Atlantic Seasonal Hurricane Frequency

Part I: El Nino and 30mb QBO Influences
Part II: Forecasting its Variability

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PART I: EL NINO AND 30 MB QBO INFLUENCES

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ABSTRACT

This is the first of two papers on Atlantic seasonal hurricane frequency. This paper discusses seasonal hurricane frequency as related to El Nino events during 1900-1982 and to the equatorial Quasi-Biennial Oscillation (QBO) of stratospheric zonal wind from 1950-1982. It is shown that a substantial negative correlation is typically present between the seasonal number of hurricanes, hurricane days, and tropical storms and moderate or strong (15 cases) El Ninos off the South American west coast. A similar negative anomaly in hurricane activity occurs when 30 mb equatorial winds are from an easterly direction and/or are becoming more easterly with time during the hurricane season. By contrast, seasonal hurricane frequency is slightly above normal in non-El Nino years and substantially above normal when equatorial stratospheric winds blow from a westerly direction and/or are becoming more westerly with time during the storm season. This association of Atlantic hurricane activity with the El Nino can also be made with the Southern Oscillation index.

El Nino events are shown to be related to an anomalous increase of upper tropospheric westerly winds over the Caribbean Basin and in the equatorial Atlantic. Such anomalous westerly winds inhibit tropical cyclone activity by developing more tropospheric vertical wind shear and a regional upper-level environment which is less anticyclonic and consequently less conducive to cyclone development and maintenance. The reason for the physical relationship between seasonal hurricane frequency and the stratospheric QBO is not known although it appears to be related to North-South variations in Caribbean Basin wind and surface pressure which are associated with different phases of the QBO. Paper two discusses the utilization of the information in this paper for the development of a forecast scheme for seasonal hurricane activity variation.

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1. Introduction

a. The El Nino

This is the first of two companion papers on Atlantic seasonal hurricane activity. This paper discusses seasonal hurricane frequency as related to El Nino/Southern Oscillation phenomena and the 30 mb equatorial Quasi Biennial Oscillation (QBO) of zonal wind direction. El Nino years are years in which anomalous warm water develops off the South American tropical west coast and in the equatorial central Pacific. Figure 1 shows the 1982 warm anomaly in sea surface temperatures (SST) which developed in the eastern half of the tropical Pacific during the most recent El Nino event.

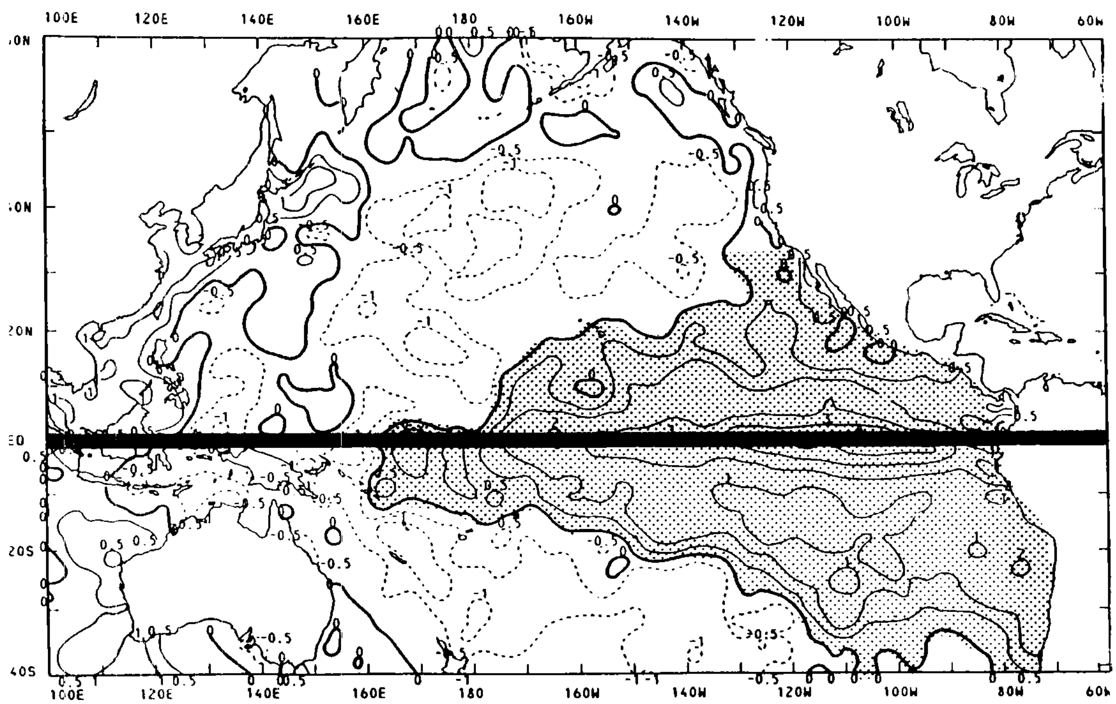

Fig. 1. Sea surface temperature anomaly (in ^{o}C) for October 1982 (from Oceanographic Monthly Summary Report of NOAA Earth Satellite Service, 1982). Shaded area shows regions of El Nino induced warming.

This paper will show that tropical eastern and central Pacific SST warming events associated with the El Nino reduce hurricane activity in the western Atlantic during the season following the onset of the El Nino event. SST and hurricane activity usually return to normal in the second summer following such an event. See the paper of Rasmusson and Carpenter (1982) for a physical description of the usual meteorological events occurring before, during, and after the onset of El Nino events.

That such an El Nino-Atlantic hurricane activity relationship occurs appears to be related to the associated extra deep cumulus convection found in the eastern Pacific during such warm water episodes. This enhanced convection causes anomalously strong westerly upper tropospheric wind patterns to occur over the Caribbean Basin and equatorial Atlantic. These enhanced westerly wind patterns are believed to be the major cause of the reduction in hurricane activity.

Fourteen strong and moderate El Nino events (as determined by Quinn, et al., 1978) for the years 1900 to 1976 together with the recent 1982 El Nino event have been studied. Comparisons are made with the non-El Nino years. In addition, seasonal hurricane activity occurring in the years 1950-1982 with easterly 30 mb QBO wind during non-El Nino years is studied and compared with the hurricane activity occurring in non-El Nino years with 30 mb QBO west winds.

b. The Equatorial 30 mb QBO in Zonal Wind Direction

When 30 mb equatorial winds are from the west and/or are becoming more westerly during the hurricane season, hurricane activity is typically 50-100 percent higher than when 30 mb winds are from the east and/or are becoming more easterly during the hurricane season. Easterly QBO events appear to have a similar suppressing influence on hurricane activity as do El Nino events.

The following sections present statistical evidence for such a surprisingly strong association of El Nino/QBO events with hurricane activity. A physical hypothesis for why such relationships might be expected for El Nino events is given. Such phenomena linkages to west Atlantic seasonal hurricane activity are, to the author's knowledge, yet to be generally realized or formally substantiated.

2. Observational Evidence for El Nino and Seasonal Hurricane Activity Association

El Nino information was obtained from Quinn, et al. (1978), who list strong, moderate, weak, and very weak El Nino years for the last two centuries. The intensity of recent El Nino events have been determined by a number of criteria such as: reported disruptions of the anchoveta fishery and marine bird life off the coast of Peru; rainfall and runoff data for the Peruvian coast; sea surface temperature data along the Peru and Southern Equator coasts; and other related parameters. El Nino events before this century are based primarily on Peruvian rainfall data and other related historical records.

To better isolate El Nino influences on tropical cyclone activity, we will only consider the 15 moderate and strong El Nino events which have occurred since 1900 as listed in Table 1. Recent evidence has shown that 1982 has experienced one of the strongest El Nino events of this century. If we can accept these 15 periods as significant El Nino events, then one can compare the number of hurricanes, hurricane days, etc. occurring in each of these 15 El Nino years to the number of such events occurring during the other 68 non-El Nino years of this century.

Figure 2 is a plot of the seasonal number of hurricane days for the years of 1900-1982. Note from this figure that in most El Nino years hurricane activity as measured by the number of hurricane days is typically much less than for non-El Nino years. Hurricane day information has been tabulated from Neumann, et al. (1981) and recent information of Lawrence and Pellissier (1982) and Clark (1983) on the 1981 and 1982 hurricane seasons. These reports give track information on all west Atlantic tropical cyclones from 1871-1982, and list the

TABLE 1

El Nino years since 1900 by intensity as determined by Quinn et al., 1978.

Strong	Moderate	Weak	Very Weak
1982*	1976	1969	1975
1972	1965	1951	1963
1957	1953	1943	1948
1941	1939	1932	1946
1925	1929	1923	
1918	1914	1917	
1911	1905		
	1902		

*1982 has been added to this table from recent observational evidence of quite widespread anomalous warm water in the eastern tropical Pacific. (See Fig. 1.).

hurricane stage of each storm since 1886. A hurricane day is any day when a tropical cyclone was considered to have a maximum sustained wind in excess of 34 m s^{-1}. In the few cases when two hurricanes simultaneously occur on a single day, two hurricane days were recorded.

This general tendency for reduction in hurricane activity in El Nino years is also indicated in Table 2, which lists the number of hurricane days occurring in each year since 1900 in decreasing order. Note that most of the strong and moderate El Nino years are placed in the lower part of the right-hand column of this table. Of the 16 years of this century with the lowest number of hurricane days, 9 are strong or moderate El Nino years. Of the 22 years with the largest number of hurricane days, none are El Nino years. The highest five values of El Nino year hurricane days range from 15-27, while values for the five highest non-El Nino year hurricane days are between 46-57. The mean number of hurricane days in moderate and strong El Nino years (as

