SUMMARY OF 1988 ATLANTIC TROPICAL CYCLONE ACTIVITY AND VERIFICATION OF AUTHOR'S SEASONAL FORECAST

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 (32 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 (31 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 ($\sim$ 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 1988, 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 1988 hurricane season should have been above average with about 7 hurricanes, 11 named storms of hurricane and tropical storm intensity, 30 hurricane days and 50 named storms days. The author also forecast that this season's tropical cyclones would be more intense than average. An updated forecast was issued on 28 July 1988 with no change from the late May estimates.

The actual number of hurricanes which occurred in 1988 was 5 (two below forecast); the number of named storms was 11 (as forecast); number of hurricane days was 26 (4 below forecast) and number of named storm days was 53 (3 above forecast). For the first 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 1988 was 75. The actual HDP number was 79 (4 above forecast). Except for 1980, this season had a higher HDP than any Atlantic hurricane season since 1969.

In terms of the overall intensity of tropical cyclones, the 1988 season was distinctly above average, particularly with regard to Caribbean Basin cyclones of African origin. There were three very intense hurricanes (Gilbert, Helene, Joan) in 1988.

The global environmental factors of the El Nino and the stratospheric QBO winds were both favorable for intense hurricane activity this season. In addition, West African summer rainfall was higher this year than in any year since 1969. Intense hurricane activity is typically related to rainy West African rainfall conditions. Surface pressure and upper tropospheric zonal winds were also favorable.

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1. 1988 Atlantic Tropical Cyclone Activity

The 1988 Atlantic hurricane season officially ends on 30 November. There were five hurricanes (maximum sustained wind >73 mph) and 26 hurricane days during 1988. Combined named storms or the sum of the number of hurricanes and tropical storms which occurred in 1988 was 11. In terms of tropical cyclone (TC) intensity, this year was a more active hurricane season than these numbers indicate. In contrast to activity for the previous 6 hurricane seasons (except for 1985) 1988 TC activity was very much higher. Global and regional environmental circulation conditions in 1988 were much more favorable for Atlantic tropical cyclone activity than in all previous years since 1980.

Table 1 and Fig. 1 gives a summary of all 1988 Atlantic named storms. Note the higher intensity of the three hurricanes Gilbert (the most intense Atlantic hurricane ever recorded), Helene, and Joan (both category 4 cyclones at one time during their existence). Since 1969 there have only been five other hurricanes in the Atlantic with reported or estimated lower central pressures than each of these three 1988 hurricanes.

Perhaps the best measure of seasonal hurricane activity is given by a cyclone's potential for wind and storm surge damage. The author has proposed such a measure in a parameter called Hurricane Destruction Potential or HDP. This is the sum of the square of each hurricane's maximum wind (V_{max}) equal or greater than 65 knots (75 mph) for each 6-hour period of its existence.* The HDP for 1988 was 79. By contrast,

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* Hurricane Destruction Potential (HDP) = ΣV^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 day or four 6-hr time periods would have a HDP of 4 units.

TABLE 1

Summary of named storms occurring during the 1988 Atlantic tropical cyclone season. Hurricanes (HUR) and Tropical Storms (TS) information has been supplied by the National Hurricane Center.

Cyclones of Tropical Storm or Hurricane Intensity	Maximum Sustained Winds in Knots* and mph in parenthesis	Minimum Sea Level Pressure (mb)	Dates of Existence as a Disturbance	No. of Hurr. Days	No. of Hurr. and Trop. Storm Days	Hurricane Destruction Potential (HDP)
1. TS Alberto	35 (40)	1002	5 Aug -8 Aug	0	2	0
2. TS Beryl	45 (52)	1001	8 Aug -10 Aug	0	2	0
3. TS Chris	45 (52)	1005	21 Aug -29 Aug	0	1	0
4. HUR Debby	65 (75)	987	31 Aug -8 Sept	2	2	0.8
5. TS Ernesto	55 (63)	994	3 Sept -5 Sept	0	3	0
6. HUR Florence	70 (80)	983	7 Sept -11 Sept	2	4	0.9
7. HUR Gilbert	160 (184)	885	8 Sept -19 Sept	7	9	31.3
8. HUR Helene	125 (144)	938	19 Sept -30 Sept	10	11	30.5
9. TS Isaac	40 (46)	1005	28 Sept -1 Oct	0	2	0
10. HUR Joan	115 (132)	936	14 Oct -28 Oct	5	12	15.4
11. TS Keith	55 (63)	985	17 Nov -24 Nov	0	5	0
			TOTAL	26	53	79

* 1 knot equals 1.15 miles per hour (mph).

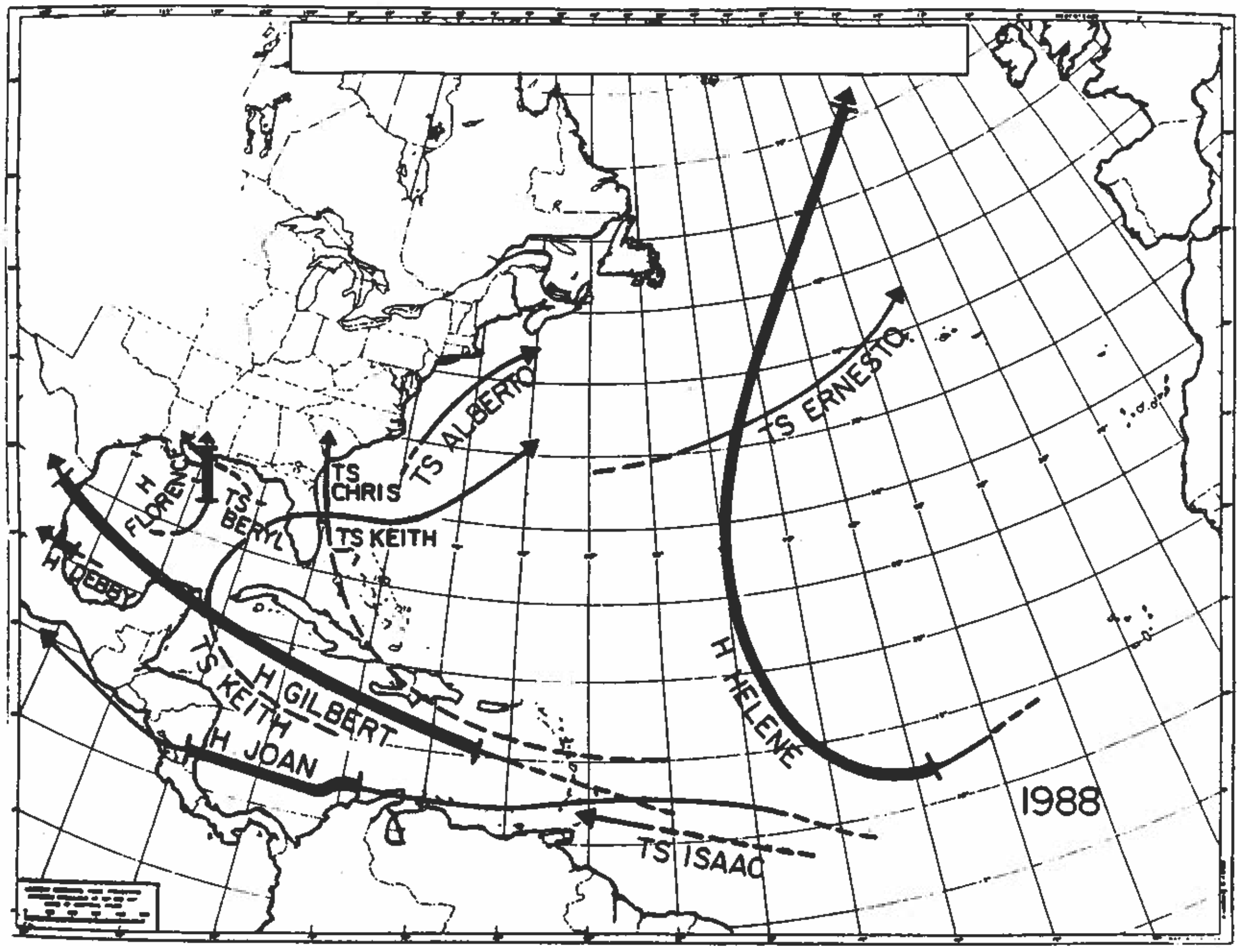

Fig. 1. Tracks of tropical cyclones for 1988. Dashed lines show periods of disturbance, solid lines indicate the periods of tropical storm intensity (maximum sustained winds with 39-72 mph), and thick lines show the periods of hurricane intensity (maximum sustained winds greater than 73 mph).

the years of 1982-1987 had HDP values of only 18 (1982), 8 (1983), 42 (1984), 61 (1985), 23 (1986) and 11 (1987).

Figure 1 gives a summary of all TC tracks for the 1988 season. Five TCs became hurricanes while another 6 systems reached tropical storm intensity. A summary of each Atlantic TC which occurred during 1988 is as follows:

1) Tropical Storm Alberto. This minimal tropical storm formed from a weak low pressure trough off the South Carolina coast on the 4th of August. It then moved rapidly to the northeast on the 6th to the 8th of August and dissipated over the colder water of the Maritime Provinces on the 8th and the 9th of August. Sustained maximum winds were only 35 knots (40 mph) and minimum pressure 1002 mb.

