UPDATED (as of 27 July 1989)

FORECAST OF ATLANTIC SEASONAL HURRICANE

ACTIVITY FOR 1989

By

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This updated forecast uses background material contained in the Colo. State Univ. Dept. of Atmospheric Science seasonal forecast report which was issued by the author on 26 May 1989. This current report utilizes additional new June and July 1989 meteorological information and is issued to coincide with the start of the more active part of the hurricane season (after 1 August).

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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 hurricane's 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 vary with 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 presents details of the author's forecast of tropical cyclone activity for the Atlantic Ocean region (including the Caribbean Sea and the Gulf of Mexico) during 1989. This forecast is based on past and ongoing research by the author and his colleagues (Gray, 1984a, 1984b, 1989a; Gray, Berry, and Mielke, 1990) which relates the amount of seasonal Atlantic tropical cyclone activity to four factors: 1) the El Nino (EN); 2) the Quasi-Biennial Oscillation of equatorial stratospheric wind (QBO); 3) Gulf of Mexico and Caribbean Basin Sea-Level Pressure Anomalies (SLPA); and 4) lower latitude Caribbean Basin 200 mb Zonal Wind Anomalies (ZWA).

Information received by the author up to 26 July 1989 indicates that the 1989 hurricane season can be expected to have about 4 hurricanes, 9 total named storms of both hurricane and tropical storm intensity, 15 hurricane days, Hurricane Destruction Potential (HDP) of 40 (55% of the recent 40-year average), and 35 named storm days. This means that the 1989 Atlantic hurricane season will likely be a below average hurricane season. This anticipated suppression is due to the hurricane suppressing effects of an easterly phase QBO and higher than normal SLPA in the Caribbean Basin. The intensity of hurricanes that do form this year is likely to be weaker than average, particularly as compared to the hurricane intensities of last year or of the 1985 season.

TABLE OF CONTENTS

1. Introduction

The Atlantic basin (including the Atlantic Ocean, Caribbean Sea and Gulf of Mexico) experiences a larger seasonal variability of hurricane activity than any other global hurricane basin. The number of hurricanes per season can be as high as 12 (as in 1969), 11 (as in 1950, 1916), 10 (1933), 9 (as in 1980, 1955), or as low as zero (as in 1914, 1907), 1 (as in 1919, 1905), or 2 (as in 1982, 1931, 1930, 1922, 1917, 1904). Until recently there has been no objective method for indicating whether a coming hurricane season was likely to be an active one or not. Recent and ongoing research by the author (Gray, 1984a, 1984b, 1989a, 1988b; Gray, Berry, and Mielke, 1989) indicates that there is a surprising 3-5 month atmospheric predictive signal available for the Atlantic basin from global and regional predictors which are generally not operative in the other global hurricane basins or in the middle latitudes.

2. Factors Known to be Associated With Atlantic Seasonal Hurricane Variability

The author's Atlantic seasonal hurricane forecast is based on the current values of indices derived from two global and two regional scale predictive factors which the author has previously shown to be statistically related to seasonal hurricane variations. Current values of these predictive factors are available either by 1 June, the official start of the hurricane season, or on 1 August, the start of the more active part of the hurricane season. The four predictive factors are:

a) The presence or absence of a moderate or strong warm water event (El Nino) in the eastern tropical Pacific. Atlantic hurricane seasons during moderate or strong El Nino events average only about 40 percent as much hurricane activity as occurs during non-El Nino seasons. This difference is related to stronger upper tropospheric (200 mb or 12 km) westerly winds which typically occur over the Caribbean Basin and western Atlantic during El Nino seasons (See Fig. 1). Currently 1989 is not expected to be a strong or moderate El Nino year.

b) The direction of the stratospheric Quasi-Biennial Oscillation (QBO) which circles the globe over the equator - See Fig. 2. On average, there is about twice as much Atlantic hurricane activity during seasons when equatorial winds at 30 mb and 50 mb (23 and 20 km altitude respectively) blow from a relatively westerly direction as compared to when they are from a relatively easterly direction. In seasons of westerly phase equatorial winds, stratospheric winds at latitudes near 10°N latitude tend to be weak and from the east (right diagram of Fig. 2).

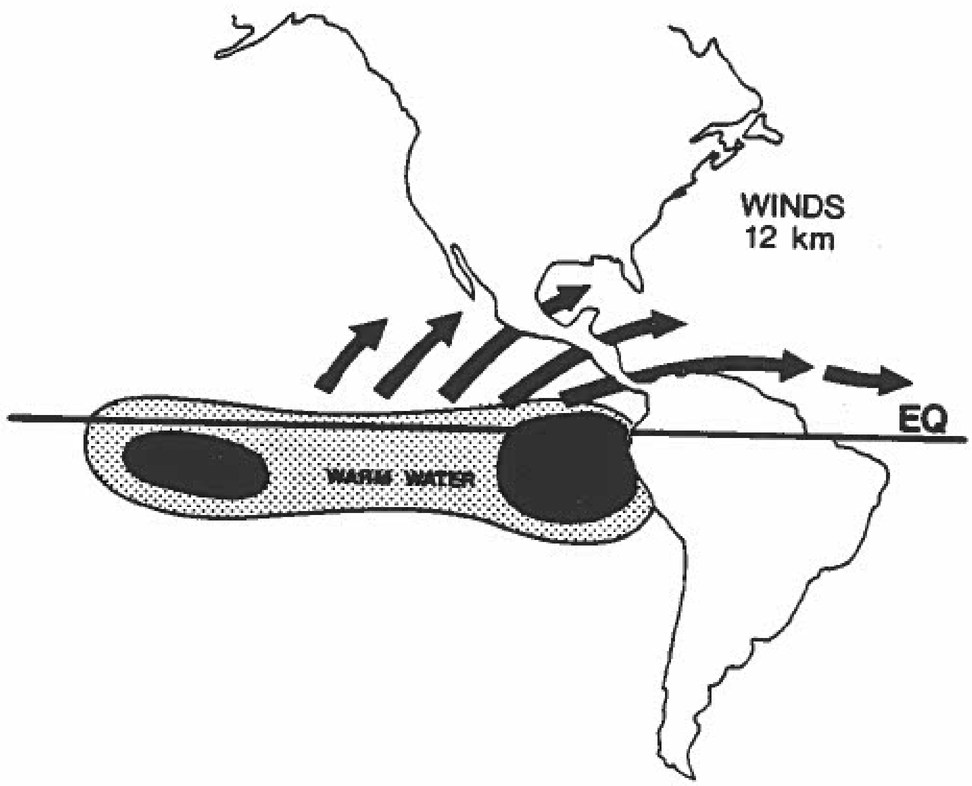


Fig. 1. Illustration of anomalously warm surface temperatures in the equatorial eastern Pacific which are associated with El Nino events. Dark regions have the warmest water. Arrows show the resulting anomalous upper tropospheric westerly winds which result from the enhanced deep cumulus convection which occurs in the equatorial Pacific as a result of these warm water events.

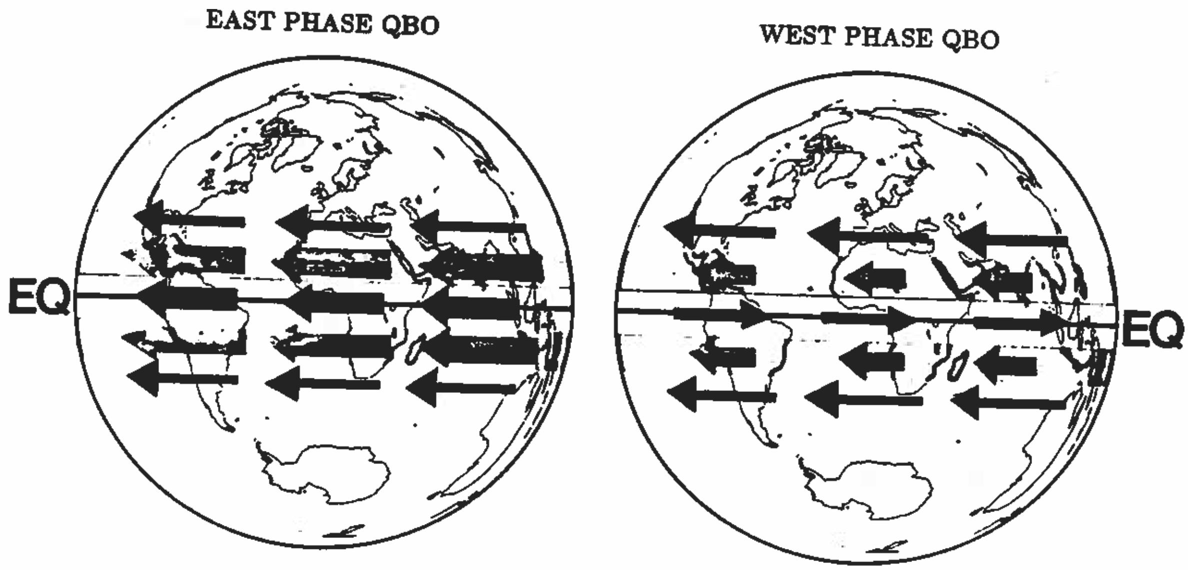


Fig. 2. Illustration of the two basic stratospheric Quasi-Biennial Oscillation (QBO) wind conditions which occur over the tropics at 50 mb or 20 km altitude during the summer seasons of both hemispheres. The left diagram shows conditions during the easterly phase of the QBO when easterly winds occur on the equator and winds at 10°N (or 10°S) are strongly from the east. The right diagram, by contrast, shows conditions during the westerly phase of the QBO when stratospheric winds on the equator are from the west and winds at 10°N (or 10°S) latitude are typically very weak and usually from the east. Hurricane activity is suppressed with conditions of the left diagram (east phase) and enhanced with conditions of the right diagram (west phase).