HURRICANE DAYS BY YEAR

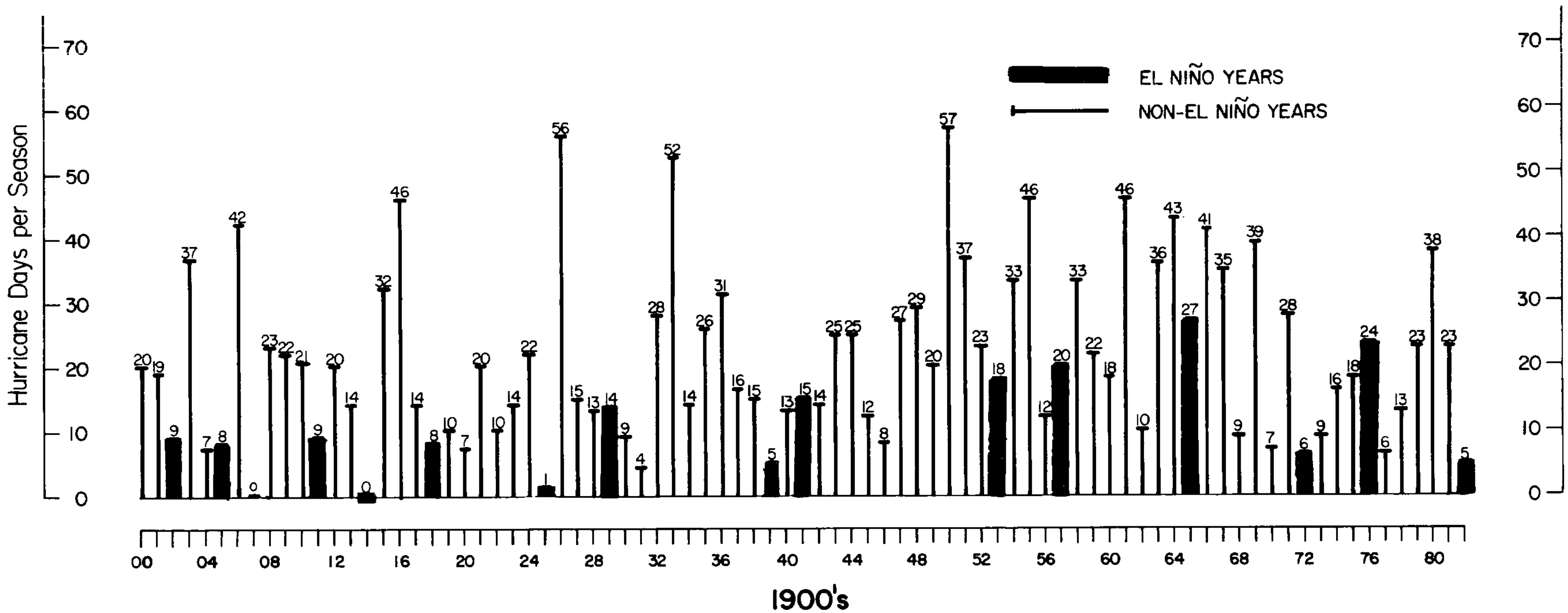

Fig. 2. Number of hurricane days (figure at top of lines) in El Nino and non-El Nino years from 1900-1982.

TABLE 2

Ranking of Atlantic tropical cyclone seasons from 1900 to 1982 by number of hurricane days. Indication of moderate or strong El Nino for each year is given on the right of each column.

Year	Hurricane Days	El Nino	Year	Hurricane Days	El Nino
1950	57		1901	19	
1926	56		1975	18	
1933	52		1960	18	
1961	46		1953	18	Moderate
1955	46		1974	16	
1916	46		1937	16	
1964	43		1941	15	Strong
1906	42		1938	15	
1966	41		1927	15	
1969	39		1942	14	
1980	38		1934	14	
1951	37		1929	14	Moderate
1903	37		1923	14	
1963	36		1917	14	
1967	35		1913	14	
1958	33		1978	13	
1954	33		1940	13	
1915	32		1928	13	
1936	31		1956	12	
1948	29		1945	12	
1971	28		1962	10	
1932	28		1922	10	
1965	27	Moderate	1919	10	
1947	27		1973	09	
1935	26		1968	09	
1944	25		1930	09	
1943	25		1911	09	Strong
1976	24	Moderate	1902	09	Moderate
1981	23		1946	08	
1979	23		1918	08	Strong
1952	23		1905	08	Moderate
1908	23		1970	07	
1959	22		1920	07	
1924	22		1904	07	
1909	22		1977	06	
1910	21		1972	06	Strong
1957	20	Strong	1939	05	Moderate
1949	20		1982	05	Strong
1921	20		1931	04	
1912	20		1925	01	Strong
1900	20		1914	00	Moderate
			1907	00	

Mean number of hurricane days per season in El Nino years is 11.3
Mean number of hurricane days per season in non-El Nino years is 23.2

defined by Quinn et al., 1978) was 11.3 vs. 23.2 during non-El Nino years. The medians are 9 and 20.5.

Table 3 lists the number of hurricanes per year in decreasing order. Again, note the concentration of moderate and strong El Nino years in the lower right hand column. Of the 27 years with three hurricanes or less, 11 years (or 40%) were moderate or strong El Nino years. Of the 56 seasons with four or more hurricanes only 4 (or 7%) were El Nino years. The mean number of hurricanes per season during El Nino and non-El Nino years is 3.0 and 5.4.

Table 4 contains similar information on both tropical storms (maximum sustained winds > 22 m s^{-1}) and hurricanes. Of the 21 years with five or fewer tropical storms and hurricanes, 10 (or 48%) were El Nino years. By contrast, only 3 of 51 years (or 6%) with seven or more tropical storms and hurricanes were El Nino years. The average number of hurricanes and tropical storms per season for El Nino and non-El Nino years is 5.4 and 9.0 respectively.

A Wilcoxon (Brownlee, 1960) two-sample rank test of the null hypothesis that there is no relationship between El Nino and non-El Nino years and hurricane activity gives P values of .00079 for seasonal number of hurricanes, .00011 for seasonal number of hurricanes and tropical storms, and .00043 for seasonal number of hurricane days.

It is also interesting to note that of the major hurricanes[(1)] striking the US coast (as determined by Hebert and Taylor, 1978) during

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[(1)] Saffir/Simpson Hurricane scale classification of 4 or 5 (surface pressure < 944 mb, sustained winds > 130 mph (Simpson, 1974).

TABLE 3

Ranking of Atlantic tropical cyclone seasons from 1900 to 1982 by number of hurricanes in each season. Indication of moderate or strong El Nino for each year is given on the right of each column.

Year	Number of Hurricanes	El Nino	Year	Number of Hurricanes	El Nino
1950	11		1974	04	
1916	11		1973	04	
1969	10		1968	04	
1933	10		1965	04	Moderate
1980	09		1960	04	
1955	09		1956	04	
1961	08		1942	04	
1954	08		1941	04	Strong
1951	08		1940	04	
1926	08		1928	04	
1903	08		1927	04	
1981	07		1921	04	
1966	07		1920	04	
1963	07		1915	04	
1959	07		1912	04	
1958	07		1909	04	
1949	07		1972	03	Strong
1944	07		1962	03	
1936	07		1957	03	Strong
1976	06	Moderate	1946	03	
1975	06		1939	03	Moderate
1971	06		1938	03	
1967	06		1937	03	
1964	06		1929	03	Moderate
1953	06	Moderate	1923	03	
1952	06		1918	03	Strong
1948	06		1913	03	
1934	06		1911	03	Strong
1932	06		1910	03	
1906	06		1902	03	Moderate
1979	05		1901	03	
1978	05		1900	03	
1977	05		1982	02	Strong
1970	05		1931	02	
1947	05		1930	02	
1945	05		1922	02	
1943	05		1917	02	
1935	05		1904	02	
1924	05		1925	01	Strong
1908	05		1919	01	
			1905	01	Moderate
			1914	00	Moderate
			1907	00	

Mean number of hurricanes per season in El Nino years is 3.0
Mean number of hurricanes per season in non-El Nino years is 5.4

TABLE 4

Same as Table 3 but for the total number of both hurricane and tropical storms.

Year	Number of Systems	El Nino	Year	Number of Systems	El Nino
1933	21		1940	08	
1936	16		1938	08	
1969	14		1924	08	
1916	14		1908	08	
1953	14	Moderate	1957	08	Strong
1949	13		1968	07	
1950	13		1960	07	
1971	13		1923	07	
1981	12		1952	07	
1955	12		1973	07	
1964	12		1974	07	
1980	11		1900	07	
1966	11		1927	07	
1961	11		1977	06	
1978	11		1935	06	
1959	11		1928	06	
1954	11		1921	06	
1945	11		1912	06	
1944	11		1946	06	
1934	11		1965	06	Moderate
1932	11		1941	06	Strong
1926	11		1982	05	Strong
1906	11		1962	05	
1951	10		1915	05	
1943	10		1904	05	
1901	10		1939	05	Moderate
1909	10		1905	05	Moderate
1942	10		1902	05	Moderate
1958	10		1918	05	Strong
1970	10		1972	04	Strong
1903	09		1907	04	
1931	09		1910	04	
1937	09		1913	04	
1947	09		1920	04	
1948	09		1922	04	
1963	09		1911	04	Strong
1979	09		1919	03	
1975	08		1929	03	Moderate
1976	08	Moderate	1917	03	
1967	08		1930	02	
1956	08		1925	02	Strong
			1914	01	Moderate

Mean number of hurricanes and tropical storms per season in El Nino years is 5.4

Mean number of hurricanes and tropical storms per season in non-El Nino years is 9.0

the period of 1900 to 1976 and with added years of 1977-1982 (by the author) only four occurred during these 15 strong and moderate El Nino years. During the other 68 non-El Nino years from 1900 to 1982, there were 50 major hurricane strikes on the US Coast. The ratio of major hurricanes per El Nino year is .27 while that of major hurricanes per non-El Nino year is .74.

Track Alterations During El Nino Years. Figures 3 to 17 show the tracks of hurricane intensity tropical cyclones in each of the 15 moderate and strong El Nino years of this century. Notice that hurricane activity is strikingly suppressed for most El Nino years and also that only a few hurricanes cross the Caribbean-West Indies region from an east to west direction during these 15 years. By contrast, in non-El Nino years, hurricanes are more frequent, and tracks across the Caribbean are much more frequent. These differences are better illustrated by comparing hurricane intensity storm tracks for a composite of 14 El Nino seasons (1982 is not included) - Fig. 19 - with 14 seasons of hurricane intensity storms one year before each El Nino year (Fig. 18) and one year after each El Nino event (Fig. 20). Notice the decreased number of hurricane intensity storm tracks during El Nino years and the increased number of westerly tracking systems in the southern part of the hurricane basin during non-El Nino years.

There can be little doubt that seasonal hurricane activity during the El Nino years of this century has been much suppressed compared with the hurricane activity occurring during non-El Nino years.

Statistics Before 1900. This strong negative association of hurricane activity with El Nino events for the 1900-1982 period is not verified for the shorter period of 1871-1899 however. The eight strong

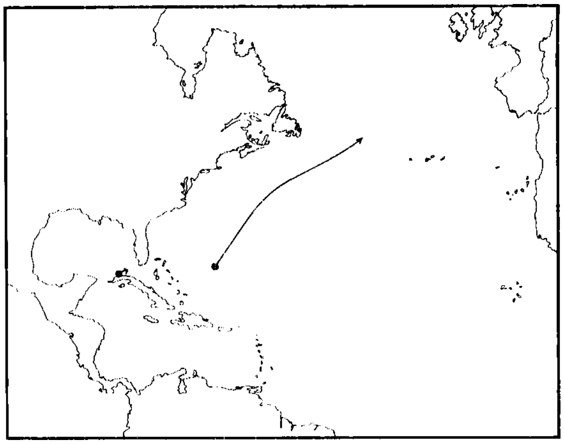

Fig. 3. Strong El Nino year of 1982.