2) Tropical Storm Beryl . This second minimal and short lived tropical cyclone formed slowly in the northwest Gulf of Mexico between the 4th and 8th of August from the remnants of a cut-off stationary upper-level trough system. Once formed it moved northwestward over the Louisiana coast and slowly dissipated. Maximum sustained winds were 45 knots (52 mph) and minimum pressure 1001 mb.

3) Tropical Storm Chris. This third tropical storm developed from an easterly wave that had moved from West Africa. It tracked WNW across the Atlantic without development. It finally strengthened to tropical storm intensity near the Georgia coast. Chris then made landfall on the Georgia-South Carolina coast and dissipated as it moved inland. Maximum sustained winds were 45 knots (52 mph) and minimum central pressure 1005 mb.

4) Hurricane Debby. Short lived Hurricane Debby formed in the southern part of the Gulf of Mexico and moved westward over the Mexican coastline halfway between Tampico and Vera Cruz on the 2nd of September. It originated from a tropical wave that could be traced from Africa. It became a hurricane just before it entered land. Maximum winds were just 65 knots (75 mph) and minimum pressure 987 mb.

5) Tropical Storm Ernesto. This 5th named storm of the season

formed in early September in the central Atlantic north of 30° from a wave disturbance that could be traced backwards to the West African coast. Once formed Ernesto was caught up in middle-latitude westerlies and moved rapidly to the ENE. It attained sustained winds of 55 knots (63 mph) and had a minimal pressure of about 994 mb.

6) Hurricane Florence. This second minimal hurricane first became a named storm on the 7th of September in the central Gulf of Mexico. It developed from a frontal system that had become stagnant over the Gulf of Mexico. Florence then moved directly northward and became a hurricane on the 9th of September just before it moved inland along the Louisiana coast and dissipated. Maximum sustained winds were 70 knots (80 mph) and minimum central pressure 983 mb.

7) Hurricane Gilbert. This was the most intense hurricane ever measured in the Atlantic. Official estimated maximum sustained winds at the surface late on the 13th of September were 160 knots (184 mph) and an estimated aircraft minimum central pressure of 885 mb (26.13 inches of mercury). The previous lowest recorded Atlantic hurricane central pressure had been 899 mb (26.55 inches of mercury) in the Labor Day Storm in the Florida Keys in 1935. A reconnaissance aircraft at this time measured a 3 km altitude one-second wind of 173 knots (199 mph).

Gilbert formed from an African origin wave disturbance just to the east of the Antilles. It then moved WNW with little alteration in course until it made landfall south of Brownsville and dissipated over northern Mexico and southern Texas. Gilbert caused massive destruction as it passed through the Caribbean and Gulf of Mexico. At least 39 tornadoes were spawned by this storm across south Texas. The death toll has been estimated to be at least 318.

8) Hurricane Helene. This fourth hurricane to form in September became a very intense (category 4) and long-lived hurricane. Fortunately it remained in the middle of the Atlantic and did not influence any land areas. Helene became a named storm on the 20th of September in the mid-Atlantic at 13°N and 34°W. It began to recurve on the 24th of September at 50°W and had a very long track to the NNE. Helene had sustained hurricane force winds for 10 days. Satellite estimated minimum central pressure was 938 mb and maximum estimated sustained winds of 125 knots (144 mph).

9) Tropical Storm Isaac. This 9th named storm of 1988 formed in late September to the east of Trinidad in the Windward Islands. Isaac developed from a westward moving low latitude disturbance on the 30th of September. This TC's intensification did not last long before it encountered dissipating vertical wind shear. It weakened and filled as it approached the Lesser Antilles. Maximum winds were 40 knots (46 mph) and minimum central pressure 1005 mb.

10) Hurricane Joan. This was the second very intense and destructive Caribbean Basin hurricane of the season. Joan had a very long lifetime. It was classified a named storm on the 11th of October and followed a long westerly track through the southern and western Caribbean until reaching landfall in Nicaragua on the 22nd of October. Joan formed from an African origin disturbance and moved for 7 days as a TS before slowing down and growing into an intense hurricane in the southwest Caribbean on the 18th of October. For two days it was nearly stationary. Joan's maximum sustained winds were 115 knots (132 mph) and minimum central pressure was

936 mb. After crossing central America it regenerated into a TS (Miriam) in the NE Pacific. Joan produced major destruction in Central America and substantial flooding in Columbia.

11) Tropical Storm Keith. This late November and last of the named storms of this season formed in the western Caribbean on the 20th of November. It then moved northward just touching the tip of Yucatan and into the central Gulf of Mexico before it recurved on the 22nd and moved ENE striking the central Florida west coast early on the 23rd. Keith had a minimum central pressure of 985 mb and maximum sustained winds of 55 knots (63 mph). It was very close to becoming a hurricane. After crossing the central Florida peninsula it rapidly moved northeast to the west of Bermuda before taking on extra tropical characteristics in the central Atlantic.

There were an additional 8 depressions (for a total of 19) that did not become named storms. The average seasonal number is 14-15.

Comparison of 1988 Hurricane Season with Other Hurricane Seasons. In terms of Hurricane Destruction Potential (HDP), the 1988 hurricane season was the second most active season since 1969. The only more active season by this measure was 1980 which had 6 hurricanes form in the mid-Atlantic, and intense Hurricane Allen which moved through the Caribbean Sea and came ashore at a much reduced intensity near Brownsville.

By the measure of HDP the 1988 hurricane season was about 7 times more active than last year, or the season of 1983, and 3-4 times more active than the 1986 and 1982 hurricane seasons. Since the period of the late 1940's there has only been one season (1955) in which three hurricanes with central pressures less than 940 mb formed. Hurricane

Gilbert was only the forth Category 5 hurricane since 1970. Since 1950 there have only been 4 previous seasons where 3 or more Saffir/Simpson category 4 (minimal SLP 920-945 mb, maximum wind 131-155 mph) or category 5 (minimal SLP < 920 mb, maximum winds > 155 mph) cyclones have occurred. All of these seasons were before 1965.

In the 39 years since 1950 when aircraft reconnaissance measurements into hurricanes has become routine, there have been 24 different hurricanes with measured central pressures less than 940 mb (27.76 inches of mercury) or an average of about 0.6 per year. Since 1970 there have been only 9 hurricanes with central pressure below 940 mb. The single season of 1988 had 3 such TCs.

<u>Late Start of Atlantic Hurricane Season</u>. The 1988 Atlantic hurricane season is distinctive by virtue of its late start and intense TC activity once it did start. Table 2 compares the first 3 months of the hurricane season (June-August) to the last three months of the season (September-November). In the average year there would have been more than two hurricanes by 1 September and in the average active year three or four. In 1988 the first hurricane did not form until early September. In the last 50 years there have only been two previous seasons (1984, 1941) in which a hurricane had not formed before the beginning of September. Of these two previous years 1941 was a strong El Nino season, and 1984 was similar to this season in its late start but the intensity of 1984 TCs was less than this year.

The 1988 season is another illustration of why one cannot necessarily judge a hurricane season by early month activity. Early TC activities are often not well related to the later season activity.

TABLE 2

Comparison of first half and second half of the 1988 Atlantic Hurricane Season.

	1st Half June through August	2nd Half September through November
	Average Year	
No. of Hurricanes	2.1 (37%)	3.6 (63%)
No. of Named Storms	4.0 (41%)	5.7 (59%)
	1988	
No. of Hurricanes	0 (0%)	5 (100%)
No. of Named Storms	3 (37%)	8 (63%)

November Cyclones. Tropical cyclone Keith continues the trend for late season TCs which has been observed in the 1980s. Since 1980 there have been 8 named TCs (including 7 hurricanes) which formed after 1 November. This is 4.6 times greater than the rate of November hurricanes which formed in the previous 80-year period and 2.5 times greater than the rate of November named storm formations in the period prior to 1980 (See Table 3).

The author has no explanation for the recent decade increase in November TC activity. It is likely that the November global general circulation features of the 1980s have been somewhat different than November circulation conditions of the earlier decades.

TABLE 3

Comparison of hurricane and named storm formations after 1 November in the 1980s vs. the period 1900-1979. Values in parenthesis give the average number per year.

Year	Hurricanes	Named Storms
1980-88	7 (.78)	8 (.89)
1900-79	14 (.175)	28 (.35)
Ratio of Annual 1980s to 1900-79 TC Activity	4.6	2.5
	TCs after 1 November by decade	
1900-09	1	3
1910-19	2	3
1920-29	2	3
1930-39	3	6
1940-49	1	2
1950-59	2	5
1960-69	2	4
1970-79	1	1
1980-88	7	8

2. Known Factors Associated with Atlantic Seasonal Hurricane Variability

The author's Atlantic seasonal hurricane forecast is based on the characteristics of two global and two regional environmental factors which the author has previously shown to be statistically related to seasonal hurricane variations. These 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 suppressed hurricane seasons. Seasons of cold water, or of La Nina are typically more active hurricane seasons.

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 (when the measure of hurricane activity is made in the number of hurricane days) in seasons when QBO winds are from a relatively westerly direction as compared with those 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, the more negative the spring-early summer sea surface pressure anomaly, generally the greater the Atlantic seasonal hurricane activity. Higher pressures are associated with reduced hurricane activity.

d) Lower 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.