These seasons are different from those easterly equatorial phase seasons wherein stratospheric winds near 10°N are strongly from the east (left diagram of Fig. 2). Strong stratospheric easterlies at 10°N are associated with reduced hurricane activity. Weak stratospheric easterly winds at 10°N are associated with enhanced seasonal hurricane activity. This season's stratospheric winds are expected to be stronger from the east.

c) Sea Level Pressure Anomaly (SLPA) in the Caribbean Basin. Other factors aside, negative pressure anomalies in the Caribbean basin are associated with active hurricane seasons and vice-versa. Pressure anomalies for April through July are well correlated with August to October surface pressures and offer a degree of seasonal hurricane predictive signal. April-May 1989 SLPA is high and should be a suppressing influence on the upcoming hurricane activity.

d) Lower latitude Caribbean Basin upper tropospheric (~ 200 mb or 12 km altitude) west to east or zonal wind anomaly (ZWA). Stronger westerly 200 mb zonal wind anomalies are associated with suppression of seasonal hurricane activity and vice-versa. April-May ZWA have been about neutral.

3. Physical Interpretation of Alterations in Seasonal Hurricane Activity

Our knowledge of hurricane structure and environmental interaction is advancing. We now have better explanations for why the physical factors just discussed can cause season to season variations in Atlantic hurricane activity.

Hurricanes form only in conditions when tropospheric vertical wind shear is a minimal, as shown by the top left diagram of Fig. 3. When vertical wind shears are too strongly positive, as indicated by the diagram on the right, hurricane formation and intensification are

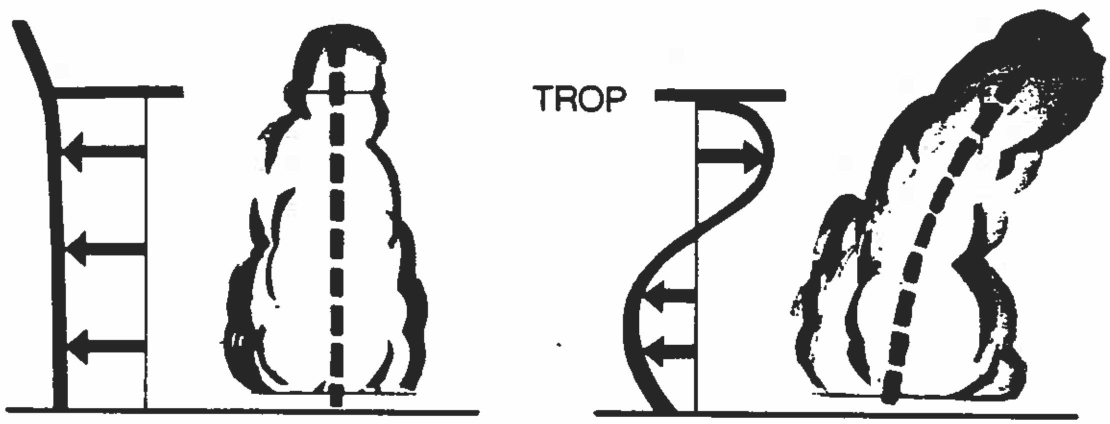


Fig. 3. Illustration of the type of tropospheric vertical wind shear which is (left diagram) and is not (right diagram) conducive to hurricane formation. The right diagram portrays conditions of excessive westerly wind shear with height which causes the tropical disturbance to be sheared to the east with height. This shearing inhibits hurricane formation while the unsheared conditions in the left diagram do not. Trop. signifies the top of the troposphere (~ 16 km altitude).

inhibited. El Nino events and seasons of strong Zonal Wind Anomaly (ZWA) cause the environmental vertical wind shear conditions shown by the right diagram of Fig. 3 and contribute to a large reduction in Atlantic hurricane activity in El Nino and strongly positive ZWA seasons.

Hurricane formation and hurricane intensity is also influenced by vertical wind shear conditions in the lower stratosphere. Hurricane formation is inhibited when lower stratospheric winds just above the tropopause (TROP.) blow too strongly from the east, as shown by the upper left diagram of Fig. 4. This configuration causes central cloud convection and related effects to be sheared off to the west, as shown

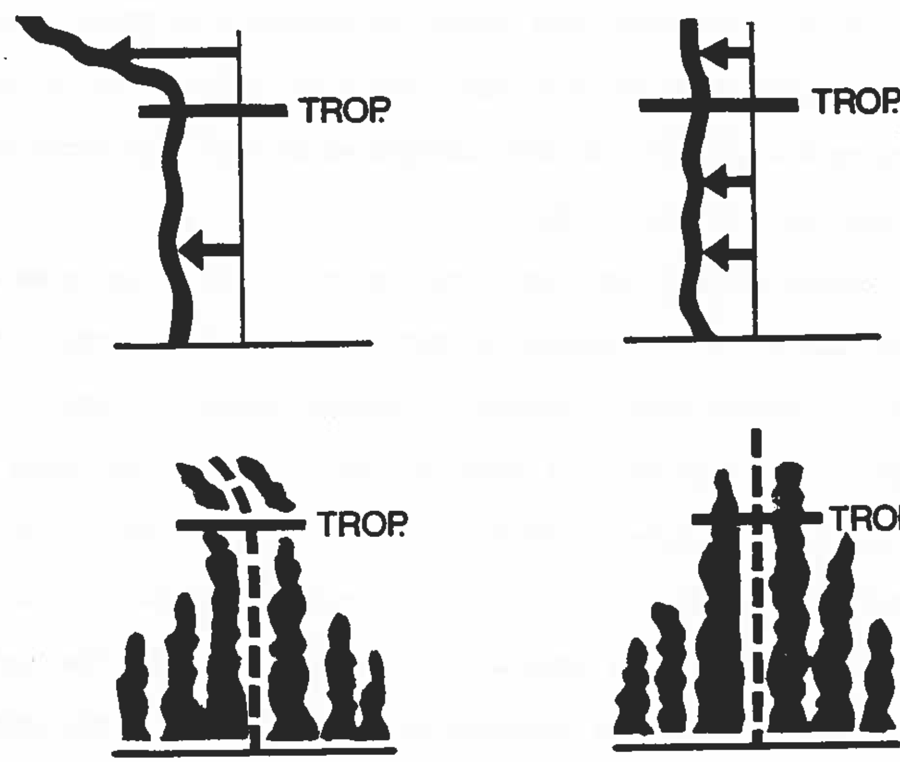


Fig. 4. Illustration of the types of vertical wind shear and cloudiness which extend through the tropopause (TROP.) into the stratosphere. Conditions in the diagrams on the right are conducive to hurricane formation and more intense hurricanes than conditions of the left diagrams.

by the lower left diagram of this figure. These conditions inhibit hurricane activity. The contrasting condition, when lower stratospheric zonal winds blow only lightly from the east, is shown by the upper right diagram of Fig. 4. In this case, vertical wind shear conditions remain weak and inner-core deep convection and related effects are not sheared off to the west in the lower stratosphere. Conditions illustrated on the right hand side of Fig. 4 are more favorable for hurricane formation and for the development of intense hurricanes. Consequently, we observe comparatively more hurricane formation and more intense hurricanes in conditions when lower stratospheric winds at about 10°N latitude blow only weakly from the east during August and September (Quasi-Biennial Oscillation (QBO) west wind phase) in relation to those times when they blow strongly from the east (QBO east wind phase). It is these weak vs. strong easterly wind velocity changes which are associated with the Quasi-Biennial Oscillation or QBO.

Figure 5 shows the time variation of average September easterly stratospheric winds measured at Balboa, Canal Zone (9°N). For the period of record (since 1949), seasons of strong easterly winds (dots) have had slightly less than half as much hurricane activity as those seasons when the Balboa stratospheric winds were only weakly from the east (crosses), demonstrating that stratospheric wind speed is a strong influence on both hurricane activity and intensity. Note that in 1989 the September 50 mb zonal wind at Balboa is expected to be strongly from the east and should contribute to a suppression of hurricane activity in general and dimish the likelihood of more intense hurricane activity.