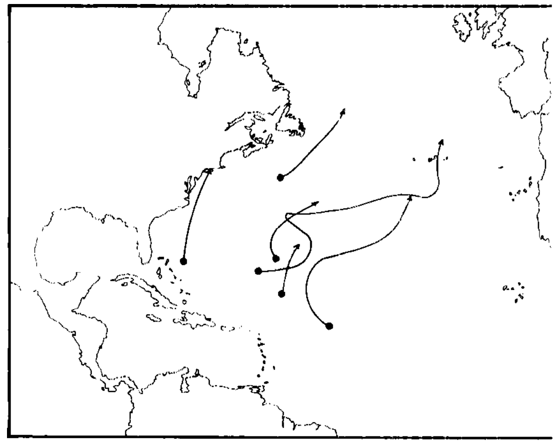

Fig. 4. Moderate El Nino year of 1976.

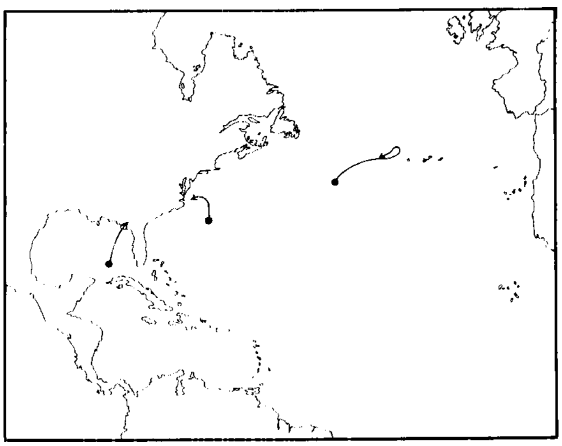

Fig. 5. Strong El Nino year of 1972.

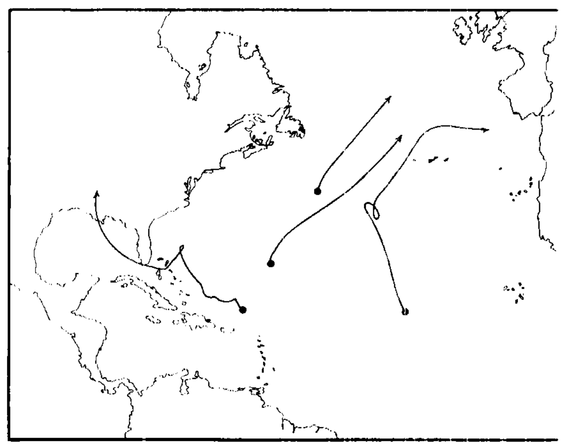

Fig. 6. Moderate El Nino year of 1965.

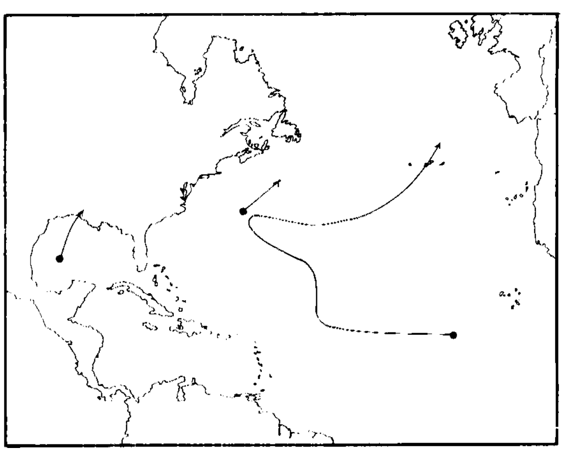

Fig. 7. Strong El Nino year of 1957.

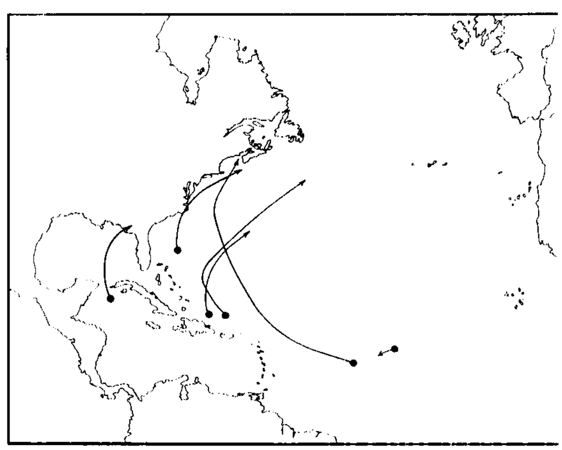

Fig. 8. Moderate El Nino year of 1953.

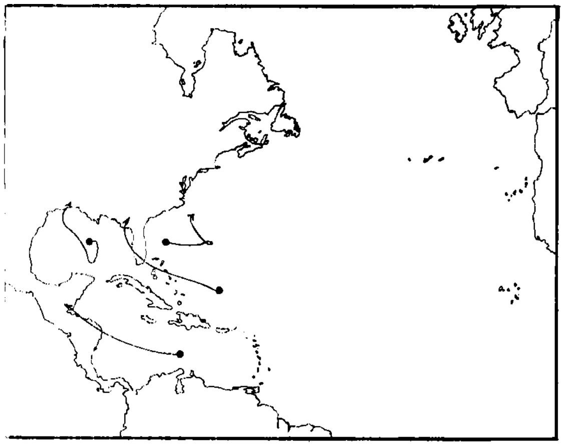

Fig. 9. Strong El Nino year of 1941.

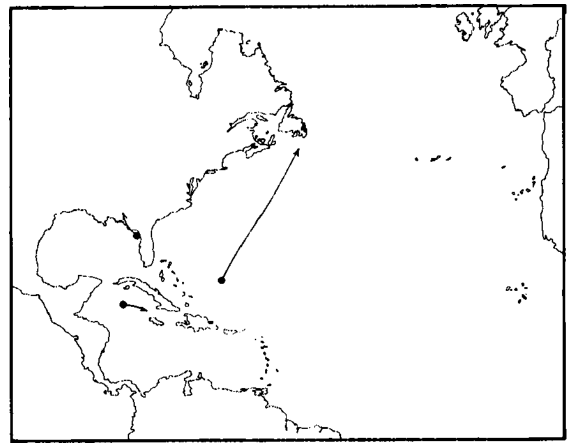

Fig. 10. Moderate El Nino year of 1939.

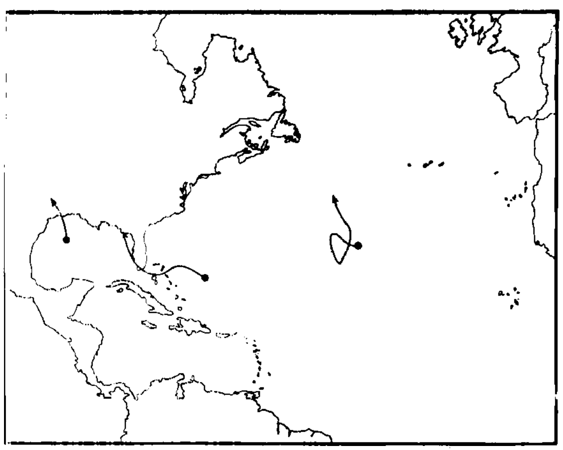

Fig. 11. Moderate El Nino year of 1929.

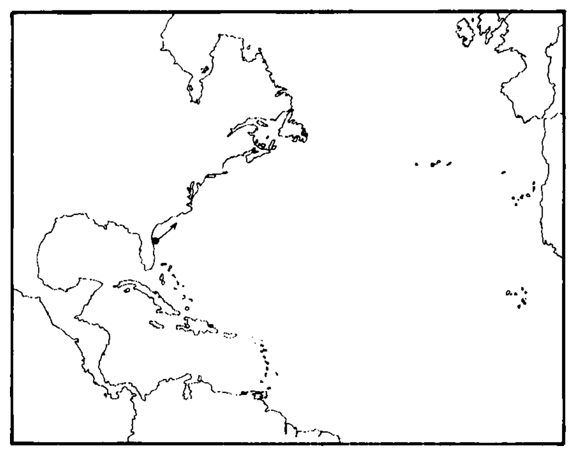

Fig. 12. Strong El Nino year of 1925.

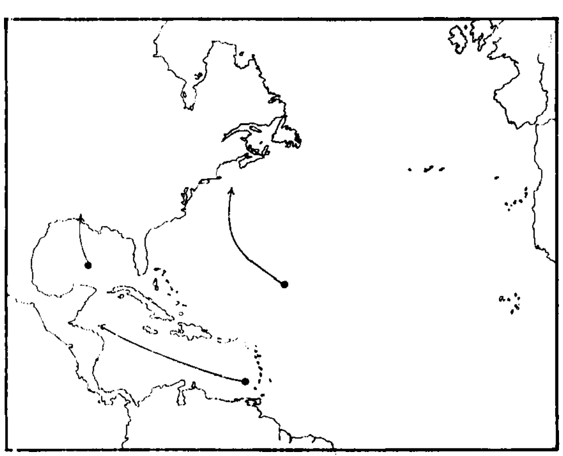

Fig. 13. Strong El Nino year of 1918.

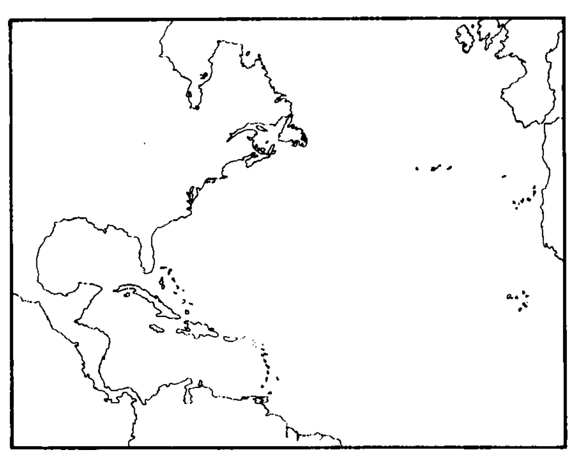

Fig. 14. Moderate El Nino year of 1914.

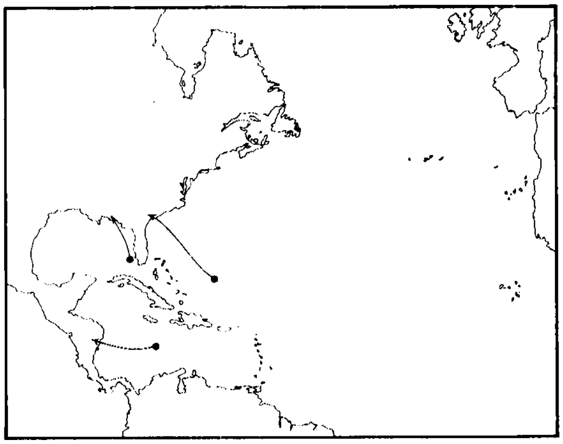

Fig. 15. Strong El Nino year of 1911.