3. Characteristics of Known Seasonal Hurricane Predictors During 1988

a) <u>El Nino</u>. No El Nino event was present in the Pacific during the 1988 season. In fact a quite cool or La Nina event was present during the whole of the 1988 hurricane season. The moderately intense El Nino event of late 1986 and 1987 had dissipated by early 1988, and a very cool sea surface temperature anomalies (SSTA) had returned to the equatorial eastern Pacific by the start of the 1988 hurricane season. Note in Fig. 2 the strong contrast of equatorial Pacific SSTA conditions in the first half of October of 1987 (top figure) in comparison with the same October

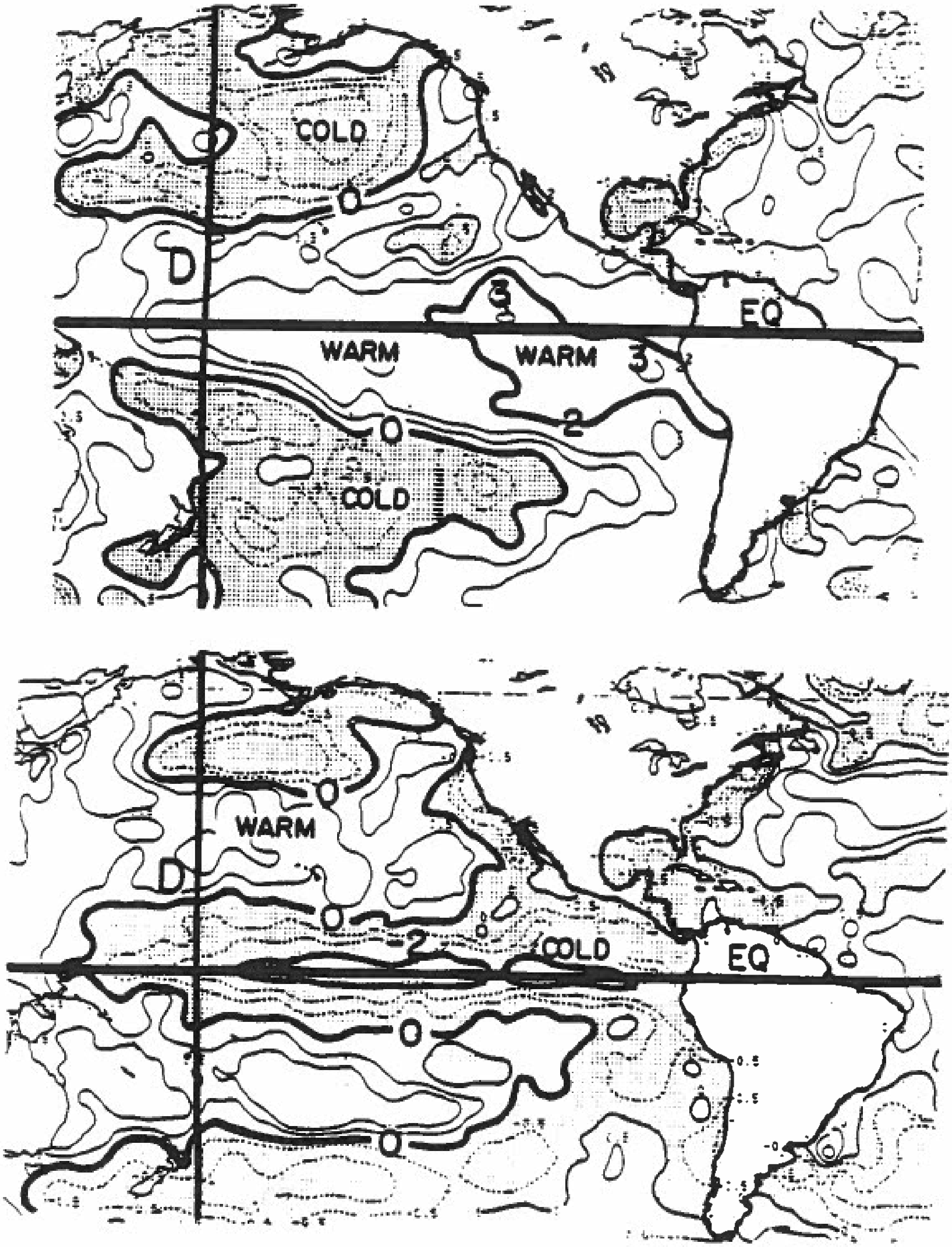

Fig. 2. 1-16 October Sea Surface Temperature Anomaly (SSTA) in °C for 1987 (top diagram) and 1988 (bottom diagram). Dotted areas show cold anomaly (-), unshaded areas positive anomaly (+). Data from NOAA blended SST anomaly analyses.

period of this year (bottom figure). At some Pacific equatorial locations SSTAs were 4-5°C cooler than last year. These are very large differences. The 1988 hurricane season thus did not experience the suppressing influences of an El Nino event.

The lack of an El Nino event for 1988 is further verified by the presence of unusually strong 200 mb (12 km altitude) easterly wind anomalies in the lower Caribbean Basin during the entire 1988 hurricane season. In El Nino seasons Caribbean Basin 200 mb zonal winds are typically anomalously from the west rather than from the east.

b) Stratospheric QBO in 1988. Table 4 shows the actual stratospheric, or QBO zonal wind as measured by upper air stations near 12°N in the Atlantic region for April-October 1988. It is at these latitudes where African spawned hurricanes form. These winds are an average of the low latitude eastern Caribbean stations of Curacoa (12°N), Trinidad (11°N), and Barbados (13°N). Table 5 shows the QBO relative wind alteration when the annual wind cycle has been removed.

Although the relative zonal component of the QBO had already shifted from a westerly to an easterly direction at 10 mb (30 km) and was shifting to a weak easterly direction at 30 mb (23 km) by August, 30 mb easterly relative zonal winds remained very weak (~1 m/s) through August to October. The lower stratospheric 50 mb and 70 mb winds remained from a relative westerly (and more favorable for TC activity) direction during the hurricane season.

Note that the 100-50 mb vertical wind shear in the lower stratosphere was very small during 1988 - see Table 4. This wind information shows that the lower stratospheric zonal winds were not very different from the

TABLE 4

April through October 1988 observed absolute value of the 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.

				Observed			
Level	Apr	May	Jun	Jul	Aug	Sept	Oct
30 mb (23 km)	-1	-6	-15	-20	-23	-25	-24
50 mb (20 km)	+3	-1	-3	-9	-10	-8	-6
70 mb (18.5 km)	+2	-1	-3	-8	-8	-7	-3
100 mb (16.5 km)	+9	+5	+1	-6	-6	-4	-1

TABLE 5

April through October 1988 relative zonal wind (u) where the annual wind cycle has been removed. Values represent an average of the eastern Caribbean Basin stations of Curacoa (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)	+7	+8	+3	+3	-1	-1	-1
50 mb (20 km)	+4	+5	+7	+5	+4	+4	+4
70 mb (18.5 km)	+2	+4	+4	+3	+3	+2	+2

mean tropospheric zonal winds of the typical low latitude Atlantic tropical disturbance moving westward in the trade winds.

It is these 50 mb and 70 mb lower level stratospheric winds which are most related to TC activity. The 50 mb and 70 mb winds in 1988 were blowing from a direction and with a speed which was favorable for making the TCs which formed in 1988 more intense. This is considered to be one of the contributing influences in explaining why this season had three such intense hurricanes.

Low latitude stratospheric wind conditions during 1988 were thus judged to be generally favorable for the development of more low latitude tropical cyclones which originate from west African disturbances. It is these disturbances which typically produce the most intense TCs.

c) <u>Sea-Level Pressure Anomaly (SLPA)</u>. Table 6 gives information on SLPA during the 1988 season. Pressure anomaly remained about neutral throughout the Caribbean-Gulf of Mexico region in the spring and early summer. August SLPA showed distinctly lower pressure. As SLPA is largely unrelated to the QBO and the EL Nino (Gray, 1984a), SLPA may be considered to be a separate and largely independent contributing factor to seasonal hurricane activity. It is noted that the August through October SLPA of the lower latitude stations was negative. This is in contrast with all but one of the previous 6 hurricane seasons of 1982-1987 where SLPA was strongly positive (the exception was 1985). By itself, SLPA in 1988 appears to have been a contributing factor to a more active hurricane season at low latitudes.

TABLE 6

1988 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)

	April-May	June-July	Aug	Sept	Oct
	6 Gulf of Mexico-Caribbean Basin Stations				
Brownsville(26°N)	+0.2	+0.8	-1.2	-0.8	+1.6
Merida (21°N)	+0.3	+0.5	-0.8	-1.0	+1.4
Miami(25.5°N)	-1.5	0.0	-0.6	+0.7	+1.5
San Juan(18.5°N)	-0.7	-0.5	-1.2	-0.5	-1.1
Curacao(12°N)	0.0	+0.2	-0.8	+0.1	-1.6
Barbados(13.5°N)	+0.2	-0.3	-1.4	-0.7	-0.8
6-Station Ave	-0.2	+0.1	-1.0	-0.4	+0.2
	5 Low Latitude Stations				
San Juan (18.5°N)	-0.7	-0.3	-1.2	-0.5	-1.1
Curacao (12°N)	0.0	+0.3	-0.8	+0.1	-0.8
Barbados (13.5°N)	+0.2	-0.3	-1.4	-0.7	-1.6
Trinidad (12°N)	+0.4	+0.5	-0.5	+0.1	-0.6
Cayenne (5°N)	+0.3	+0.2	-1.1	+0.9	-0.7
Average	.0	+0.1	-1.0	0.0	-1.0

d) Upper-tropospheric Zonal Wind Anomaly (ZWA). Table 7 shows the lower Caribbean Basin 200 mb (12 km altitude) west to east zonal wind anomaly for the period of June through October as an anomaly from the period of 1970-1986. Note that 200 mb relative zonal winds were very strong from the east throughout the hurricane season, particularly in the southeastern Caribbean. August easterly anomalies were particularly strong. It is most unusual to have Caribbean Basin monthly easterly wind anomalies as great as -10 m/s. The strong easterly anomalies of -8 m/s for the entire June through August period were greater than previously recorded. These strong easterly wind anomalies are a response to the

TABLE 7

Lower Caribbean Basin 1988 200 mb (12 km) Zonal Wind Anomaly from 1970-1986 average conditions - in m/s.