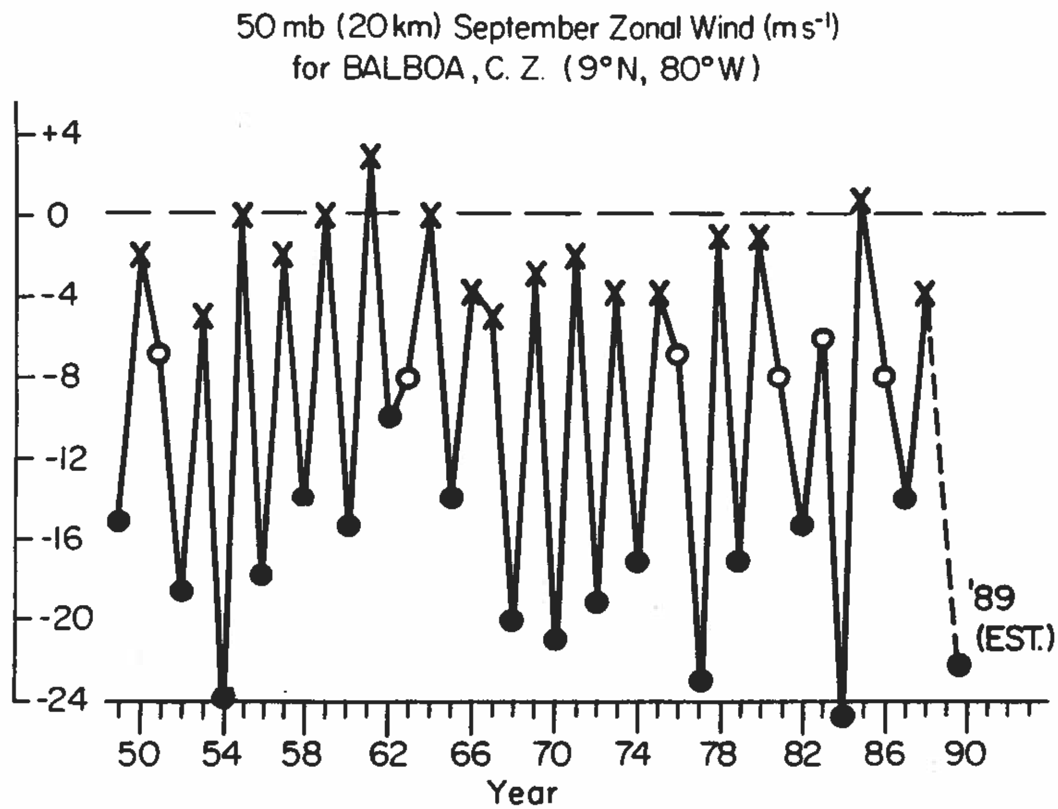


Fig. 5. 50 mb (20 km) September zonal wind (m s^{-1}) for Balboa, C.Z., (9°N, 80°W). Heavy dots show seasons of strong easterly stratospheric winds, X's represent seasons of weak easterly stratospheric winds and open circles indicate seasons with intermediate easterly winds.

The two other influences affecting seasonal hurricane activity result from variations of Sea Level Pressure Anomaly (SLPA) and 200 mb (12 km) Zonal Wind Anomaly (ZWA). These influences are often linked together and are associated with the latitude at which the Intertropical Convergence Zone (ITCZ) establishes itself relative to the north coast of South America during August-September. When the ITCZ establishes itself more equatorwards than normal, surface pressures and upper tropospheric zonal winds over the Caribbean are typically stronger than normal, as shown by the left diagram of Fig. 6. These conditions inhibit seasonal hurricane activity.

By contrast, in those seasons when the ITCZ establishes itself poleward of normal, the reverse condition occurs. Caribbean Basin SLPA and ZWA are negative and seasonal hurricane activity is usually enhanced. It is for these reasons that we closely monitor sea level pressure and upper tropospheric zonal wind conditions as indicators of the probable location of the ITCZ during August-September and its consequent influence on seasonal hurricane activity. These SLPA and the ZWA variations (where ZWA is taken only in non-El Nino years) are independent of the El Nino and QBO influences.

It is important to closely monitor the conditions of the El Nino, QBO, SLPA, ZWA in order to be able to better understand and predict the variations of Atlantic seasonal hurricane activity.

4. Cyclical Trends in Atlantic Hurricane Destruction Potential (HDP)

The wind and storm surge destruction of a hurricane is better represented by the square of the storm's maximum winds than by the maximum wind itself. This potential for damage from hurricane winds and storm surge might be termed Hurricane Destruction Potential (HDP). We define <u>H</u>urricane <u>D</u>estruction <u>P</u>otential (HDP) as

$$HDP = \Sigma (V_{max})^2$$

for V_{max} equal or greater 65 knots for each 6-hour period a hurricane is in existence. HDP is given in units of $10^4 knot^2$.

The HDP for the 23-year period of 1947-1969 was more than twice that of the 18-year period of 1970-1987 (see Fig. 7). Although the number of

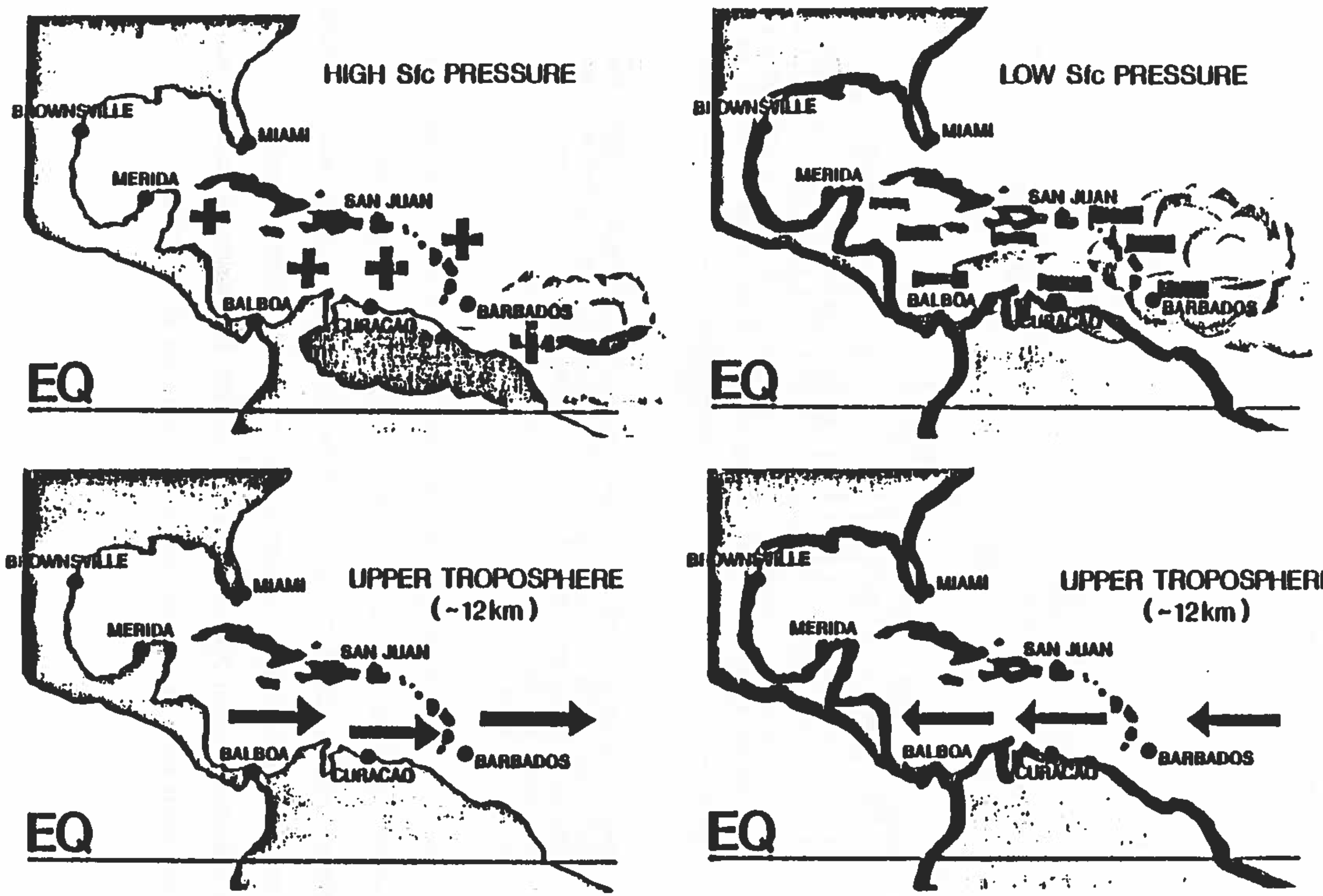


Fig. 6. Typical conditions for August-September when the Intertropical Convergence Zone (ITCZ) is displaced southward (left diagrams) resulting in positive Sea Level Pressure Anomaly (SLPA) and above normal upper tropospheric zonal wind anomaly (ZWA). The opposite conditions for August-September with the ITCZ displaced poleward is portrayed by the two right diagrams.

hurricanes per season averaged only 31% higher during the period of 1947–1969, as compared with 1970–1987, the Hurricane Destruction Potential (HDP) was more than twice as great during the earlier period.