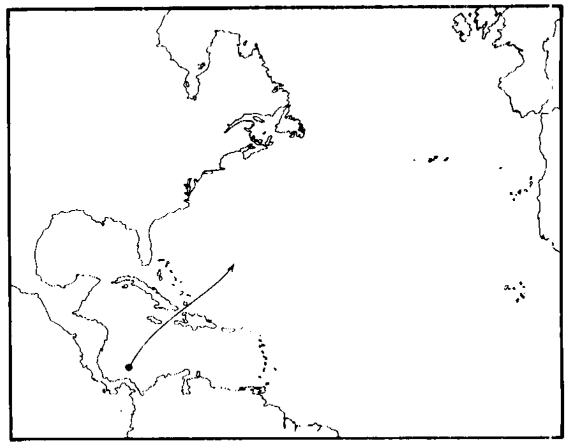

Fig. 16. Moderate El Nino year of 1905.

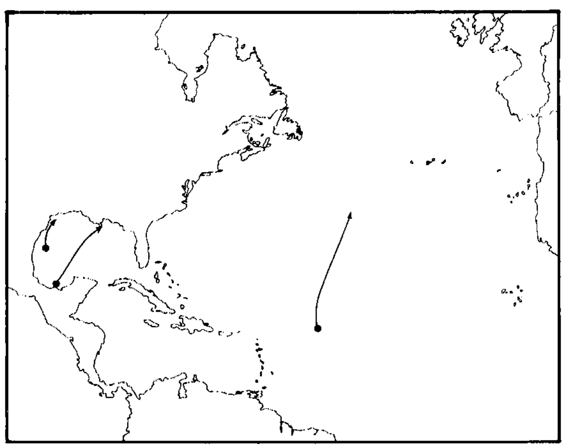

Fig. 17. Moderate El Nino year of 1902.

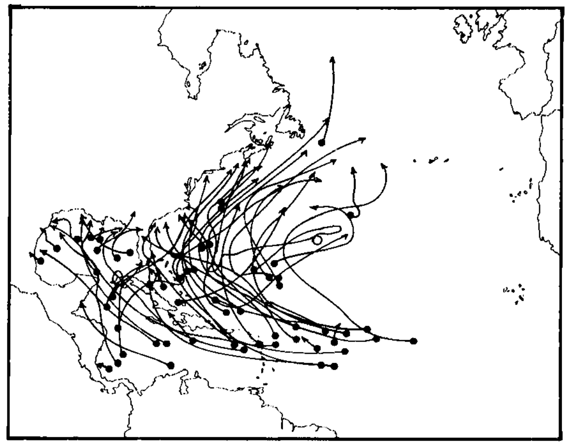

Fig. 18. Fourteen years of hurricane intensity storm tracks occurring one year before each of 14 El Nino years between 1900-1976.

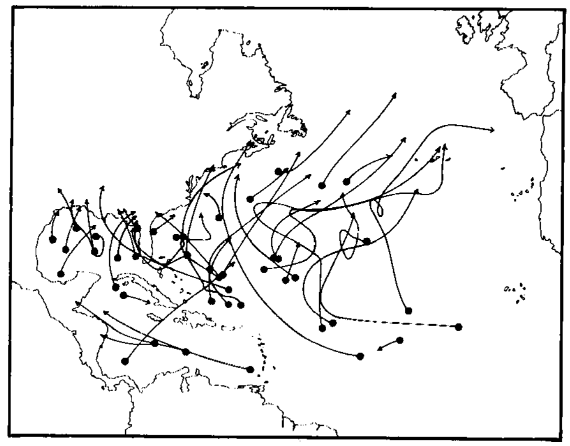

Fig. 19. Fourteen years of hurricane intensity storm tracks during 14 El Nino years between 1900-1976.

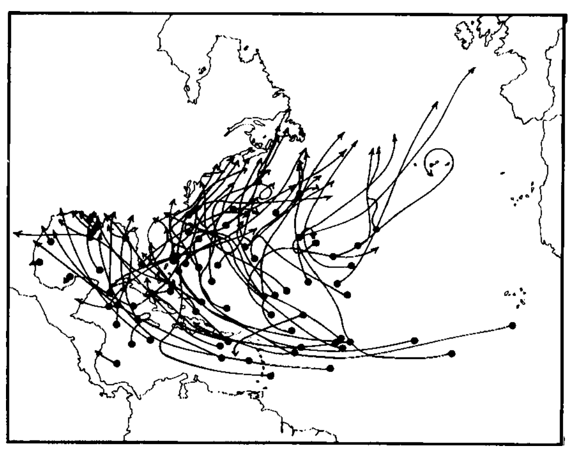

Fig. 20. Same as Fig. 18 but for hurricane intensity tracks one year after each of these 14 El Nino years.

and moderate El Nino events of this earlier period as listed by Quinn _et al_. (1978) occurred during the years of 1871, 1877, 1880, 1884, 1887, 1891, 1896, and 1899. These last century El Nino years actually show more hurricane activity than in non-El Nino years. This is an opposite correlation to that observed in this century. The year of 1887 was reported to be a particularly active year with 10 hurricanes, 7 tropical storms, and 73 hurricane days. This year was also reported by Quinn _et al_. (1978) to be a moderate El Nino year. The author cannot explain why the El Nino-hurricane activity association during the period of 1871-1899 is opposite to the much longer 20th century information. It is likely that the El Nino and hurricane data for this earlier period are less reliable than the information of recent decades. Or, it may be that the physical association of El Nino and hurricane activity to be discussed in the next section was not active during this earlier period. This latter explanation seems less likely, however.

3. Physical Processes Responsible for El Nino Suppression of Hurricane Activity.

Satellite imagery shows that the warm water that develops in the eastern tropical Pacific during the typical El Nino year causes extra amounts of deep cumulus convection throughout this region. It is suggested that this enhanced deep convection develops upper tropospheric (~ 200 mb) outflow patterns which produce enhanced westerly winds (or weaker easterly winds) over the downwind Caribbean and western equatorial Atlantic regions. An idealization of this process is shown in Fig. 21.

These more a-typical upper tropospheric westerly winds that occur during El Nino years lead to a situation in which seasonal 200 mb anticyclonic wind flow over the Caribbean Basin and western Atlantic is significantly reduced from conditions normally occurring in non-El Nino years. For a large number of hurricanes to form and be maintained through an active hurricane season, it is necessary that seasonal 200 mb winds in the latitude belt of 5-15^{o}N be from an easterly direction and that 200 mb westerly winds be present in the subtropical latitude belt of 20-30^{o}N. Such seasonal climatological flow patterns are a necessary background ingredient for individual pre-storm weather systems to develop into cyclones. As discussed by the author in previous studies (Gray, 1975, 1979) the more favorable the background seasonal environment is, the greater the probability that individual cloud cluster systems will develop into cyclones rather than remain as traveling depressions and disturbances.

Figure 22 is taken from data composited around the early stages of tropical disturbances beginning to develop into tropical storms in the Caribbean Basin region (Gray, 1968). Similar information on the necessary environmental conditions for tropical cyclone formation is also contained in the more recent papers of McBride (1981) and McBride and Zehr (1981). This figure shows the type of 200 mb north-south zonal wind shears that are usually associated with individual case hurricane development and maintenance. Figure 23 is a meridional vertical cross-section showing the typical zonal wind patterns which are necessary for tropical cyclone formation. The greater the seasonal easterly winds are at point A or westerly winds at point B, the greater the likelihood of an above average number of seasonal hurricanes. Hurricane activity is greater or less by any process which enhances or suppresses such seasonally averaged upper tropospheric wind patterns. During El Nino years, upper level equatorial easterly winds are weaker (or winds are

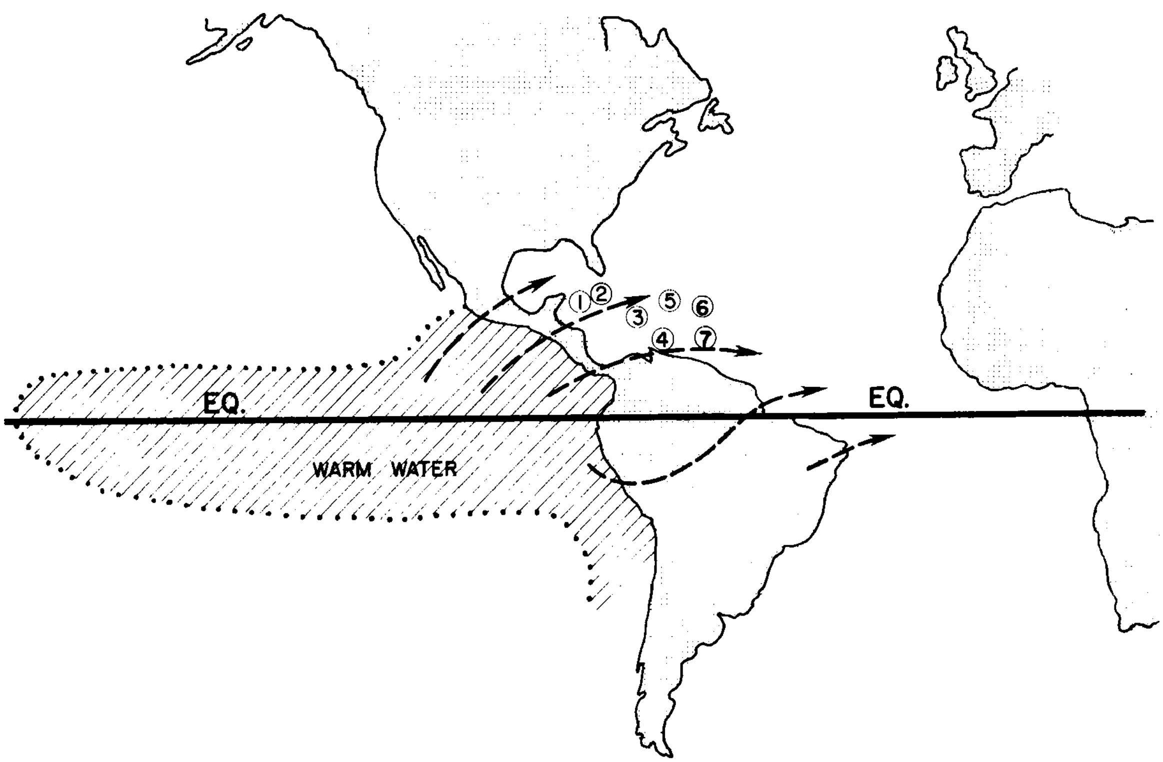

Fig. 21. Upper tropospheric (~200 mb) wind patterns which are hypothesized to occur during El Nino years due to anomalous eastern Pacific warm water and enhanced eastern Pacific deep cumulus convection. (Number indicate upper air stations of Swan Island (1), Grand Cayman (2), Kingston, Jamaica (3), Curacao (4), San Juan (5), St. Maarten (6), and Barbados (7)).