	Months				
Station	June	July	Aug	Sept	Oct
Trinidad (11°N)	-12	-2	-8.5	-3.5	-5.5
Curacao (12°N)	-13	-4.5	-12	-5	-5
Barbados (13.5°N)	-15.5	-3.5	-9	-5.5	-1.5
Kingston (18°N)	-3	-5	-8	-1	+3
Average	-10.9	-3.8	-9.4	-3.8	-2.5
Average (June through August) ←----	-8.0 ------→				

combined conditions of the cold water La Nina event in the eastern Pacific and the strong summer monsoon trough which existed over West Africa this summer. It appears that West Africa had more summer rainfall in 1988 than any previous summer since 1969. It is known that Caribbean Basin 200 mb zonal wind anomalies are related to the El Nino and the strength of the West African monsoon trough. But it is rare that they become this strong in July and August. These negative anomalies were a very positive contribution to an active 1988 TC season.

4. Factors Associated with 1988 Early Season Inactivity

As the 1988 hurricane season unfolded the most perplexing question being asked was why there were no hurricanes from June through August. The author had predicted an earlier start of the hurricane season this year. In years when conditions for hurricanes were very favorable, like 1988 appeared to be, one might have expected 3-4 hurricanes to have formed by early September. Why did this not occur this year? This was surprising because strong tropical wave activity was observed to move westward off of Africa in July and August. The west African monsoon trough appeared strong and above average amounts of West African rainfall were occurring. Caribbean Basin Sea Level Pressure Anomaly (SLPA) was highly negative (-1.0 mb) in August, upper tropospheric 200 mb zonal wind anomalies (ZWA) showed no westerly anomaly which is a typical major inhibitor of hurricane development. No TC suppressing influence of an El Nino event was present. Lower stratospheric QBO winds were not unfavorable for TC formation. All ingredients for hurricane formation appeared to be present in the latter half of July and throughout August. Why then were there no hurricanes?

It appears that conditions were too favorable in the sense that the July and August west African monsoon trough and its upper tropospheric westward extension across the Atlantic and into the lower Caribbean Basin was too well established. This caused the Caribbean Basin upper tropospheric zonal winds to blow too strong from the east. Promising wave disturbances were frequently being sheared off to the west when normally the primary inhibiting factor in TC formation is upper-tropospheric shearing to the east. Figure 3 shows the NOAA climate analysis center 200 mb mean wind anomalies for the months of July (top diagram) and August (bottom diagram). Note how strong the equatorial wind anomalies were in these months. This type of westerly directed upper-level shear phenomena is rare in the Atlantic but is often seen in the northwest Pacific when the Asian monsoon trough becomes very strongly established in the middle of the summer. Typhoon activity is then greatly reduced.

Once these anomalously strong July and August upper tropospheric

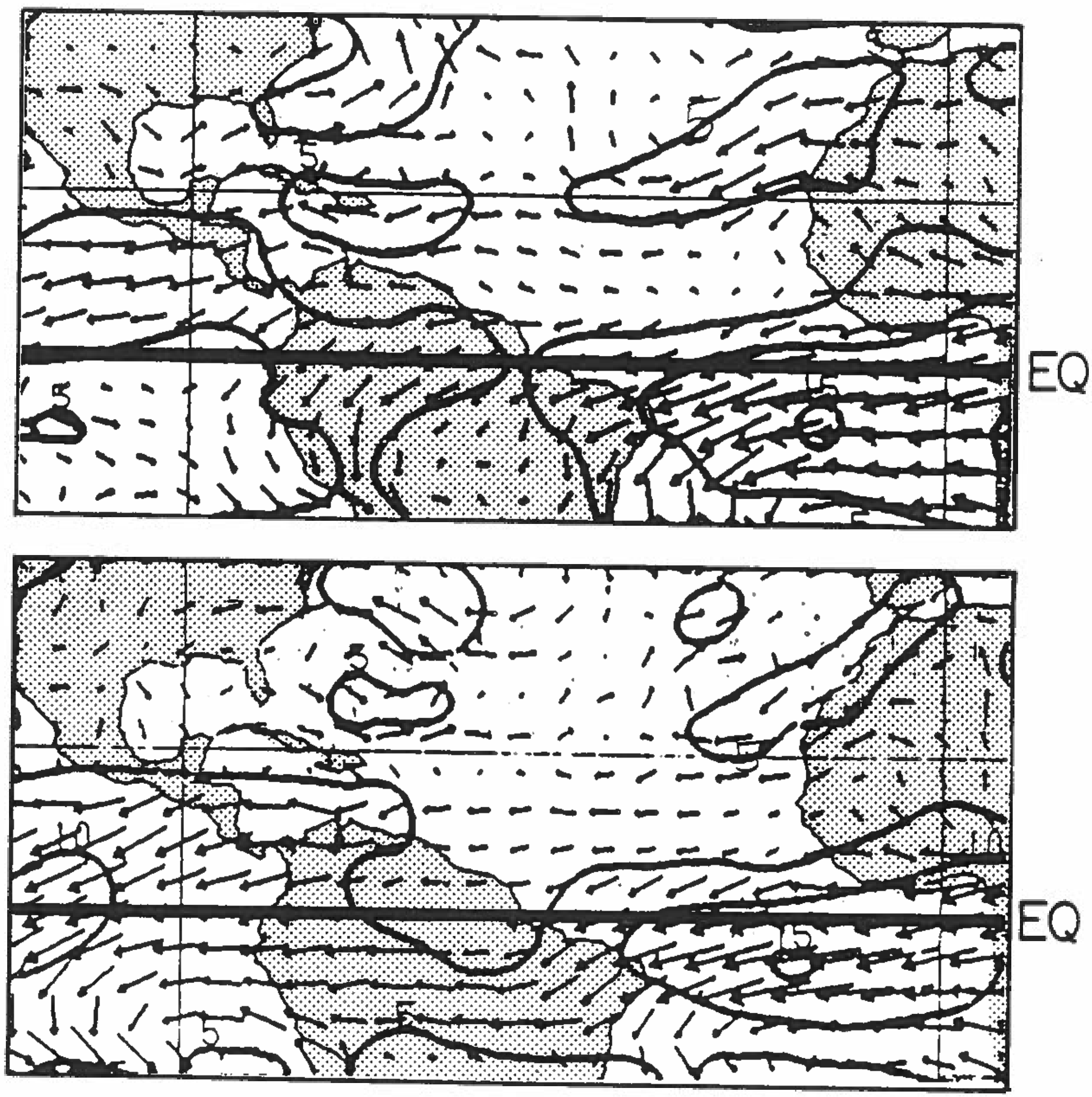

Fig. 3. 200 mb (12 km altitude) wind vector anomaly for the months of July 1988 (above) and August 1988 (below) as determined by the NOAA Climate Analysis Center. Vector interval of 5° represents wind speed of 20 m/s. Contour interval is 5 m/s.

easterly or negative wind anomalies subsided somewhat (as occurred in early September) than upper level shearing factors become ideal for hurricane formation. This appears to be the situation in 1988. Overall conditions throughout the entire 1988 hurricane season were too favorable not to have had active hurricane activity not break out at some period during the season.

The hurricane season most closely analogous to 1988 is 1961. In 1961 one named storm formed (Anna in late July) before the beginning of a very active September through early November TC period in which 7 hurricanes and 3 other tropical storms formed. Hurricanes in 1961 were also very intense. Five 1961 hurricanes had central pressures less 950 mb.

The 1961 hurricane season was also distinguished by one where (like 1988) 200 mb zonal winds anomalously in the eastern Caribbean were strongly from the east. As in 1988 a lot of low latitude African origin TCs formed that year.

This type of August reduction in TC activity is more frequently observed in the northwest Pacific when the Asian monsoon trough becomes established far poleward of its normal position. At this time very few typhoons develop in the region around Guam and equatorwards. This is because too strong tropospheric wind shears develop. This situation occurred in 1977 when, for the first time since reliable records were kept no typhoons formed in the NW Pacific in August.

An analogous situation has occurred in the NW Pacific this year. Only two typhoons were observed to form in the months of July and August 1988 (the average is 6.0). Of these two typhoons one (Doyle 17-19 August) formed far to the east ($\sim$170°E). It then tracked directly north to near the Dateline. The other typhoon (Warren, 15-19 July) was the only named storm in July and August to form at a latitude below 20°N.

For the entire three month period (June through August 1988) anomalously low typhoon activity occurred in the NW Pacific, particularly at latitudes equatorward of 20°. There were only 6 typhoon days for all TCs located equatorwards of 20°N during the 3-month period of June-July-August 1988. This was substantially below the climatological average.