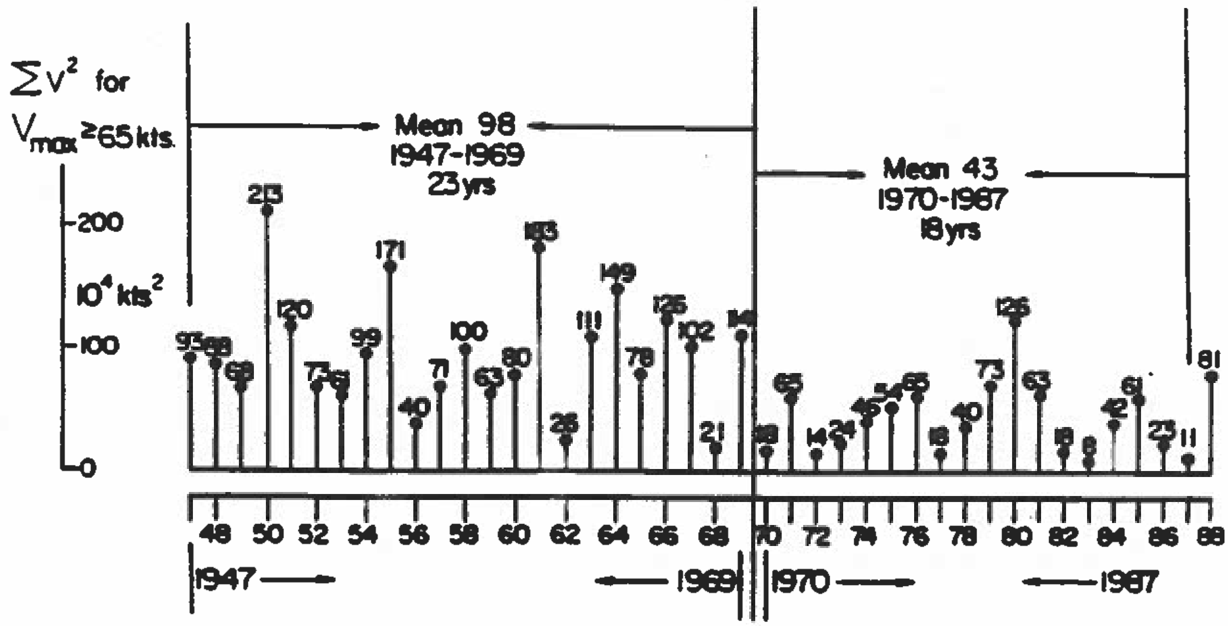


Fig. 7. Yearly variations of Hurricane Destruction Potential (HDP) for 1947–1988. HDP is defined as the sum of all hurricane maximum wind speeds squared for $V_{max} \geq 65$ knots for each 6-hour observing period throughout the hurricane season. Units 10^4 kts^2.

The more inactive hurricane period between 1970–1987 parallels with the extended period of west African drought which has persisted during these years (compare Figs. 7 and 8). This inactive period is also related to the occurrence of higher Caribbean Basin surface pressure and of greater Caribbean Basin 200 mb (12 km or 40,000 ft) westerly zonal winds which have been present during the summer periods since 1970.

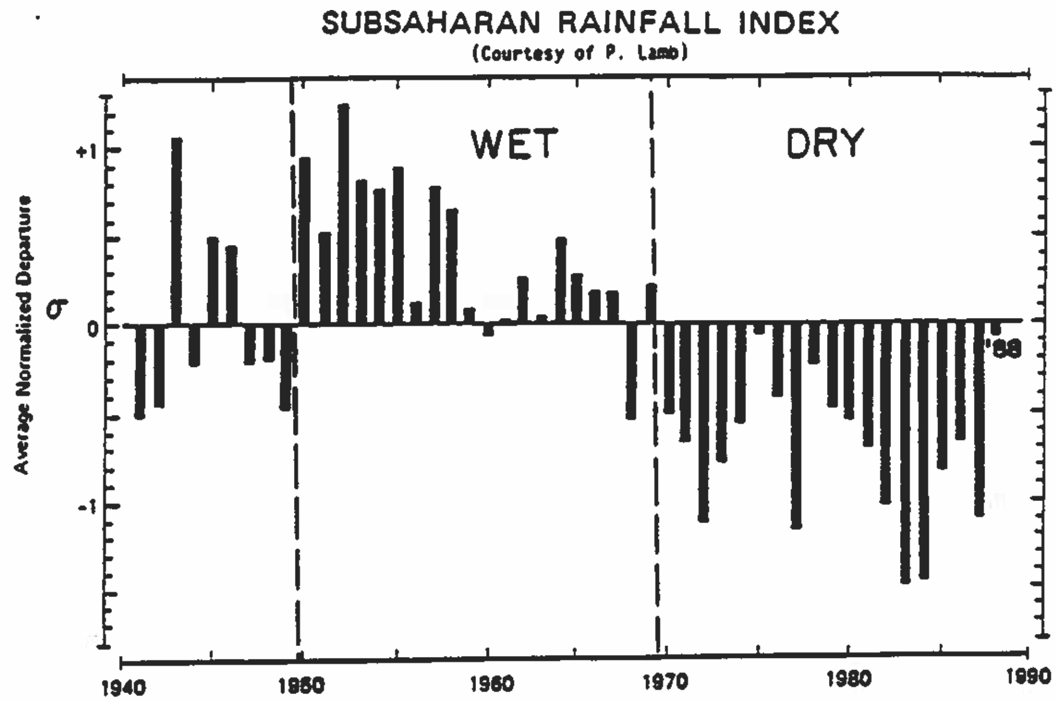


Fig. 8. An estimate of Lamb's West African rainfall index. Note the general drought conditions between 1970-1987.

5. Possibilities for Prediction of Seasonal Hurricane Intensity

It is possible to offer a degree of skillful probabilistic estimates of the potential for intense and long lived hurricanes duirng a coming hurricane season. For instance, intense and long track hurricanes typically occur in seasons with comparatively weak easterly zonal winds at 50 mb (12 km) over stations near 10°N latitude (see Fig. 5). The majority of intense hurricanes occur in situations with weak 50 mb winds. Of the 101 most intense hurricanes (V_{max} greater than 100 knots or 115 mph) in the 40-year period of 1949-1988, 59 (58%) occurred in seasons when 50 mb zonal winds at Balboa were only weak from the east vs. 29 (29%) for seasons when they were strong from the east. Easterly winds of intermediate strength for the other 13 (13%) intense storms were present. It is also of interest to note that 69 of these 101 most intense hurricanes occurred during the 1950s and 1960s versus only 29 during the period of 1970-1987; the other 3 occurred in 1988.

The 50 mb zonal wind direction can be reliably forecast before the start of the hurricane season. Primarily because of its comparatively long record, we have used the stratosphere measuring station of Balboa (9°N,80°W) in the Canal Zone. This station is fairly representative of the western Atlantic latitude belt between 8 to 15°N where most of the intense hurricanes of African origin form. In 1989 it is expected that the Balboa 50 mb zonal wind will be strong from the east and should act to reduce intense hurricane activity during this season.

6. Rainfall Conditions in West Africa

Although yet to be explicitly incoporated in the author's forecast scheme, West African summer rainfall conditions are related to Atlantic hurricane activity and need to be monitored. West Africa had higher amounts of rainfall in 1988 than in any year since 1969. We cannot tell if 1988 represents the beginning of a new multi-decadal regime of heavier rainfall, but it may. It is important to note that through the 20th of July of this year, seasonal West African rainfall has been generally higher and vegetation is generally more advanced for this time of year than it has been since 1969 with the exceptions of last season (1988) and 1975. The current summer has seen few of the normal late June and July dust outbreaks that originate in West Africa and travel across the Atlantic. The absence of these dust clouds is likely another indication of the advanced nature of West African vegetation for this time of year.

Comparatively, warm SST anomalies have recently appeared off the West African coast and warm SST anomalies in the tropical South Atlantic (an inhibiting factor to West African summer rains) have recently cooled somewhat. The numerical model of the UK Met. Office predicts above normal summer rainfall conditions for West Africa this year. The UK Met. Office's statistical prediction for West African summer rainfall (issued in April) had forecast a dry year. This statistical prediction has recently been amended in the direction of more rainfall. Zonal wind anomalies at 850 mb and 200 mb for June and the first-half-of-July over West Africa and the eastern Atlantic indicate a more active west African monsoon trough with conditions being generally favorable for more rainfall.

All of the above factors taken in combination are indicative of 1989 West African Sahel precipitation being near normal for only the third year since 1969. If this proves to be the casee, we may be seeing the beginning of the break in the multi-decadal West African Sahel drought. Such a trend might also signal the start of a return to the more active hurricane seasons as were experienced in the 1950s and 1960s. The next couple of years of West African rainfall need to be carefully monitored.

7. Rationale for Making a Seasonal Forecast of Atlantic Hurricane Activity

Figure 9 shows the average annual distribution of hurricane and tropical storm activity by calendar date for a 95 year period. Note that although the official start of the hurricane season is 1 June, the active part of the hurricane season does not begin in earnest until after the 1st of August. In consideration of the distribution in Fig. 13, a forecast scheme using QBO, EN, SLPA and ZWA information is based on several premises including:

1) the strength of the stratospheric 50 mb easterly QBO wind speed changes on such a long time interval (~ 14-18 months) and in such a uniform manner, that the trend in these wind speeds can be reliably extrapolated for 3 to 6 months into the future.