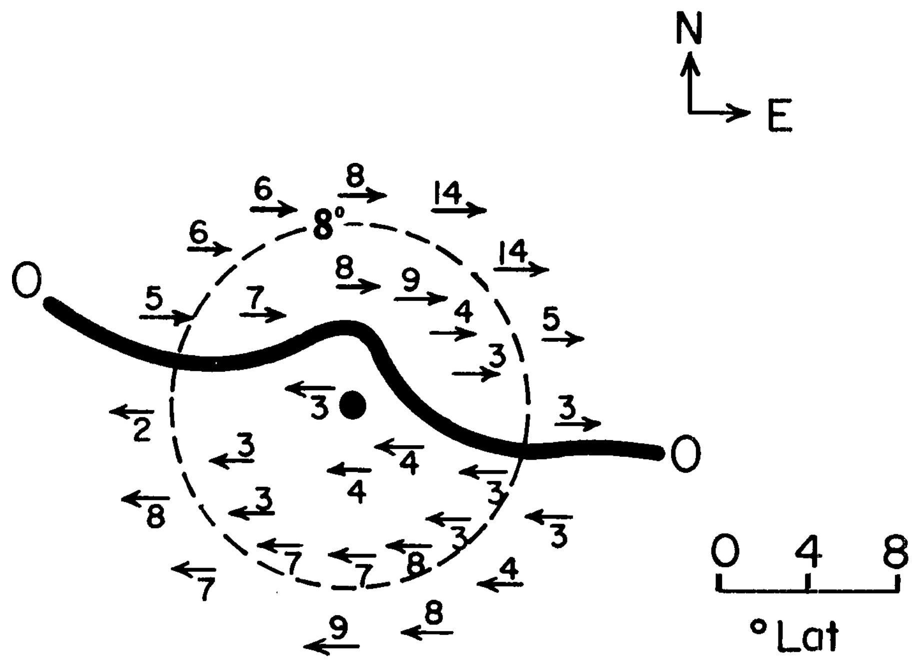

Fig. 22. Composite of 200 mb zonal winds (in m/s) about the center point (large dot) of Caribbean Basin tropical weather systems in an early stage of cyclone development (adapted from Gray, 1968).

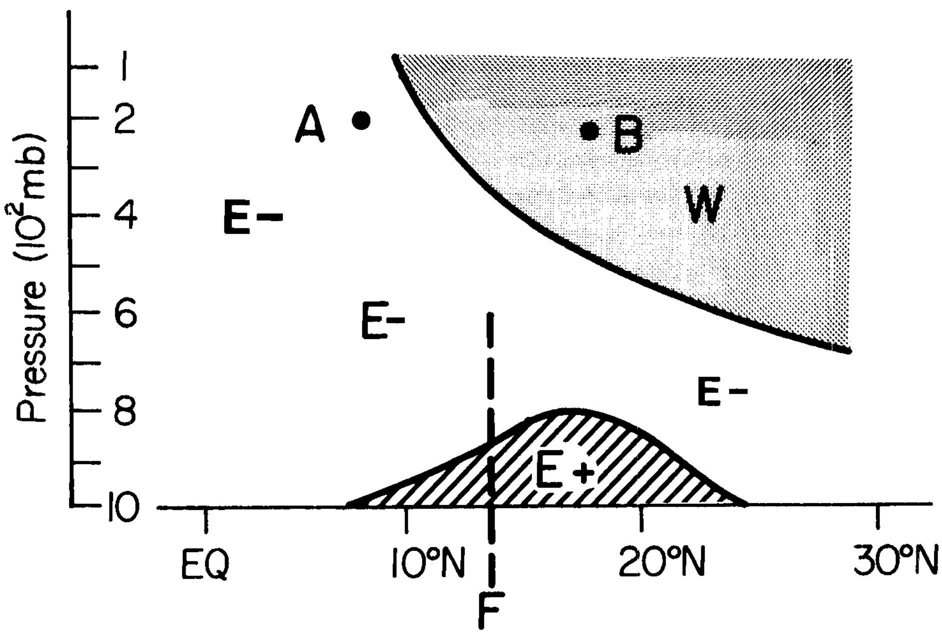

Fig. 23. Schematic north-south vertical cross section of zonal winds in the western Atlantic-Caribbean Basin in August-September relative to the typical latitudinal position of tropical cyclone formation indicated by the dashed line marked F. W and E stand for West and East winds respectively. + and − means strong and weak wind speeds respectively.

from the west) due to the enhanced upper tropospheric outflow from the eastern Pacific. This reduces the upper tropospheric 200 mb anticyclonic flow over the Caribbean and western tropical Atlantic -- the very regions where storm development typically occurs.

Figures 24 to 27 indicate the type of average August and September upper level zonal wind changes which El Nino events produced at the four Caribbean Basin stations of Swan Island (1), Curacao (4), Kingston, Jamaica (3), and Barbados (7).[2] Upper level winds have been averaged for the five El Nino years of 1957, 1965, 1972, 1976 and 1982 and 18 other non-El Nino years since 1957. Similar 200 mb average zonal wind differences for various hurricane season months for these and other Caribbean Basin stations are shown in Table 5. In general, upper tropospheric winds average 2-7 m/s more from a westerly direction during El Nino years than in non-El Nino years. A Wilcoxon Two Sample Rank test that 200 mb winds are the same between El Nino and non-El Nino years for the period of August-September is .00019 and for the period June through October .00074. A similar statistical analysis by individual months before the onset of the most active part of the hurricane season shows the probability that no difference exists in 200 mb Caribbean Basin zonal winds between El Nino and non-El Nino years is for April (.374), for May (.041), for June (.015) and for July (.001). Wind data for May through July thus contains a predictive signal that might also be used for verification or knowledgement refinement of the El Nino signal.

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(2) Figure 21 indicates the location of each of these stations.

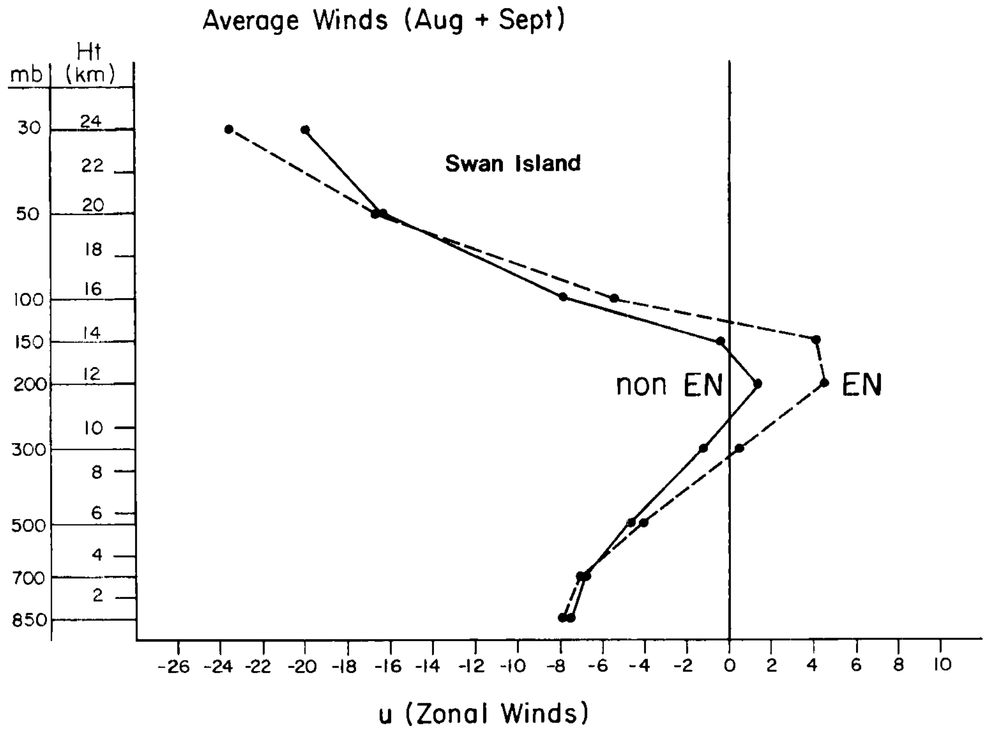

Fig. 24. Vertical profile of zonal wind during August and September at Swan Island (point 1 in Fig. 21) for an average of the last 5 El Nino years (1957, 1965, 1972, 1976 and 1982) - denoted EN- and 18 other non-El Nino years (non EN).

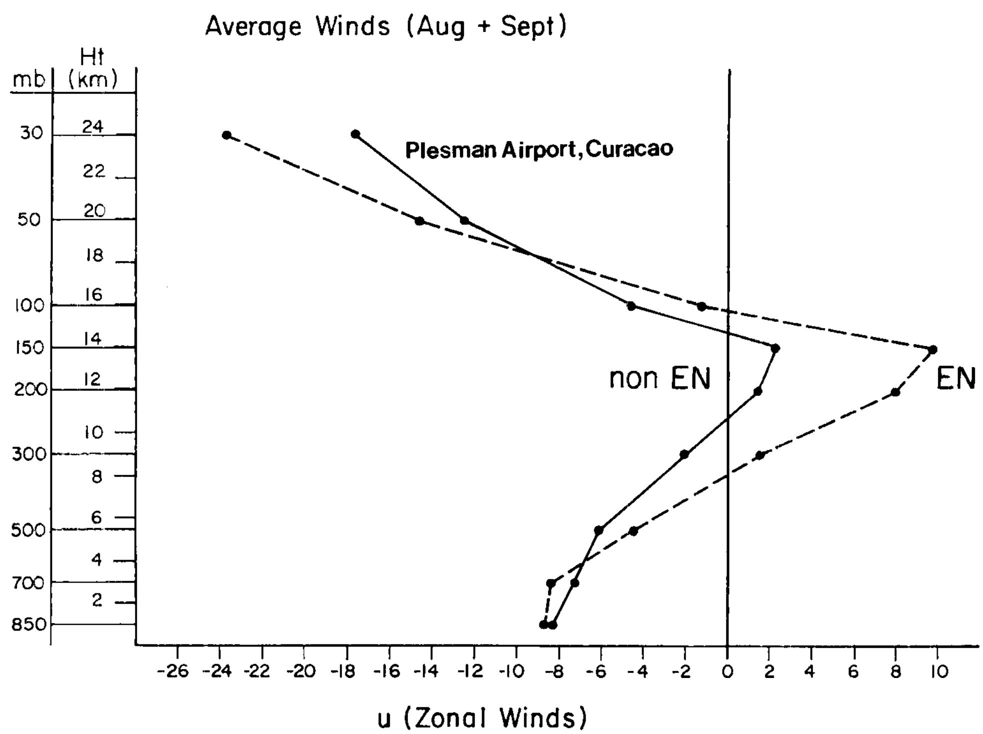

Fig. 25. Same as Fig. 24 but for Curacao - point 4 in Fig. 21.