There is no question that NW Pacific typhoon activity during the months of June through August 1988 was much suppressed as was hurricane activity in the Atlantic during these same months. This is likely related to the strong cold water La Nina event of this period. The cold water suppression of eastern Pacific tropical precipitation likely lead to a compensating enhancement of the monsoon trough precipitation over West Africa and a more poleward penetration of the monsoon trough in east Asia.

5. Possible Beginning Break of the Multi-decadal West African Drought and Implication for More Intense Atlantic Hurricanes.

Because of the more intense and lower latitude formation of tropical cyclones in 1988, this season appears to be more typical of the hurricane seasons of the 1950s and 1960s.

Atlantic hurricane activity during the 23-year period of 1947-1969 (as measured by HDP) was much higher than it has been during the 1970-87 period - See Fig. 4. Since 1970 hurricane intensity has, by this standard, been very low. Although the number of hurricanes per season has averaged only 31% higher during the period of 1947-1969 compared with 1970-1987 (see Table 8), the Hurricane Destruction Potential (HDP) was more than twice as great during the earlier period. Name storm activity was only 19 percent higher for the earlier period. By contrast, the potential destruction from hurricanes with maximum winds > 100 knots (115 mph) was nearly 3 times greater in 1947-1969 as compared with 1970-1987. Table 9 shows how many intense hurricane situations were reported in the 1947-1969 period in comparison with the period since 1970. Values have been normalized per season to the average of the period 1970-1987. There were, on average, nearly 3 times as many reports per season of hurricane maximum winds greater than 100 knots (~115 mph) in the early 1947-1969 period and over 3.1 times as many reports of hurricane winds greater than 120 knots (~138 mph) per season in the earlier period. These are striking differences. They are also verified in the statistical analysis of measured minimum surface pressure.

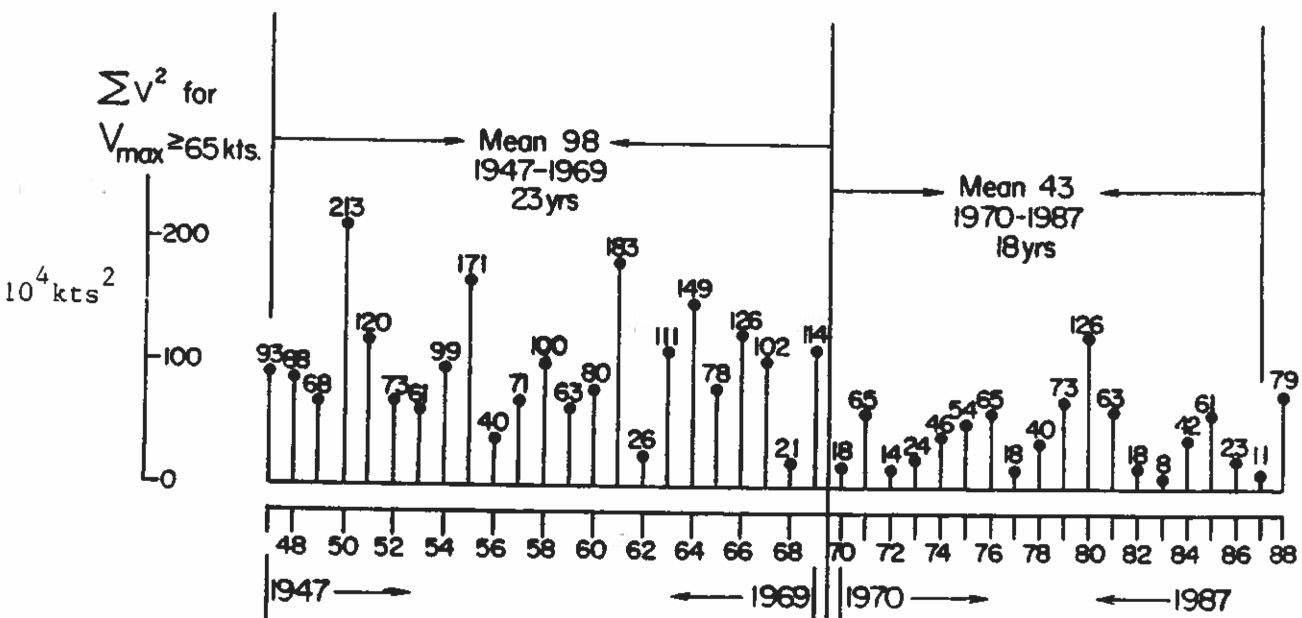

Fig. 4. Yearly variations of Hurricane Destruction Potential (HDP) from 1947-1988. HDP is defined as the sum of all hurricane maximum wind speeds squared for $V_{max} \geq 65$ knots for each 6-hour observing period throughout the hurricane season. Units 10^4 kts^2.

TABLE 8

Comparison of various measures of Atlantic tropical cyclone in the period of 1947-1969 to the period of 1970-1987. Values have been normalized per season and to the 1970-1987 period. 1 knot (kt) = 1.15 miles per hour (mph).

Normalized Per Year	1947-1969	1970-1987
No. of Named Storms	1.19	1.00
No. of Hurricanes	1.32	1.00
Sum of all $V_{max} \geq 30$ kts	1.50	1.00
Sum of all $V_{max}^2 \geq 30$ kts	1.75	1.00
No. of Hurricane Days	1.83	1.00
Sum of all $V_{max} \geq 65$ kts	2.00	1.00
Sum of all $V_{max}^2 \geq 65$ kts	2.24	1.00
Sum of No. of $V_{max} \geq 100$ kts	2.93	1.00
Sum of No. of $V_{max}^2 \geq 100$ kts	3.06	1.00

Another illustration of the difference in hurricane intensity between the 1950s and 1960s and the 1970s and 1980s is the seasonal numbers of Saffir/Simpson (See Table 10) category 3, 4, and 5 hurricanes. Table 11 shows how many more seasons there were with multinumbers of category 3-4-5 hurricanes in the 1950-69 period in comparison with the 1970-87 period.

TABLE 9

Ratios of numbers of tropical cyclone maximum wind values equal to or greater than various speeds for the period of 1947-69 in comparison with the period 1970-87. Values have been adjusted for length of period differences and normalized to the period of 1970-1987.

Normalized Number of 6-hourly Maximum Wind Speeds Above Various Speed Categories

Number of Maximum Winds Above Various Speed Categories in Knots (1 Knot = 1.15 mph)	III 1947-1969 23 Years	IV 1970-1987 18 Years
≥ 120	3.13	1.00
≥ 110	2.30	1.00
≥ 100	2.23	1.00
≥ 90	1.89	1.00
≥ 75	1.78	1.00
≥ 65	1.40	1.00
≥ 50	1.35	1.00
≥ 30	1.27	1.00

TABLE 10

Saffir/Simpson Damage Potential Scale.

Scale Number Category	Central Pressure Millibars	Central Pressure Inches	Winds (mph)	Surge (ft)	Damage
1	≥980	≥28.94	74-95	4-5	Minimal
2	965-979	28.50-28.91	96-110	6-8	Moderate
3	945-964	27.91-28.47	111-130	9-12	Extensive
4	920-944	27.17-27.88	131-155	13-18	Extreme
5	<920	<27.17	>155	>18	Catastrophic

TABLE 11

Number of hurricane seasons with various numbers of Saffir/Simpson category 3, 4, and 5 hurricanes by multi-decadal periods (data from C. Landsea).

Number of Seasons With	1950-1969	1970-1987
Two category-5 Storms	2	0
Four category-4 or 5 Storms	2	0
Three or more category 4 or 5 Storms	4	0
Two or more category 4 or 5 Storms	11	2
Four or more category 3, 4, or 5 Cyclones	8	0

The most intense hurricanes usually form at low latitudes from disturbances propagating westward from Africa. Figure 5 shows hurricane intensity cyclone tracks equatorwards of 25°N in the period of 1970-1987 vs. the period of 1947-1969. Note the much larger concentration of low latitude hurricane tracks in the earlier period.

The more inactive hurricane period between 1970-1987 is well associated with the extended period of west African drought which has occurred during this period - See Fig. 6. This inactive period is also