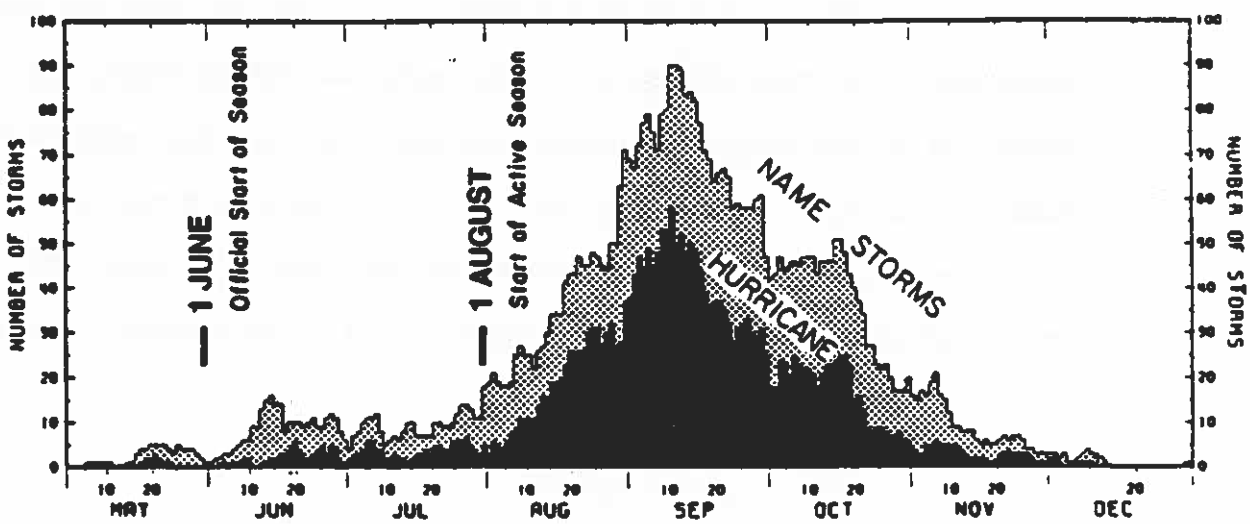


Fig. 9. Number of tropical storms and hurricanes (open curve) and hurricanes (solid curve) observed on each day, May 1, 1886 through December 31, 1980 (from Neumann, et al., 1981).

2) the oceanography and meteorological communities are normally able to detect the presence and approximate intensity of a forthcoming El Nino event by late May with good success and by late July with even greater certainty.

3) information on the Caribbean Basin-Gulf of Mexico sea level pressure anomaly (SLPA) and 200 mb zonal wind anomaly (ZWA) for the four pre-hurricane months of April through July are readily available.

8. Characteristics of Four (EN, QBO, SLPA, ZWA) Predictors for the 1989 Hurricane Season

An evaluation of these two global and two regional predictors, indicates that the coming 1989 hurricane season will be a below average hurricane season.

a) El Nino.

The intense cold water of the La Nina (LN) event of 1988 has mostly dissipated and near normal Sea Surface Temperatures (SST) have returned to much of the central and eastern tropical Pacific. Thermocline depths are also near normal. Therefore, the 1989 hurricane season is not expected to experience either the hurricane suppressing influence of a warm SST anomaly or of the enhancing influence of a cold SST event and this factor is expected to be neutral.

b) QBO.

Stratospheric winds near 10°N at the key levels of 30 mb (23 km altitude) and 50 mb (20 km) will be strongly from an easterly direction during the remaining of the 1989 hurricane season. Winds at 50 mb have only recently reserved themselves but are increasing rapidly from the east.

Figure 10 shows recent and anticipated (extrapolated) global relative QBO zonal winds for the coming 1989 season (solid horizontal black line). Table 1 shows the absolute value of the current and extrapolated QBO zonal winds near 10°N for August-October 1989 based on a combination of the QBO relative wind alteration and annual wind cycle variations at the low latitude stations of Balboa (9°N), Curacao (12°N), Trinidad (11°N), and Barbados (13°N). Table 2 is similar to Table 1 but shows both the current and the forecast relative zonal winds in this same latitude belt. Note that during the 1989 hurricane season, the 70 mb (18.5 km) through 30 mb (23 km) easterly stratosphere winds are expected to be substantially stronger than normal. Figure 11 provides an estimate of where within the QBO cycle the current hurricane season fits. Note that at 30 mb, the 1989 season will be at the height of the easterly phase and will then start to fade out of its current easterly cycle. At 50 mb, the QBO zonal winds are just now beginning the easterly phase. Because these winds will be usually strong from the east at all lower stratospheric levels, the QBO should act as a suppressing influence on both hurricane activity and the intensity of these hurricanes that do form as discussed with Figs. 4 and 5).

c) SLPA.

Table 3 shows the average 1 April-May and 1 June-26 July 1989 SLPA for both the Caribbean-Gulf of Mexico 6-station average and for the special 5-station low latitude average. Note that SLPA is above average for nearly all stations. These higher pressure anomalies indicate that 1989 hurricane activity will likely be reduced. There have been very few

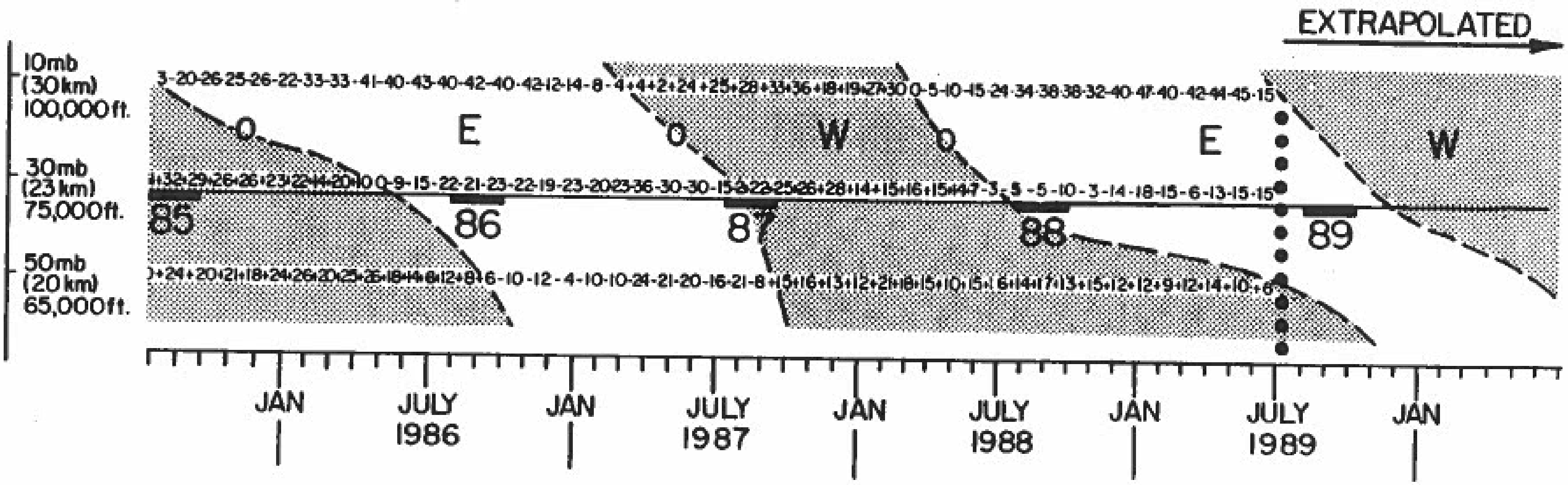


Fig. 10. Vertical cross-section of recent monthly average QBO west to east (or zonal) wind in knots. This figure represents an average of the Balboa, C.Z. (9°N) and Ascension (8°S) rawinsondes with Trinidad (11°N) being substituted for Balboa during parts of 1988 and 1989. The mean annual cycle has been removed from each sounding before averaging. Winds from a westerly direction have been shaded. Information beyond July 1989 has been extrapolated. Thick horizontal lines show the active portion of each hurricane season from 1986 to 1989.

TABLE 1

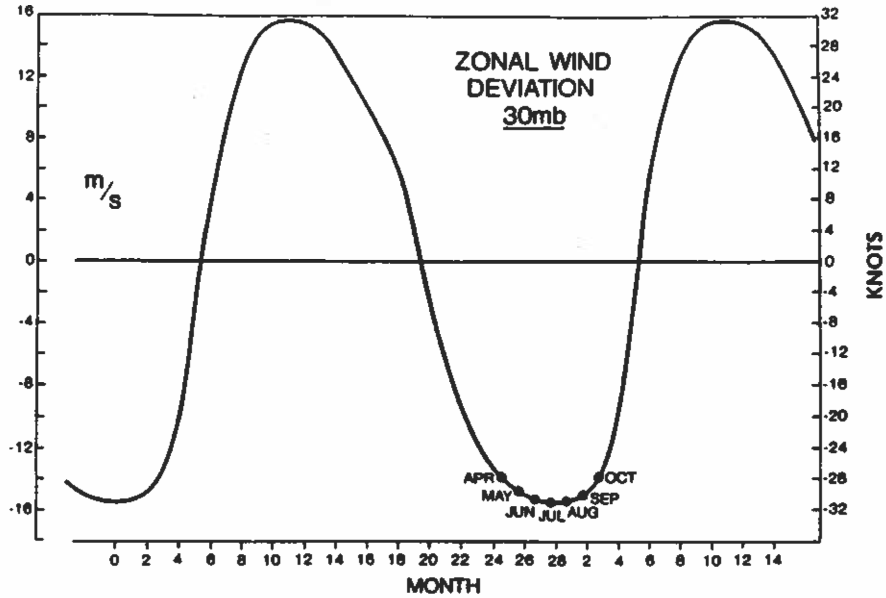
April through October observed and extrapolated absolute value of stratospheric zonal wind (U) in the latitude belt between 8-12°N as obtained from lower Caribbean basin stations of Curacao, Barbados, Trinidad, and Balboa. Values in m/s.