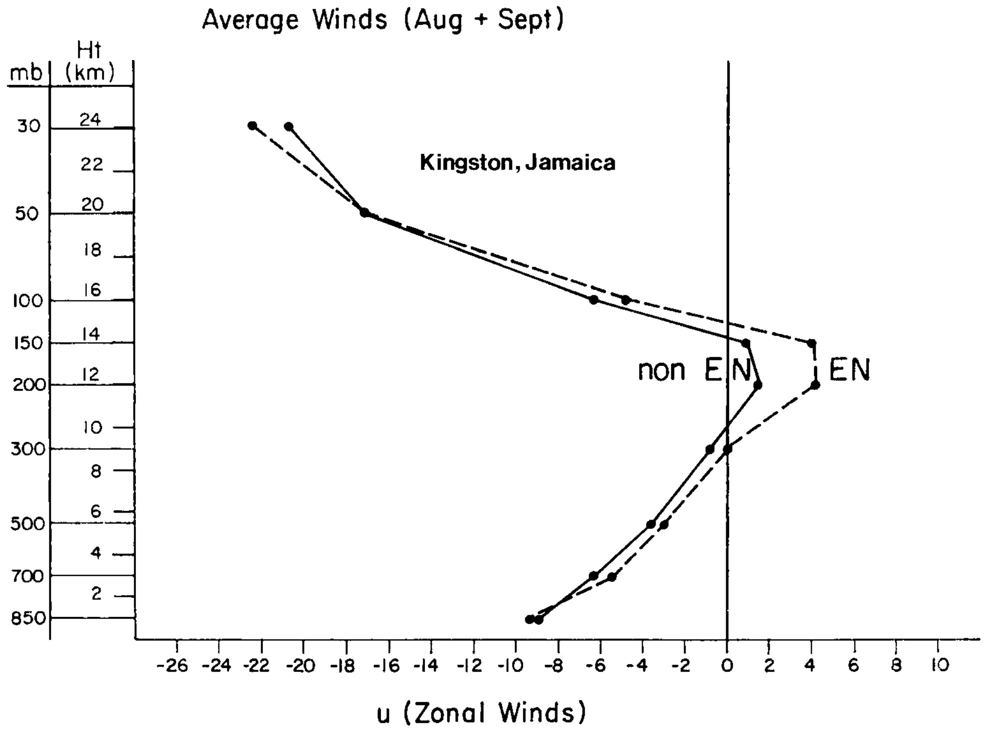

Fig. 26. Same as Fig. 24 but for point 3 in Fig. 21.

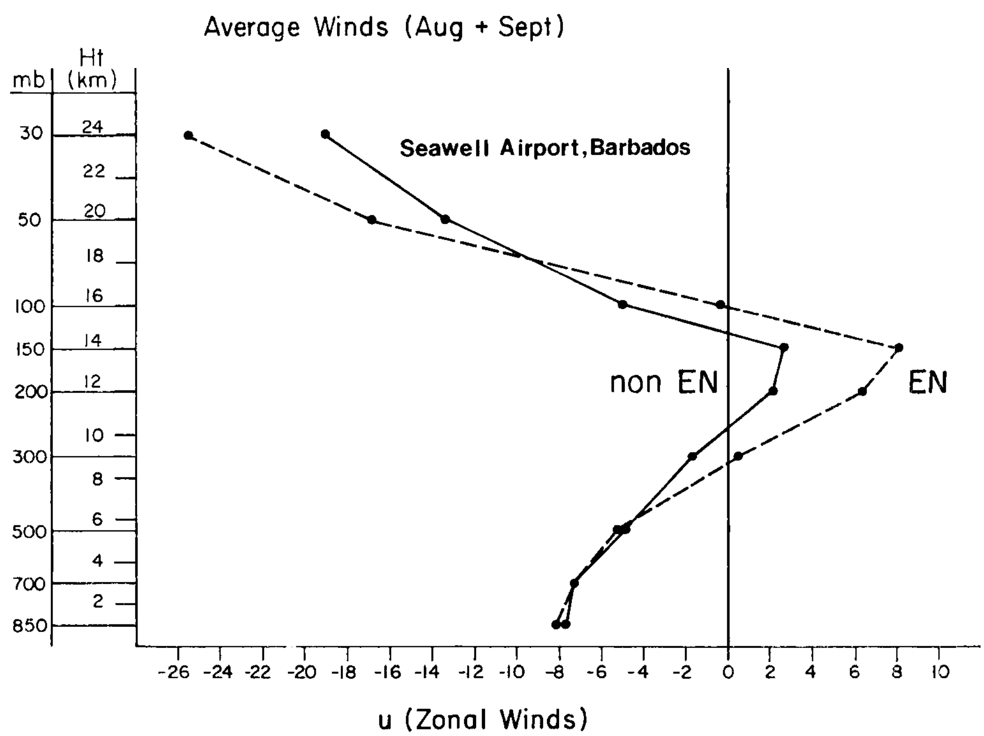

Fig. 27. Same as Fig. 24 but for point 7 in Fig. 21.

TABLE 5

Caribbean Basin 200 mb multi-month average zonal winds by station (in m/s) for the last 5 El Nino years and 21 other non-El Nino years.

Station	El Nino		Non-El Nino		Difference El Nino Minus Non-El Nino	
	Aug Sept Ave.	June, July Aug, Sept, Oct Ave.	Aug Sept Ave.	June, July Aug, Sept Oct Ave.	Aug Sept Ave.	June, July Aug, Sept Oct Ave.
Swan Island	4.0	5.3	1.2	2.5	2.8	2.8
Santo Domingo 18°N (Lat.) 70°W (Long.)	4.3	5.8	2.1	3.9	2.2	1.9
San Andres, Island 12°N (Lat.) 82°W (Long.)	4.0	3.0	-1.8	-0.7	5.8	3.7
Seawell Airport, Barbados	5.0	7.0	2.1	4.6	2.9	2.4
Raizet, Guadeloupe 16°N (Lat.) 62°W (Long.)	5.0	7.8	2.4	4.8	2.6	3.0
Juliana, St. Maarten	3.8	6.6	2.5	4.3	1.3	2.3
Kingston, Jamaica	4.3	6.0	1.8	3.5	2.5	2.5
Grand Cayman, B.W.I.	2.4	4.8	.1	2.5	2.3	2.3
Plesman, Curacao	7.5	8.0	1.7	3.6	5.8	4.4
San Juan, Puerto Rico	4.8	6.6	2.5	4.3	2.3	2.3

Precipitation Departures During El Nino Years. An analysis of precipitation anomalies throughout the Caribbean Basin region during the last five moderate and strong El Nino years of 1957, 1965, 1972, 1976 and 1982 show that, in general, precipitation is suppressed by only 0-10 percent. Table 6 shows the percentage of precipitation departure from

TABLE 6

Average percentage precipitation departure of 15-20 West Indies region stations for each summer month of the last 6 strong and moderate El Nino events.

Year	JUN.	JUL.	AUG.	SEPT.	OCT.	AVE.
1953	-23	-3	-10	+20	-3	-4
1957	-3	+17	+20	-13	+17	+8
1965	-11	-8	-6	+11	-10	-5
1972	-12	+4	-15	-19	-12	-11
1976	-5	-17	-9	-11	+2	-8
1982	-13	-23	-22	-7	-8	-13
AVE.	-11	-5	-7	-3	-2	-5

normal by month for each of these five El Nino years. Monthly precipitation has been averaged for 15-20 stations within the Caribbean Basin. Although precipitation during the five months of June through October was 11 and 13 percent below normal in the strong El Nino years of 1972 and 1982, it was 8 percent above normal for the strong El Nino year of 1957. For all 6 El Nino years, average precipitation during the August to October period is only observed to be 5 percent below that of the non-El Nino years.

These data indicate that summertime Caribbean Basin precipitation is hardly altered by El Nino events. It is not the number or intensity of individual west Atlantic rain producing weather systems which are altered in El Nino years but, rather, the proximity of these rain producing weather systems to favorable large-scale environmental flow patterns which allow the weather systems to properly organize themselves into tropical cyclones.

Pressure Departures During El Nino Years. A similar analysis of sea level pressure differences between El Nino and non-El Nino years

(Table 7) shows no meaningful results. In addition, upper level pressure-height, temperature, and moisture differences between El Nino and non-El Nino years also showed no apparent differences. It is thus concluded that the primary meteorological processes responsible for the suppression of hurricane activity in El Nino years are increased upper tropospheric westerlies and related anomalous dynamical factors.

TABLE 7

Sea level pressure (in mb - with 10 before each value omitted) occurring in various months at Caribbean Basin stations during El Nino and non-El Nino years between 1950-1982 and differences between these pressures.

Station	El Nino			Non-El Nino			Difference El Nino Minus Non-El Nino		
	May	Aug Sept Ave.	June, July Aug, Sept, Oct Ave.	May	Aug Sept Ave.	June, July Aug, Sept Oct Ave.	May	Aug Sept Ave.	June, July Aug, Sept Oct Ave.
Cayenne French Guiana	12.6	12.9	12.8	12.5	12.8	12.9	.1	0.1	-0.1
Jackson-ville Florida	16.6	17.1	17.2	16.8	16.8	17.1	-.2	0.3	.1
Maracay Venezuela	12.6	12.2	12.6	12.7	13.7	13.6	-.1	-1.5	-1.0
Merida Mexico	11.8	13.0	13.3	11.7	12.5	13.1	-.1	0.5	0.2
Nassau Bahamas	16.1	15.3	16.1	16.8	16.0	16.3	-.7	-.7	-.2
Plesman Curacao	11.7	11.6	11.8	11.6	11.3	11.4	.1	0.3	0.4
San Juan Puerto Rico	15.9	15.3	15.6	15.7	15.1	15.5	.2	0.2	0.1
Seawell Barbados	13.9	13.7	14.1	14.2	13.4	13.7	-.3	0.3	0.4
Swan Island	12.0	13.0	13.0	13.4	12.9	12.7	-1.4	0.1	0.3
Raizet Guadeloupe	15.2	14.3	14.8	14.8	14.1	14.5	.4	0.2	0.3

El Nino-Southern Oscillation Association. As El Nino events are usually associated with low values of surface pressure in the southeastern Pacific subtropical high, it is to be expected that West Atlantic hurricane activity is also below normal in years when the Southern Oscillation Index (SOI) is low. This is true. An inspection of the Santiago, Chile (33°S) minus Darwin, Australia (12°S) surface pressure as presented by Quinn et al. (1978) shows that all 14 strong and moderate El Nino events from 1900-1976 (and also the 1982 El Nino events) had distinctly lower than normal values of the Santiago minus Darwin time averaged surface pressure. The lowest values of this pressure gradient were usually associated with the strongest El Nino events. The SOI was also very low during the 1982 El Nino year. Thus, a positive correlation between Atlantic hurricane activity and the Southern Oscillation is definitely present.

Figure 28 has been adapted from the recent paper by Arkin (1982). It shows 200 mb wind differences over the tropical Atlantic between 17 seasons with high (SOI > 0.65) and 14 seasons with low (SOI < -0.65) southern oscillation index. The greater seasonal 200 mb anticyclonic flow which is associated with high SOI (shown in the dashed region of this figure) should be associated with higher values of seasonal hurricane activity. The opposite occurring wind patterns related to low SOI will lead (as observed) to a suppression of seasonal hurricane activity.