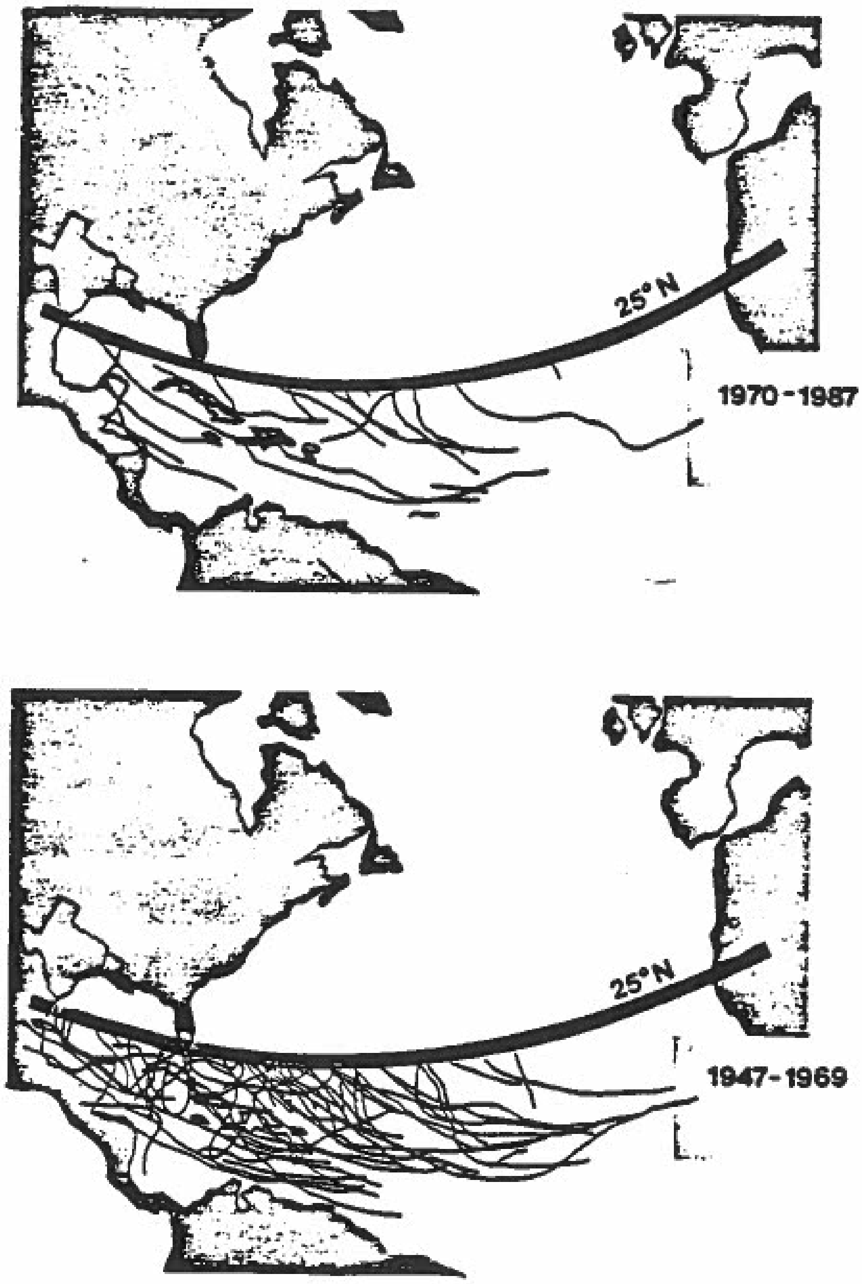

Fig. 5. Tracks of hurricane-intensity cyclones for the period of 1970 -1987 vs. that of the period of 1947-1969.

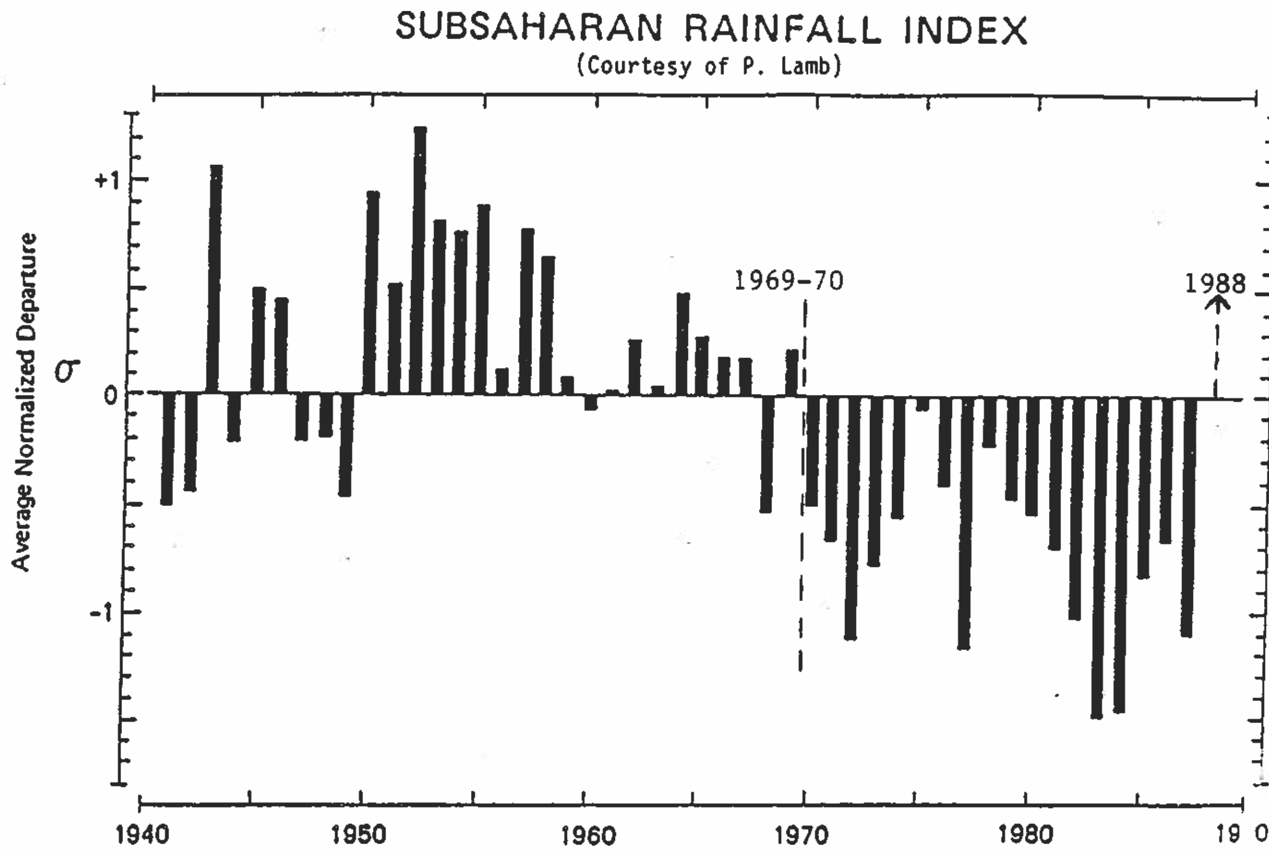

Fig. 6. An estimate of Lamb's West African rainfall index with 1988 rainfall estimate. Note general drought conditions between 1970-1987.

TABLE 12

Average of Caribbean-Gulf of Mexico Sea Level Pressure Anomaly (SLPA) for the period of 1950-1969 versus the period of 1970-1987. Values in mb.

	III 1950-1969	IV 1970-1987	Difference
June and July	-.24	+.29	+.53
Aug. through Oct.	-.27	+.34	+.61
June through Oct.	-.26	+.33	+.59

related to the occurrence of higher Caribbean Basin surface pressure (Table 12), and greater Caribbean Basin 200 mb (12 km or 40,000 ft) westerly zonal winds which have been present during the summer periods since 1970 in comparison with the summer periods of the 1950's and 1960's (See Table 13 and Fig. 7).

The coastal populations of the US and Caribbean Basin have been fortunate that intense hurricane activity has been so low during the period of 1970-1987. It is to be expected that a return to more intense hurricane activity will occur when the atmosphere's global wind systems experience an expected change in their multi-decadal circulation patterns. The historical rainfall records of Africa indicate that such multi-decadal circulation changes have occurred many times in the past.

West Africa had above average amounts of rainfall in 1988 for this first time since 1969. The exact rainfall figures are not in but overall West African rainfall was very much more wet this year. And, as we have observed, hurricane activity was correspondingly increased. Does this break in summertime West African drought represent a return to a multi-decadal rainier period that was more characteristic of the 1950s and 1960s and earlier mutli-decadal periods? We cannot tell if 1988

TABLE 13

Lower Caribbean Basin 200 mb Zonal Wind Anomaly (ZWA) for 1954-1969 versus 1970-1987. Values in m/s.

	III 1954-1969	IV 1970-1987	Difference
June and July	-.74	+1.30	+2.04
Aug. through Oct.	-1.10	+2.30	+3.40
June through Oct.	-.91	+1.77	+2.68

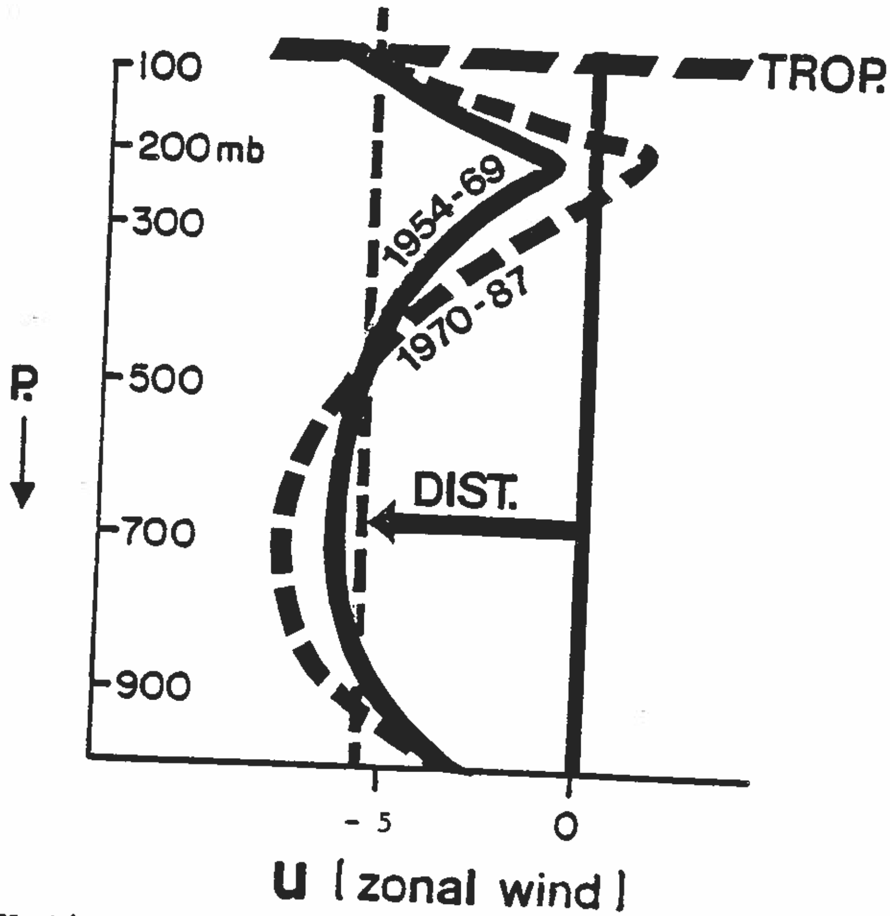

Fig. 7. Vertical profile of lower Caribbean Basin zonal winds for the August-September period of 1954-1969 vs. the period of 1970-1987. In m/s.

represents the beginning of a new multi-decadal heavier rainfall regime, but it may. The next couple of years of West African rainfall need to be carefully monitored.