	Observed				Extrapolated		
Level	Apr	May	Jun	Jul	Aug	Sept	Oct
30 mb (23 km)	-18	-23	-25	-33	-33	-30	-25
50 mb (20 km)	-1	-4	-11	-17	-20	-22	-23
70 mb (18.5 km)	-1	+4	-6	-11	-14	-15	-14

TABLE 2

Same as Table 1 but for the relative zonal wind where the annual wind cycle has been removed. Values in m/s.

	Observed				Extrapolated		
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	-6	-12	-16
70 mb (18.5 km)	-1	+5	0	-1	-3	-6	-8



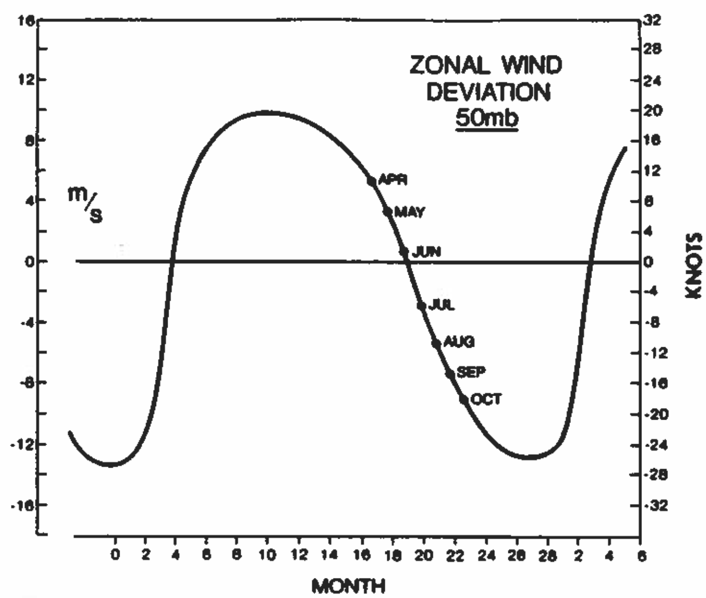


Fig. 11. Portrayal of where in the QBO zonal wind cycle the 30 mb (top diagram) and 50 mb (bottom diagram) zonal wind (U) are estimated to be by month in 1989. Curves have been constructed showing the average amplitude and period of the QBO cyclone at both levels over the last 35 years.

TABLE 3

Average April-May and 1 June-26 July Gulf of Mexico-Caribbean Basin and Low Latitude Sea-Level Pressure Anomalies (SLPA) (data from Colin McAdie of NHC) from data of 1949-1988 - in mb.

Gulf of Mexico-Caribbean Basin SLPA	April -May	1 June -26 July
Brownsville	+0.5	-0.6
Merida (Mex.)	+1.8	+0.9
Miami	+0.7	+1.4
San Juan	+0.5	+0.3
Curacao	+0.8	+1.1
Barbados	+1.1	+0.8
Average	+0.9	+0.7

Low Latitude SLPA	April -May	1 June -26 July
San Juan	+0.5	+0.3
Curacao	+0.8	+1.1
Barbados	+1.1	+0.8
Trinidad	+1.5	+1.1
Cayenne	+0.6	+0.9
Average	+0.9	+0.8

seasons during the last 40 years wherein SLPA during April through July has been as high as has been observed during this season.

d) ZWA

The April-May and 1 June-26 July Lower-Caribbean Basin Zonal 200 mb Wind Anomalies (ZWA), although not explicitly used in the 1 June forecast, are important for the updated 1 August forecast. Table 4 shows these values in comparison to both the 1970-88 and 1954-69 zonal wind averages. Since 1970, 200 mb lower Caribbean basin zonal winds have been stronger than in the earlier period. Note that ZWA values are about neutral in comparison to the prior 19-year climatology but are about 2 m/s stronger from the west in comparison to the 1954-69 climatology. Although a high ZWA acts to reduce hurricane activity, the current zonal wind anomalies are not judged to be large enough to warrent an addition or subtraction to the anticipated 1989 hurricane activity.

TABLE 4

Lower Caribbean basin 200 mb Zonal Wind Anomaly (ZWA) for 1989 relative to 1970-88 and 1954-69 Average (as supplied by Colin McAdie of NHC). Values in m s^{-1}.

Station	1970-88 Ave.		1954-69 Ave.	
	April -May	1 June -26 July	April -May	1 June -26 July
Kingston (18°N, 77°W)	0	-1	+2	+1
Curacao (12°N, 69°W)	+1	0	+4	+3
Barbados (13.5°N, 60°W)	0	+1	+2	+4
Trinidad (11°N, 62°W)	0	0	+2	+2
Balboa, C.Z.,9°N,80°W	+1	+1	+2	+2
Average	0	+0.2	+2.4	+2.4

9. Author's 1989 Forecast

The author's Atlantic seasonal forecast scheme takes the following form:

$$\begin{pmatrix}\text{Predicted Amount} \\ \text{of Hurricane} \\ \text{Activity per Season}\end{pmatrix} = \begin{pmatrix}\text{Average} \\ \text{Season}\end{pmatrix} + \overbrace{(\text{ QBO + EN + SLPA + ZWA + MEM })}^{\text{Adjustment Terms}} \quad (1)$$

where

QBO = 30 mb and 50 mb Quasi-Biennial Oscillation equatorial zonal wind corrections, positive for west phase, negative for east phase.

EN = El Nino influence. Warm water reduces hurricane activity, cold water enhances it.

SLPA = Average SLPA for April-May, from selected Caribbean-Gulf of Mexico and tropical stations. Subtract if SLPA is significantly above average, add if below average. Make no correction when SLPA is near normal (between -0.4 and 0.4 mb).

ZWA = Zonal Wind Anomaly at 200 mb (12 km) for five low latitude upper air Caribbean stations. Valid for June and July wind data in non-El Nino years. Not directly used for the 1 June forecast.

MEM. = MEMORY correction term from last 5 years August-September values of SLPA and ZWA. Applied to HDP forecast.

Table 5 shows the current values for the five adjustment terms and how they enter the author's seasonal forecasts for the number of hurricanes, named storms, hurricane days, named storm days and Hurricane Destruction Potential (HDP) for the coming 1989 hurricane season based on the information as just discussed.

TABLE 5

1989 PREDICTED SEASONAL HURRICANE ACTIVITY

(Predicted No. of Hurricanes per Season) = 6 + QBO + EN + SLPA + ZWA

(-1) + (0) + (-1) + (0) = <u>4</u>

(Predicted No. of Hurricanes and Tropical Storms Per Season) = 9 + QBO + EN + SLPA + ZWA

+ (-1) + (0)+ (-1) + (0) = <u>7</u> (Raise to 9)

(Predicted No. of Hurricane Days Per Season) = 25 + 5 (QBO + EN + SLPA + ZWA)

(-1) + (0)+ (-1) + (0) = <u>15</u>

(Predicted No. of Named Storm Days) = 2.0 x (No. of Hur. Days) = <u>30</u> (Raise to 35)

(Hurricane Destruction Potential - HDP) = 75 + (QBO + EN + SLPA + ZWA + MEM.)

75 + -15 + 0 + -15 ÷ (0) - 5 = <u>40</u>

10. New Statistical Forecasts

The author and two CSU research colleagues (Professors Paul Mielke and Kenneth Berry of the statistics department) have, over the last 3 years, been performing a large variety of new statistical analyses of Atlantic seasonal hurricane activity. We are attempting to find ways in which the author's (Gray, 1984a, 1984b) original seasonal hurricane prediction scheme can be more thoroughly documented quantitatively and how it may be improved by new predictive parameters and alternative combinations of the forecast parameters we presently use.

Our statistical testing employs a method of analysis which has been developed by Mielke and Berry called Multiple Regression Permutation Procedure, or MRPP (Mielke, 1985; Berry and Mielke, 1985). MRPP is believed to improve on standard statistical methods because it does not square outlier deviations, a procedure which often tends to skew analyses but rather treats variations as linear deviations.

Berry and Mielke have made over 1500 new statistical test runs to examine a wide variety of parameters related to seasonal hurricane activity. These new analyses involve variations in Atlantic hurricane activity occurring during the 40-year period of 1949-1988. A 'jackknife' type of statistical approach (see Efron, 1982) has been used whereby forecast test statistics are developed from all years of data other than the year being forecast. Each forecast year is thus systematically excluded from the developmental data set and in this sense may be considered to be independent.