Figure 29 (also adopted from Arkin, 1982) shows 200 mb wind anomalies for three summers following the onset of three El Nino SST warming events in the eastern Pacific for the years of 1969 (weak El Nino), 1972 (strong), and 1976 (moderate). These seasonal 200 mb wind

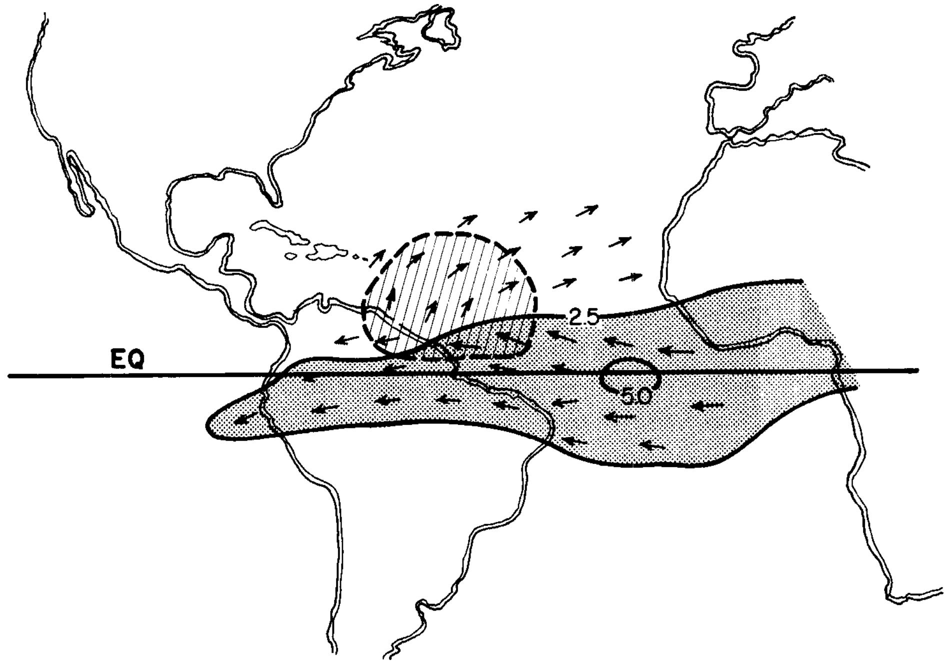

Fig. 28. 200 mb wind vector differences (length proportional to magnitude with isotachs m/s) of 200 mb wind between 17 (summer, fall, winter and spring) seasons when the SOI > 0.65 and 14 seasons when the SOI < -0.65. This figure has been adapted from Arkin (1982).

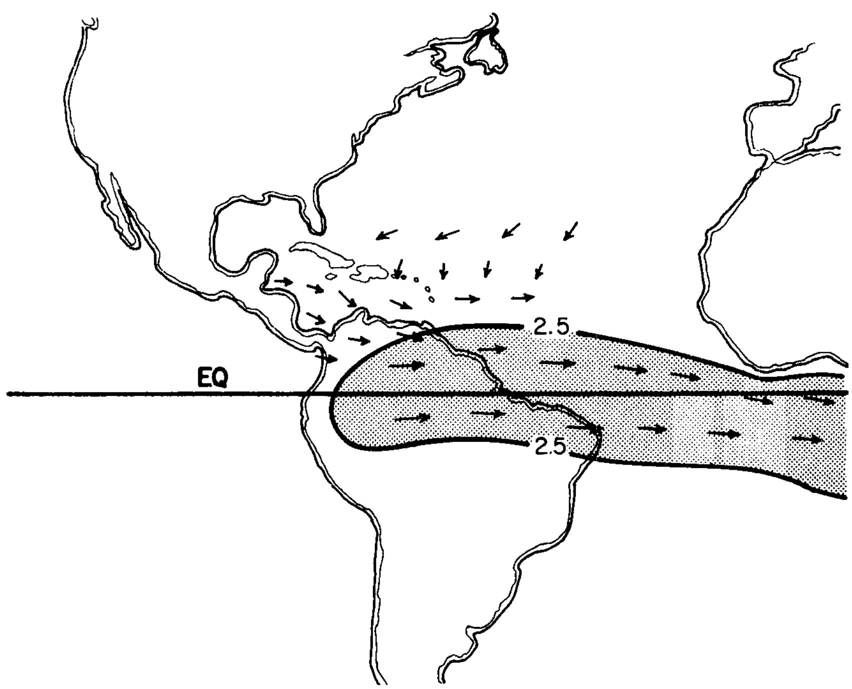

Fig. 29. 200 mb wind vector anomalies with isotachs for the three summer seasons following the onset of El Nino type SST warming off the South American Coast for the years 1969, 1972, and 1976. This figure has been adopted from Arkin (1982). Shaded area shows speeds greater than 2.5 m/s.

anomaly patterns decrease upper level anticyclonic flow (other factors being equal) and should lead to a suppression of hurricane activity. This information is of general agreement with the data of Figs. 24-27.

Summary. It thus appears that the role of the El Nino in suppressing seasonal hurricane activity results primarily from the forcing of a-typically strong upper tropospheric westerly wind patterns in the equatorial west Atlantic and Caribbean Basin. The direct El Nino influence on other meteorological parameters is at best very weak.

4. Stratospheric Quasi-Biennial Oscillation (QBO) and Seasonal West Atlantic Tropical Cyclone Activity

Information on the Quasi-Biennial Oscillation (QBO) of the stratospheric equatorial zonal winds is available only since 1950. Continuous and reliable equatorial wind information at levels of 30 mb and higher was not available before that time. Zonal wind oscillations since 1950 are shown in the two diagrams of Fig. 30. The top diagram data is from Coy (1979), for the period up to 1978. The bottom diagram is for information since 1978 as furnished the author by R. Quiroz of the US NOAA Climate Analysis Center. The shaded areas on these diagrams denote periods when the global equatorial stratospheric winds are from a westerly direction. No-shading denotes times when equatorial winds are from the east. The near biennial nature of this wind oscillation is clearly evident.

This paper will not discuss the physical processes responsible for these zonal wind oscillations which have been a subject of study by a large number of scientists over the last two decades. This chapter only explores the apparent and quite remarkable association of this stratospheric QBO wind oscillation and Atlantic seasonal hurricane activity.

Despite the extensive literature available on the QBO, the author is aware of no research which has been directed towards attempts to relate such biennial stratospheric wind alterations to seasonal variations in hurricane activity. It appears, however, that a strong relationship is indeed evident. It is likely that the physical processes occurring in the troposphere which act to cause such a two-year stratospheric wind oscillation also have a modulating influence on Atlantic hurricane activity.

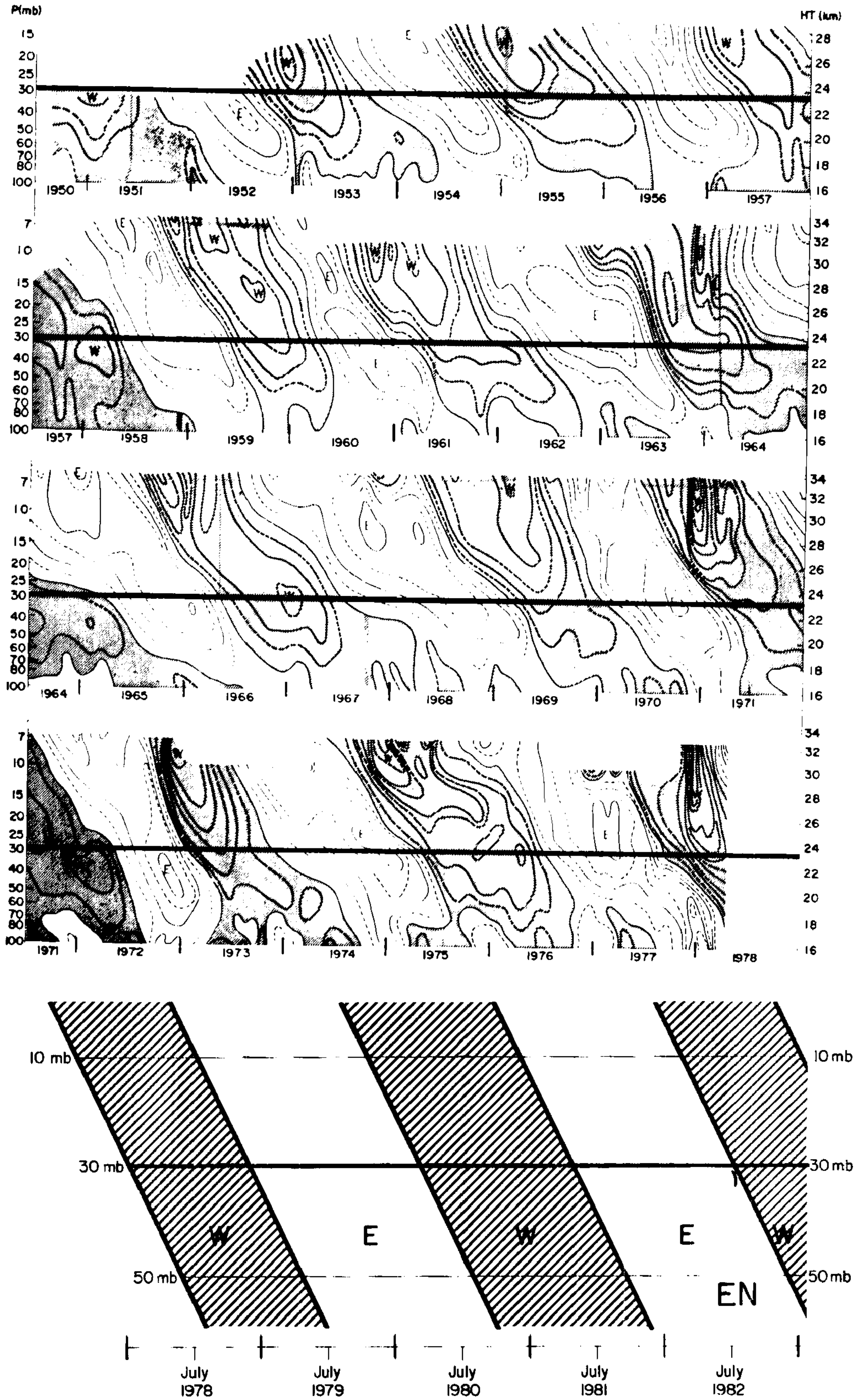

Fig. 30. Vertical plot of stratospheric zonal wind from 1950 through 1982. Westerly winds are shaded. Top plot is from Coy (1979); bottom plot is from information furnished to the author by R. Quiroz, 1982 - personal communication.