With the large increases of coastal populations and building construction which has taken place along the US southeast coast since 1970 and the increases that will likely continue to occur in the future, we may well be in store for many more future hurricane problems than we have had in the recent past. Coastal populations, real estate, insurance interests, etc. should be made aware of this likely future increase in Atlantic hurricane activity.

6. Verification of Author's Seasonal Prediction

Table 14 gives a summary of the author's end of May 1988 hurricane season forecast and the end of July updated forecast (unchanged from May) and their verification. The number of hurricanes was overforecast by two and the number of hurricane days was overforecast by 4. The number of named storms was correctly forecast. The number of named storm days and HDP was underforecast by 2 and 4, respectively. The annual average of these parameters during the last 40 years (1949-88) has been 5.8 hurricanes, 9.2 named storms, 23.6 hurricane days, 45 named storm days and 77 HDP.

TABLE 14

Forecast and Verification of 1988 Seasonal TC Forecast

	Original 26 May and Updated 28 July Forecast	Observed Verification
No. of Hurricanes	7	5
No. of Named Storms (Hurricanes and Tropical Storms)	11	11
No. of Hurricane Days	30	26
No. of Hurricane and Tropical Storm Days	50	53
Hurricane Destruction Potential (HDP)*	75	79

*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 exist for 1 day (or four 6-hour time period) has a HDP of 4.

Of these 5 predictors all were forecast to be above the last 40-year average. Four of the five were observed to be above average.

In the author's 26 May 1988 seasonal forecast he stated:

> "It is thus expected that 1988 will be a more active hurricane season than any season since 1981 except for the active season of 1985. Activity should be especially higher than it has been for the last two seasons. Statistical odds favor more 1988 low latitude tropical cyclones (TCs) which develop from African spawned disturbances. It is these tropical cyclones which typically develop into the most intense hurricanes. There has been a great reduction of these types of cyclones since 1980. Only one hurricane (Emily, 1987) has moved through the Caribbean Sea from the east since Allen in 1980. There is a higher probability that this season will have more African origin hurricanes than in recent years and in association with this a higher probability of more intense TCs than has occurred during the last 6 hurricane seasons except for 1985. The Hurricane Destruction Potential (HDP) of TCs this year should be appreciably higher than it has been in recent years except for the 1985 season."

This forecast has been generally verified. By the measure of HDP the 1988 season has been more active than any season since 1969 except for 1980. This season has been especially more active than the two previous seasons of 1986-1987 and the seasons of 1982-83. Although the number of hurricanes was overforecast by two, the intensity of those hurricanes which did form was much more severe than in most seasons. The Caribbean experienced quite an increase in hurricane activity from recent seasons. There were many more (6) low latitude named storm formations than in recent years. Hurricanes Gilbert, Helene, and Joan formed from systems of African origin at latitudes equatorwards of 20 degrees. These three hurricanes were, in combination, more intense than any 3 hurricanes of any season since 1961.

<u>Verification of Previous Seasonal Forecast</u>. The author has formally made his seasonal hurricane predictions for 5 years. It may now be

possible to make a general evaluation of how accurate my forecasts have been. Table 15 gives verification for the four previous years in which the author's seasonal forecasts were made.

During the last five years in which the author has formally made his seasonal forecast, the variance of observed seasonal TC activity from climatological has been appreciably larger than the variance of the author's forecast from observed activity. Table 16 gives the ratio of the author's forecast variance from observation to the variance of individual season TC activity from climatology. The late July forecasts have been superior to the late May forecasts. Forecasts of named storms have been especially skillful in both late May and late July forecasts. There has been a higher degree of skill in forecasting the season's number of hurricane days than in forecasting the number of hurricanes. These forecasts, in general, represent a significant improvement over climatology, the previous only objective seasonal prediction that was available. If one assumes that the three forecasts: number of hurricanes, named storms and hurricane days, are in combination, equal to a season's net TC activity, then one can see that the author's late May seasonal forecasts reduced the expected seasonal variability from climatology about 35 percent and the late July forecasts by nearly 60 percent. These are considered to be skillful predictions. See the Appendix for more information.

TABLE 15

Verification of the author's previous seasonal predictions of Atlantic tropical cyclone activity for 1984-1987.

1984	Predicted 24 May and in 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 (implied from hurricane forecast)	61

1985	Prediction as of 28 May 1985	Updated Prediction of 27 July 1985	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
	(implied from hurricane forecast)		

1986	Original Forecast as of 29 May 1986	Revised Forecast as of 28 July 1986	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	Original Forecast as of 26 May 1987	Revised Forecast as of 28 July 1987	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

TABLE 16

Ratio of variance of author's seasonal TC forecasts from observation to the variance of observed seasonal TC activity from climatology during 1984-88 period and to the variance from climatology during the period 1949-88 (in parenthesis). See Appendix for more details.

	No. of Hurricanes	No. of Named Storms	No. of Hurricane Days
For Late May Forecast	.94 (.55)	.31 (.21)	.71 (.35)
For Late July Forecast	.65 (.38)	.20 (.14)	.40 (.20)

But this is only a 5-year sample. We have also made many backward in time forecast analyses of the potential for seasonal TC activity prediction on past year data sets. These backwards in time statistical tests are currently being accomplished by Professors Paul Mielke and Kenneth Berry of the CSU Statistics Department in conjunction with the author (see Gray et al., 1987b). A large number of new statistical runs have recently been made with new forecast parameters. These new analyses involve variations in Atlantic hurricane activity occurring during the 39-year period of 1949-1987. A 'jackknife' type of statistical approach has been used whereby forecast test statistics are developed from all years of data but the year being forecast. Each forecast is thus not in the developmental data set and in this sense may be considered to be independent.

These new statistical runs indicate a potential for independently forecasting about 40 percent of the seasonal TC variations in late May and about 50 percent of the variance with the late July forecast.

We are finding that HDP can be forecast with better skill than can the seasonal number of hurricanes, named storms, and/or hurricane days. This was the first year that HDP was forecast. It will be made part of the author's future seasonal predictions.

7. Outlook for 1989

It is to be expected that the 50 mb (20 km altitude) and 70 mb (18.5 km altitude) stratospheric QBO winds will blow from a relatively easterly direction during the 1989 season. This should be a factor to reduce the intensity of next season's strongest hurricanes. It is not to be expected that the suppressing influence of a moderate or strong El Nino event will occur in 1989. It is problematical if the heavier West African rainfall of 1988 will continue into the 1989 season. It is too early to estimate next season's Caribbean Basin surface pressure of upper tropospheric zonal wind anomalies.

The author's best estimate is that the 1989 Atlantic hurricane season will be a season of average TC activity based on statistics of the last 40 years but an above average season in comparison to average conditions of 1970-87. It is to be expected that the intensity of hurricanes in 1989 should be less than 1988 however.

8. Acknowledgements

The author dedicates his seasonal forecast efforts this year to Arthur Pike of the National Hurricane Center who is now gravely ill. Arthur Pike has been a long time research colleague of the author and has given me much assistance with my seasonal hurricane forecast endeavors over the last five years.

The author is most thankful to Colin McAdie who has furnished me with the recent NHC data needed for this verification. The author also thanks James Angell, Vernon Kousky and Harold Garrish of NOAA, for meteorological information and beneficial discussion. I have also appreciated the statistical advice and assistance I have received on this topic from CSU statisticians, Paul Mielke and Kenneth Berry.

The author has profited from the many discussions he has had with his project colleagues Ray Zehr, Chris Collimore, James Kossin and Stephen Hodanish. Chris Landsea has been especially helpful in the author's statistical analysis. We have all been closely monitoring 1988 Atlantic TC activity in real time. We have been much assisted by the new NOAA VDUC satellite system recently installed on the CSU Atmospheric Science building complex, which allows real time looping capability and the receipt of NHC tropical map analysis.

The author would also like to acknowledge the encouragement he has received over recent years for this type of forecasting research application from Neil Frank and Robert Sheets, former and current directors of the National Hurricane Center (NHC) and the other forecasters at the National Hurricane Center.