Besides the obvious implications for forecast improvement and testing, we also find that these statistical analyses are shedding new insights into relationships between seasonal environmental parameters and hurricane activity. We find that hurricane activity and intense hurricane activity in particular can be better predicted than can the level of activity for weaker tropical cyclones. The best seasonal predictors are obtained for the lower latitude hurricanes of African origin. The best pre-seasonal predictions and current season TC associations are found with the most intense cyclones. A significantly better prediction can be made from June-July data than can be made from April-May information.

Residual Corrector. As seasonal hurricane activity and especially HDP have undergone a general multi-decadal decrease during the 1970s and 1980s from the more active period of the 1950s and 1960s, we have also built a long term trend or Residual Corrector (RC) into the forecast. HDP in the period 1970-86 was only 45% of the value for the period 1949-69. This quasi-decadal decrease in HDP (less noticeable in seasonal numbers for named storms and hurricanes) is not related to the QBO or El Nino but rather to changing decadal values of ZWA and SLPA. We have devised a corrective term for these quasi-decadal changes which can either increase or decrease the seasonal forecast made on 1 June or 1 August according to trends during the previous 5 August-September values of ZWA and SLPA. If values of the residual corrector have been higher than average in the five previous hurricane seasons then one should expect the next season's values to also be higher or vice-versa. This trend or residual corrector improves our forecast.

11. Predictors

The data needed for a detailed statistical prediction of the number of hurricanes (NH), number of named storms (NNS), number of hurricane days (NHD) and hurricane damage potential (HDP) for the updated 1 August forecast are given in Table 6. Table 7 gives the author's measured or extrapolated values of these parameters for the 1989 season. These eight variables are coded and linearly combined into 4 prediction equations. EN can be classified as a weak or no El Nino year (0), a moderate El Nino year (M), and a strong El Nino year (S). $\overline{SLPA_{AS}}$ for a given year is the average of the values of August-September SLPA for the preceding five years. Similarly, ZWA_{AS} for a given year is the average of the values of ZWA_{AS} for the preceding five years.

TABLE 6

Definitions of the variables in the above equations.

$SLPA_{JJ}$	- June-July average Sea Level Pressure Anomaly at the 5 tropical stations of San Juan, Curacao, Trinidad, Barbados, and Cayenne.
ZWA_{JJ}	- June-July average 200mb Zonal Wind Anomaly at Balboa, Curacao, Trinidad, and Barbados.
$SLPA_{AS}$	- Average SLPA for the five previous August-September periods.
ZWA_{AS}	- Average ZWA for the five previous August-September periods.
U_{50}	- Extrapolated September 50mb zonal wind near 10 N.
U_{30}	- Extrapolated September 30mb zonal wind near 10 N.
EN	- El Nino event of zero or weak, moderate or strong intensity.

TABLE 7

Eight forecast parameters used for assistance with the 1989 1 August updated forecast of Atlantic Seasonal Hurricane activity as determined from meteorological data available in late July 1989.

$$SLPA_{JJ} \quad +0.8mb$$
$$ZWA_{JJ} \quad +1.2m/s$$

$$\overline{SLPA}_{AS} = +.29mb$$
$$\overline{ZWA}_{AS} = -.06m/s$$

$$U_{50} = -22m/s$$
$$U_{30} = -30m/s$$

$$U_{30}-U_{50} = 8m/s$$

$$EN = 0$$

The construction of the predictors for NH, NNS, NHD, and HDP is as follows: $SLPA_{JJ}$ and ZWA_{JJ} are linearly combined into one predictor, reflecting pressure and wind anomaly quantities in the Caribbean basin; U_{30} and U_{50} (the 30mb and 50mb September forecast wind data, respectively) are combined into a second predictor, reflecting QBO; and $\overline{SLPA}_{AS}$, $\overline{ZWA}_{AS}$ and EN are linearly combined into a third predictor, reflecting historical and trend quantities. The coefficients for each predictor are empirically selected weights which maximize agreement between the observed and cross-validated predicted values. The best prediction for the Number of Hurricanes (or NH) is given by

$$\begin{aligned} NH = b_0 + b_1[4.5(SLPA_{JJ}) + ZWA_{JJ}] + b_2[U_{30} - 6.0|U_{30} - U_{50}|] \\ + b_3[8.3(\overline{SLPA}_{AS}) + 0.9(\overline{ZWA}_{AS}) + EN] \end{aligned} \qquad (1)$$

where EN takes on weights of 0, 5, and 10 for weak, moderate, and strong El Nino years, respectively, $b_0 = 7.02817$, $b_1 = -0.19271$, $b_2 = 0.0173583$, and $b_3 = -0.11192$. Other parameters are defined as in Table 6. The cross-validated probability value (i.e., the probability that the apparent associations are due to chance) for these results is 2.53×10^{-6} and the cross-validated agreement measure (variance explained) is 0.424. Thus, over 42 percent of the variability over and above that which could be attributed to chance in the number of hurricanes for the updated 1 August forecast is independently (by jackknife method) explained by this equation.

The prediction equation for the Number of Named Storms (NNS) is

$$NNS = b_0 + b_1[4.8(SLPA_{JJ}) + ZWA_{JJ}] + b_2[U_{30} + 6.3|U_{30} - U_{50}|] + b_3[14.3(\overline{SLPA}_{AS}) + \overline{ZWA}_{AS} + 1.9(EN)] \quad (2)$$

where EN takes on weights of 0, 5, and 10 for weak, moderate, and strong El Nino years, respectively, $b_0 = 11.2958$, $b_1 = -0.295964$, $b_2 = -.047477$, and $b_3 = -.059556$. The cross-validated probability value for these results is 1.44×10^{-5} and the cross-validated agreement measure is 0.396. Thus, almost 40 percent of the variability in the number of named storms for the updated 1 August forecast is explained by the equation, over and above that which could be attributed to chance.

The prediction equation for HDP is

$$HDP = b_0 + b_1[10.7(SLPA_{JJ}) + ZWA_{JJ}] + b_2[2.8U_{50} + |U_{30} - U_{50}|] + b_3[4.1(\overline{SLPA}_{AS}) - 3.0(\overline{ZWA}_{AS}) - EN] \quad (3)$$

where EN takes on weights of 0, 8, and 10 for weak, moderate, and strong El Nino years, respectively, b_0 = 82.2966, b_1 = -2.01461, b_2 = 0.573187, and b_3 = 3.6121. The cross-validated probability value for these results is 3.86 x 10^{-8} and the cross-validated agreement measure is 0.505. Thus, more than 50 percent of the variability of seasonal HDP for the updated 1 August forecast is explained by this equation, over and above that which could be attributed to chance.

The prediction equation for NHD is

$$\begin{aligned} NHD = b_0 + b_1[45.4(SLPA_{JJ}) + ZWA_{JJ}] + b_2[3.2U_{50} + |U_{30} - U_{50}|] \\ + b_3[-1.7(\overline{SLPA}_{AS}) + 1.5(\overline{ZWA}_{AS}) + EN] \end{aligned} \quad (4)$$

where EN takes on weights of 0, 8, and 10 for weak, moderate, and strong El Nino years, respectively, b_0 = 30.8599, b_1 = -0.122484, b_2 = 0.204422, and b_3 = -1.60086. The cross-validated probability value for these results is 5.93 x 10^{-8} and the cross-validated agreement measure is 0.523. Thus, more than 52 percent of the variability in the seasonal number of hurricane days for the updated 1 August forecast is explained by this equation, over and above that which could be attributed to chance.

Note that more than half of the seasonal variance for Hurricane Destruction Potential (HDP) and for the Number of Hurricane Days (NHD) are independently explained by forecast equations (3) and (4). It is quite unexpected that the potential for estimating the seasonal sum of such infrequent and meso-scale events as Atlantic hurricanes have an independent prediction signal this high. See the forthcoming paper by

Gray, Berry, and Mielke (1990) which gives more background information on this statistical forecasting scheme.

12. Comparison of Predictions for 1989

The above prediction equations when applied with the forecast parameters of Table 6 yield the 1989 seasonal hurricane forecasts shown in Table 8. The author's more simplified forecast of Table 5 is shown with

TABLE 8

Summary of 1989 Forecasts

	Statistical Prediction	Late May Forecast	Final Rectified 1 August Prediction	Last 40-year Climatology
No. of Hurricanes (NH)	= 4.49	4	<u>4</u>	6
No. of Named Storms (NNS)	= 8.59	7	<u>9</u>	9
No. of Hurricane Days (NHD)	= 14.44	15	<u>15</u>	24
Hurricane Destruction Potential (HDP)	= 36.86	40	<u>40</u>	73
No. of Named Storm Days	(not made)	30	<u>35</u>	45

the underline. Note how close the statistical forecasts are to the author's previous (May 1989) forecast and his rectified predictions (Table 5). Both forecast methods indicate a below average hurricane season. See Appendix A for the details of these statistical predictions.

