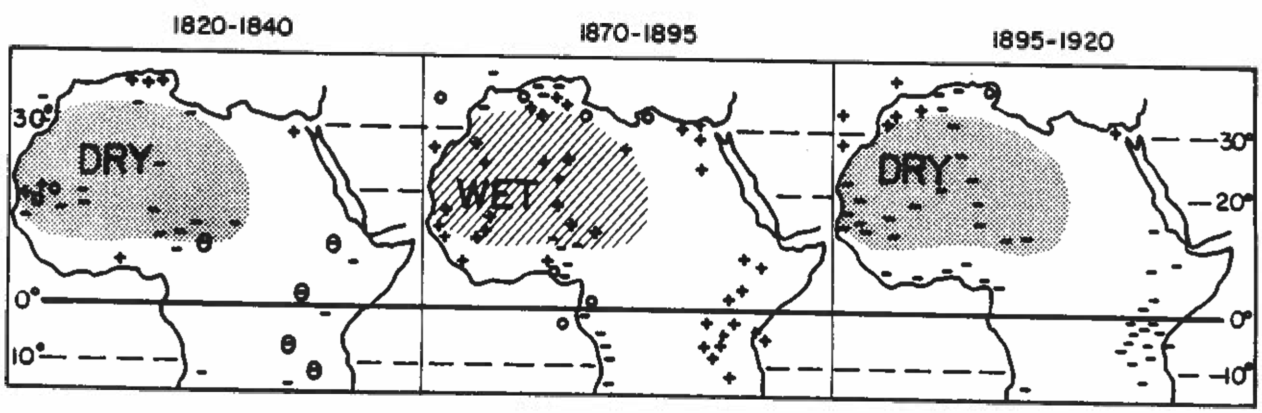

Fig. 13. African rainfall anomalies during three 19th century periods. MINUS signs denote evidence of drier conditions; PLUS signs denote evidence of above-average rainfall, SMALL CIRCLES denote average conditions (adopted from Nicholson, 1978).

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