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APPENDIX

Comparisons of 5 year variance of author's seasonal forecast errors to the variance of the last 5 years and last 40 years. Observational differences from climatology.

a) Atlantic Basin TC statistics

b) late May forecast of number of hurricanes

c) late May forecast of number of named storms

d) late May forecast of number of hurricane days

e) late July forecast of number of hurricane days

f) late July forecast of number of named storms

g) late July forecast of number of hurricane days

a)
Atlantic Basin Hurricane, Named Storm, and Hurricane day Statistics (1949-1988)

	No of Hurricanes			No.of Named Storms			No. of Hurricane Days		
Year	Hur	Dev	Dev²	Storm	Dev	Dev²	Days	Dev	Dev²
1949	7	1.2	1.44	13	3.8	14.4	20	3.6	12.9
1950	11	5.2	27.04	13	3.8	14.4	57	33.4	1115.6
1951	8	2.2	4.84	10	.8	.6	37	13.4	179.6
1952	6	.2	.04	7	2.2	4.8	23	.6	.4
1953	6	.2	.04	14	4.8	23.0	18	5.6	31.4
1954	8	2.2	4.84	11	1.8	3.2	33	9.4	88.4
1955	9	3.2	10.24	12	2.8	7.8	46	22.4	501.8
1956	4	1.8	3.24	8	1.2	1.4	12	11.6	134.6
1957	3	2.8	7.84	8	1.2	1.4	20	3.6	13.0
1958	7	1.2	1.44	10	.8	.6	33	9.4	88.4
1959	7	1.2	1.44	11	1.8	3.2	22	1.6	2.6
1960	4	1.8	3.24	7	2.2	4.8	18	5.6	31.4
1961	8	2.2	4.84	11	1.8	3.2	46	22.4	501.8
1962	3	2.8	7.84	5	4.2	17.6	10	13.6	185.0
1963	7	1.2	1.44	9	.2	.04	36	12.4	153.8
1964	6	.2	.04	12	2.8	7.8	43	19.4	376.4
1965	4	1.8	3.24	4	5.2	27.0	27	3.4	11.6
1966	7	1.2	1.44	11	1.8	3.2	41	17.4	302.8
1967	6	.2	.04	8	1.2	1.4	35	11.4	130.0
1968	4	1.8	3.24	7	2.2	4.8	9	14.6	213.2
1969	12	6.2	38.44	16	6.8	46.24	39	15.4	237.2
1970	5	.8	.64	10	.8	.6	7	16.6	275.6
1971	6	.2	.04	13	3.8	14.4	28	4.4	19.4
1972	3	2.8	7.84	4	5.2	27.0	6	17.6	309.8
1973	4	1.8	3.24	7	2.2	4.8	9	14.6	213.2
1974	4	1.8	3.24	7	2.2	4.8	16	7.6	57.8
1975	6	.2	.04	8	1.2	1.4	18	5.6	31.4
1976	6	.2	.04	8	1.2	1.4	24	.4	.2
1977	5	.8	.64	6	3.2	10.2	6	17.6	309.8
1978	5	.8	.64	11	1.8	3.2	13	10.6	112.4
1979	5	.8	.64	8	1.2	1.4	23	.6	.4
1980	9	3.2	10.24	11	1.8	3.2	38	14.4	207.4
1981	7	1.2	1.44	12	2.8	7.8	23	.6	.4
1982	2	3.8	14.44	5	4.2	17.6	5	18.6	346.0
1983	3	2.8	7.84	4	5.2	27.0	6	17.6	309.8
1984	5	.8	.64	12	2.8	7.8	21	2.6	6.8
1985	7	1.2	1.44	11	1.8	3.2	29	5.4	29.2
1986	4	1.8	3.24	6	3.2	10.2	13	10.6	112.4
1987	3	2.8	7.84	7	2.2	4.8	7	16.6	275.6
1988	5	.8	.64	11	1.8	3.2	26	2.4	5.8
SUM	231	69.4	191.0	368	102.0	344.9	943	418.0	6935.3
40 yr Mean	5.8	1.74	4.77	9.2	2.55	8.62	23.6	10.45	173.4
1970-87 Mean	5.2			8.9			17.7		

(b)
Five Year Summary of Late May Forecast
of Seasonal No. of Hurricanes.
(40 year seasonal mean 5.8)

Year	Forecast	Observation	Forecast Error	Error Squared
1984	7	5	2	4
1985	8	7	1	1
1986	4	4	0	0
1987	5	3	2	4
1988	7	5	2	4

Forecast mean error and mean 5-year error variance	1.40	2.60
Observed mean and Observed mean variance of 1984-88 from climatology	1.48	2.76
Observed mean and Observed mean variance of 1949-1988 from climatology	1.74	4.77

$$\frac{\text{5 Year Forecast Error Variance}}{\text{1984-88 Ob. Variance from Clim.}} = \frac{2.60}{2.76} = .94$$

$$\frac{\text{5 Year Forecast Error Variance}}{\text{1949-88 Ob. Variance from Clim.}} = \frac{2.60}{4.77} = .55$$

c)
Five Year Summary of Late May Forecast
of Seasonal No. of Named Storms.
(40 year seasonal mean 9.2)

Year	Forecast	Observation	Forecast Error	Error Squared
1984	10	12	2	4
1985	11	11	0	0
1986	8	6	2	4
1987	8	7	1	1
1988	11	11	0	0

Forecast mean error and mean 5-year error variance	1.00	1.80
Observed mean and Observed mean variance of 1984-88 from climatology	2.36	5.88
Observed mean and Observed mean variance of 1949-1988 from climatology	2.55	8.62

$$\frac{\text{5 Year Forecast Error Variance}}{\text{1984-88 Ob. Variance from Clim.}} = \frac{1.80}{5.88} = .31$$

$$\frac{\text{5 Year Forecast Error Variance}}{\text{1949-88 Ob. Variance from Clim.}} = \frac{1.80}{8.62} = .21$$

d)
Five Year Summary of Late May Forecast
of Seasonal No. of Hurricane Days.
(40 year seasonal mean 23.6)

Year	Forecast	Observation	Forecast Error	Error Squared
1984	30	21	9	81
1985	35	29	6	36
1986	15	13	2	4
1987	20	7	13	169
1988	30	26	4	16
Forecast mean error and mean 5-year error variance			6.80	61.2
Observed mean and Observed mean variance of 1984-88 from climatology			8.62	85.9
Observed mean and Observed mean variance of 1949-1988 from climatology			10.45	173.4

$$\frac{\text{5 Year Forecast Error Variance}}{\text{1984-88 Ob. Variance from Clim.}} = \frac{61.2}{85.9} = .71$$

$$\frac{\text{5 Year Forecast Error Variance}}{\text{1949-88 Ob. Variance from Clim.}} = \frac{61.2}{173.4} = .35$$

e)
Five Year Summary of Late July Forecast
of Seasonal No. of Hurricanes.
(40 year seasonal mean 5.8)

Year	Forecast	Observation	Forecast Error	Error Squared
1984	7	5	2	4
1985	7	7	0	0
1986	4	4	0	0
1987	4	3	1	1
1988	7	5	2	4

Forecast mean error and mean 5-year error variance	1.00	1.80
Observed mean and Observed mean variance of 1984-88 from climatology	1.48	2.76
Observed mean and Observed mean variance of 1949-1988 from climatology	1.74	4.77

$$\frac{\text{5 Year Forecast Error Variance}}{\text{1984-88 Ob. Variance from Clim.}} = \frac{1.80}{2.76} = .65$$

$$\frac{\text{5 Year Forecast Error Variance}}{\text{1949-88 Ob. Variance from Clim.}} = \frac{1.80}{4.77} = .38$$

f)
Five Year Summary of Late July Forecast
of Seasonal No. of Named Storms.
(40 year seasonal mean 9.2)

Year	Forecast	Observation	Forecast Error	Error Squared
1984	10	12	2	4
1985	10	11	1	1
1986	7	6	1	1
1987	7	7	0	0
1988	11	11	0	0
Forecast mean error and mean 5-year error variance			0.80	1.20
Observed mean and Observed mean variance of 1984-88 from climatology			2.36	5.88
Observed mean and Observed mean variance of 1949-1988 from climatology			2.55	8.62

$$\frac{\text{5 Year Forecast Error Variance}}{\text{1984-88 Ob. Variance from Clim.}} = \frac{1.20}{5.88} = .20$$

$$\frac{\text{5 Year Forecast Error Variance}}{\text{1949-88 Ob. Variance from Clim.}} = \frac{1.20}{8.62} = .14$$

g)
Five Year Summary of Late July Forecast
of Seasonal No. of Hurricane Days.
(40 year seasonal mean 23.6)

Year	Forecast	Observation	Forecast Error	Error Squared
1984	30	21	9	81
1985	30	29	1	1
1986	10	13	3	9
1987	15	7	8	64
1988	30	26	4	16

Forecast mean error and mean 5-year error variance	5.00	34.2
Observed mean and Observed mean variance of 1984-88 from climatology	7.52	85.9
Observed mean and Observed mean variance of 1949-1988 from climatology	10.45	173.4

$$\frac{\text{5 Year Forecast Error Variance}}{\text{1984-88 Ob. Variance from Clim.}} = \frac{34.2}{85.9} = .40$$

$$\frac{\text{5 Year Forecast Error Variance}}{\text{1949-88 Ob. Variance from Clim.}} = \frac{34.2}{173.4} = .20$$