13. Discussion

With 50 mb QBO winds expected to be strongly out of the east, the probability of having a number of very intense hurricanes like those that occurred in 1980, 1985 and 1988 is relatively low. Seasons with easterly QBO winds (as 1989 will be) usually have a suppression of low-latitude (African spawned) systems which usually form the most intense hurricanes. The statistical odds thus favor reduced hurricane activity for the Caribbean Basin which was so devastated last year. Except for 1988, Caribbean Basin hurricane activity has been very low during the 1980s.

Higher Caribbean basic surface pressure appear to be a consequence of the ITC being shifted further south of its normal position. This is a suppressing influence on hurricane activity.

Indications as of late July are that the West African Sahel regions will likely receive near normal amounts of rainfall in 1989. This is consistent with recent reports of late June and July West African rainfall and vegetation. Increased West African rainfall in 1989 is a factor which may lead (other factors held constant) to an increase in Atlantic hurricane activity.

It is anticipated, however, that the hurricane inhibiting influences of the easterly QBO and high Caribbean surface pressure, will, despite the possible implications of increased West African rainfall, be the more dominate influence and lead to a below average Atlantic hurricane season for 1989.

Although it is anticipated that the upcoming 1989 hurricane season will be below average it is still expected to be more active than the four recent hurricane seasons of 1982, 1983, 1986, and 1987. The Hurricane

Destruction Potential (HDP)* this year should be much lower than last season or of the recent 1985 season. In that there have already been two minimal tropical storms (Allison and Barry) the author has chosen to raise his prediction of named storms to 9, of which only 4 should be expected to become hurricanes.

14. Cautionary Note

It is important that the reader realize that this forecast scheme, although showing promising statistical skill in the standard meteorological sense, can only predict about 50% 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.

This forecast scheme also does not predict where within the Atlantic Basin the storms will strike. For instance, although 1983 was one of the most inactive seasons on record, Hurricane Alicia caused over a billion dollars of damage to the Houston area.

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* The wind and storm surge destruction of a hurricane is better represented by the square of the storm's maximum winds than by the maximum wind itself. This potential for damage from hurricane winds and storm surge might be termed Hurricane Destruction Potential (HDP). We define Hurricane Destruction Potential (HDP) as HDP = $\Sigma\ (V_{max})^2$ for V_{max} equal or greater 65 knots (74 mph) for each 6-hour period that a hurricane is in existence during a full season.

15. Acknowledgements

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APPENDIX A

Details of Statistical Prediction for 1989 Using Observed or Forecast Parameter Variables as Given in Table 7.

1. NO. OF HURRICANES (NH)

$$NH = b_0 + b_1[4.5(SLPA_{JJ}) + ZWA_{JJ}] + b_2[U_{30} - 6.0|U_{30} - U_{50}|] + b_3[8.3(\overline{SLPA}_{AS}) + 0.9(\overline{ZWA}_{AS}) + EN] \quad (1)$$

b_0	=	7.02817
b_1 (4.5) ($SLPA_{JJ}$) (−0.19271) (4.5) (0.8)	=	− .6938
b_1 (ZWA_{JJ}) (−0.19271) (+1.2)	=	− .2313
b_2 (U_{30}) (.0173583) (−30.0)	=	− .5207
b_2 (−6.0) ($\|U_{30}-U_{50}\|$) (.0173583) (−6.0) (8.0)	=	− .8332
b_3 (8.3) ($SLPA_{AS}$) (−.11192) (8.3) (+.29)	=	− .2694
b_3 (0.9) (ZWA_{AS}) (−0.11192) (0.9) (−.06)	=	+ .0060
b_3 (EN) (−.11192) (0)	=	0
Total NH	=	4.4858

2. NO. OF NAMED STORMS (NNS)

$$NNS = b_0 + b_1[4.8(SLPA_{JJ}) + ZWA_{JJ}] + b_2[U_{30} + 6.3|U_{30} - U_{50}|] + b_3[14.3(\overline{SLPA}_{AS}) + \overline{ZWA}_{AS} + 1.9(EN)] \tag{2}$$

b_0	=	11.2958
b_1 (4.8) ($SLPA_{JJ}$) (−0.295964) (4.8) (0.8)	=	− 1.1365
b_1 (ZWA_{JJ}) (−0.295964) (+1.2)	=	− .3552
b_2 (U_{30}) (−.0474772) (−30.0)	=	1.4243
b_2 (6.3) (U_{30}−U_{50}) (−.0474772) (6.3) (8.0)	=	− 2.3929
b_3 (14.3) ($SLPA_{AS}$) (−.059560) (14.3) (+.29)	=	− .2467
b_3 (ZWA_{AS}) (−.0595560) (−.06)	=	+ .0036
b_3 (EN) (−1.60086) (0)	=	0
Total NNS	=	8.5924

3. HURRICANE DESTRUCTION POTENTIAL (HDP)

$$HDP = b_0 + b_1[10.7(SLPA_{JJ}) + ZWA_{JJ}] + b_2[2.8U_{50} + |U_{30} - U_{50}|] + b_3[4.1(\overline{SLPA}_{AS}) - 3.0(\overline{ZWA}_{AS}) - EN] \quad (3)$$

b_o

b_1 (10.7 ($SLPA_{JJ}$)	=	82.2966
(-2.01461) (10.7) (0.8)	=	-17.2451
b_1 (ZWA_{JJ})		
(-2.01461) (1.2)	=	- 2.4175
b_2 (2.8 U_{50})		
(.573187) (2.8) (-22)	=	-35.3083
b_2 1 U_{30} - U_{50} 1		
(.573187) (8.0)	=	+ 4.5855
b_3 [4.1 ($SLPA_{AS}$)		
(3.6121) (4.1) (+.29)	=	+ 4.2948
b_3 (ZWA_{AS}		
(3.6121) (-3.0) (-0.6)	=	+ .6502
b_3 (EN)		
(3.6121) (0)	=	0
TOTAL HDP	=	36.8562

4. NO. OF HURRICANE DAYS (NHD)

$$NHD = b_0 + b_1[45.4(SLPA_{JJ}) + ZWA_{JJ}] + b_2[3.2U_{50} + |U_{30} - U_{50}|] + b_3[-1.7(\overline{SLPA}_{AS}) + 1.5(\overline{ZWA}_{AS}) + EN] \tag{4}$$

b_0	=	30.8599
b_1 (45.4) ($SLPA_{JJ}$) (-.122484) (45.4) (0.8)	=	- 4.4486
b_1 (ZWA_{JJ}) (-.122484) (+1.2)	=	- .1470
b_2 (3.2 U_{50}) (.204422) (3.2) (-22)	=	-14.3913
b_2 ($\lvert U_{30}-U_{50} \rvert$) (.204422) (8.0)	=	1.6354
b_3 (1.7) ($SLPA_{AS}$) (-1.60086) (-1.7) (+.29)	=	.7892
b_3 (1.5) (ZWA_{AS}) (-1.60086) (1.5) (-.06)	=	+ .1441
b_3 (EN) (-1.60086) (0)	=	0
Total NHD	=	14.4417

APPENDIX B

Verification of the Author's Previous Five Seasons of Forecasts

Table B1 gives verification data for five previous formal seasonal forecasts of Atlantic hurricane activity by the author. Note the difference between observed seasonal hurricane activity and climatology. Over the last 40 years there has been an average of 6 hurricanes per year, 9 named cyclones of tropical storm or hurricane intensity, 24 hurricane days, 45 named storm days, and an HDP of 73.

Data in Table B2 compare the ratio of variance for the author's 1984-1988 forecasts (relative to observation) to variance for forecasts based on the climatology of yearly activity for 1984-88 and relative to the seasonal activity variances of 1949-88 (in parentheses). This table shows that the yearly variance values of the author's forecasts in relation to observed hurricane data have been considerably lower than have the observed seasonal hurricane data in relation to climatology. The late July forecasts have been superior to the late May forecasts and the forecasts of named storm activity have been especially successful. Forecasts for 1984-1988 have thus been a significant improvement over climatology, the only objective seasonal prediction that had previously been available.

TABLE B1

Verification of ths previous seasonal predictions of Atlantic tropical cyclone a or 1984-1988.

1984	Prediction of 24 May and 30 July Update		Observed
No. of Hurricanes	7		5
No. of Named Storm	10		12
No. of Hurricane I	30		21
No. of Named Storm	45		61

1985	Prediction of 28 May	Updated Prediction of 27 July	Observed
No. of Hurricanes	8	7	7
No. of Named Stor	11	10	11
No. of Hurricane	35	30	29
No. of Named Stor	55	50	60

1986	Prediction of 29 May	Updated Prediction of 28 July	Observed
No. of Hurricanes	4	4	4
No. of Named Sto	8	7	6
No. of Hurricane	15	10	13
No. of Named Sto	35	25	27

1987	Prediction of 26 May	Updated Prediction of 28 July	Observed
No. of Hurricanes	5	4	3
No. of Named Sto	8	7	7
No. of Hurricane	20	15	7
No. of Named Sto	40	35	36

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

TABLE B2

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

	No. of Hurricanes	No. of Named Storms	No. of Hurricane Days
For Late May Forecast	.94 (.55)	.29 (.23)	.71 (.35)
For Late July Forecast	.65 (.38)	.21 (.16)	.40 (.20)