Tables 8 and 9 present numerical rankings of the number of hurricanes and number of hurricane days per season since 1950. The direction of the 30 mb seasonal zonal wind from West (W) or East (E), is given in the right hand column of these figures. Note that hurricane activity is, in general, more frequent when the 30 mb stratospheric winds are from a westerly direction and less frequent when 30 mb winds are from the east. The average number of hurricanes per year with 30 mb west winds is 6.9 while for east winds it is 4.6. The number of hurricane days per season for 30 mb winds from the west and east is 31 days and 16 days respectively, nearly a two to one difference.

Figure 31 shows a graphical plot of the number of hurricane days per year for each year from 1949 through 1982 by east and west wind category.(3) Disregarding El Nino years these ratios are 7.4:5.2 for seasonal number of hurricanes, and 34:18 for hurricane days per season. The obvious association of seasonal number of hurricane days with the QBO zonal wind direction is quite apparent.

Figures 32 and 33 compare the tracks of all cyclones of hurricane intensity for 12 non-El Nino years between 1950-1982 when 30 mb seasonal winds were from the west with a similar sample of 12 non-El Nino years when 30 mb seasonal winds were from the east. Note the greater number of hurricane tracks and the large increase in westward tracking hurricanes through the West Indies region in 30 mb west wind situations.

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(3) Because of the biennial nature of these QBO winds and the observation of 30 mb westerly winds in 1950, it is assumed (through backward extrapolation) that the 1949 30 mb wind was from the east.

TABLE 8

Ranking of the number of Atlantic hurricanes per season in association with the direction of 30 mb equatorial zonal winds from the east (E) or from the west (W).

Year	Number of Hurricanes	Direction of 30 mb Winds	
1950	11	W	
1969	10	W	
1980	09	W	
1955	09	W	
1961	08	W	
1954	08		E
1951	08	–	
1981	07	–	
1966	07	W	
1963	07	–	
1959	07	W	
1958	07		E
1976	06	–	
1975	06	W	
1971	06	W	
1967	06	–	
1964	06	W	
1953	06	W	
1952	06		E
1979	05		E
1978	05	W	
1977	05		E
1970	05		E
1974	04		E
1973	04	W	
1968	04		E
1965	04		E
1960	04		E
1956	04		E
1972	03		E
1962	03		E
1957	03	W	
1982	02		E

6.9 hurricanes per season with west wind cases

4.6 hurricanes per season with east wind cases

TABLE 9

Ranking of the number of Atlantic hurricane days per season in association with the 30 mb QBO winds from the east (E) or west (W).

Year	Number of Hurricane Days	Direction of 30 mb Winds
1950	57	W
1955	46	W
1961	46	W
1964	43	W
1966	41	W
1969	39	W
1980	38	W
1951	37	-
1963	36	-
1967	35	-
1954	33	E
1958	33	E
1971	28	W
1965	27	E
1976	24	-
1952	23	E
1979	23	E
1981	23	-
1959	22	W
1949	20	E
1957	20	W
1953	18	W
1960	18	E
1975	18	W
1974	16	E
1978	13	W
1956	12	E
1962	10	E
1968	09	E
1973	09	W
1970	07	E
1972	06	E
1977	06	E
1982	05	E

Average of 31.3 hurricane days per season for west wind cases

Average of 16.5 hurricane days per season for east wind cases

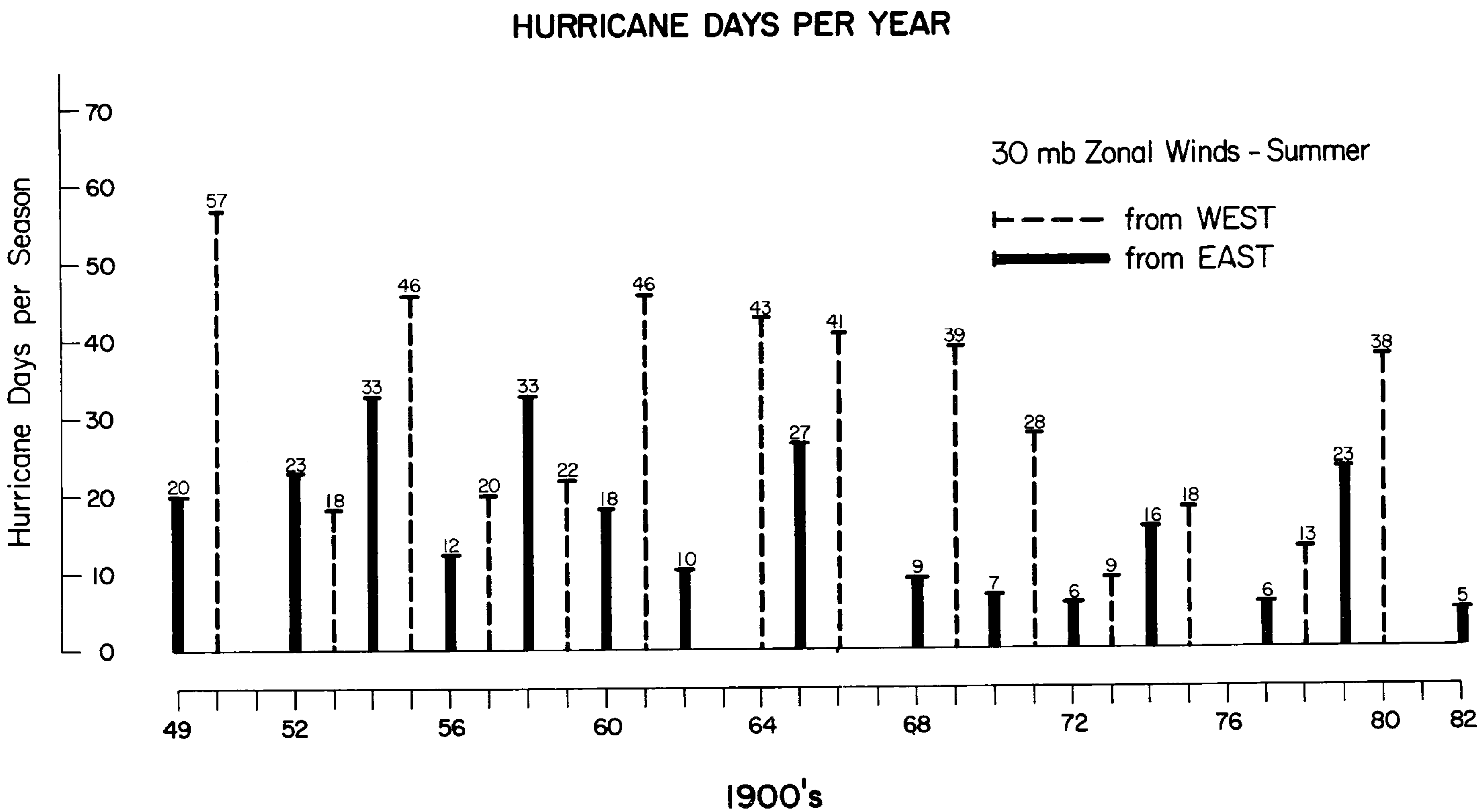

Fig. 31. Relationship between 30 mb stratospheric wind direction and seasonal number of hurricane days from 1949-1982. Years with no observation are those in which the 30 mb zonal wind is changing direction or is very weak during the hurricane season.

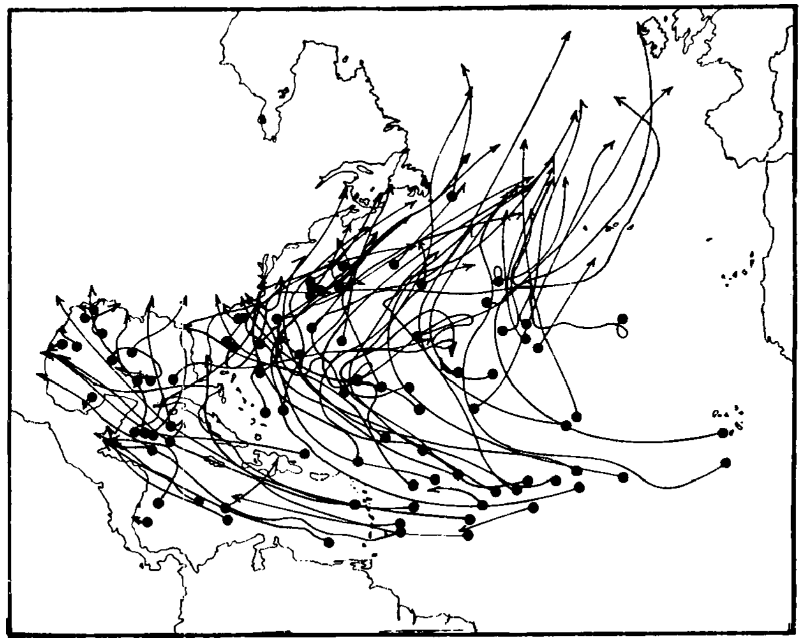

Fig. 32. Tracks of 12 non-El Nino years (1951, 1955, 1959, 1961, 1964, 1966, 1969, 1971, 1973, 1975, 1978, 1980) of hurricane intensity cyclones when seasonal 30 mb equatorial winds were from the west.

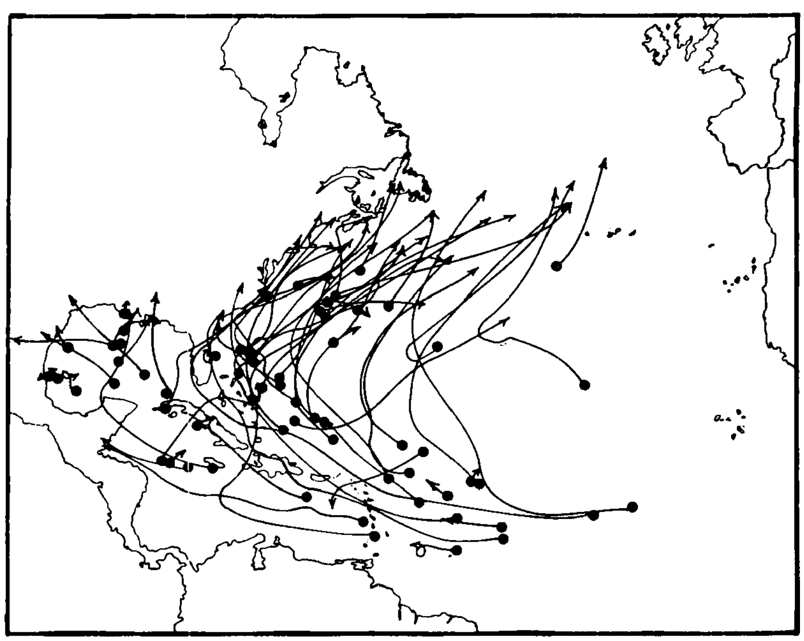

Fig. 33. Tracks of 12 non-El Nino years (1952, 1954, 1956, 1958, 1960, 1962, 1968, 1970, 1974, 1977, 1979, 1981) of hurricane intensity cyclones when seasonal 30 mb equatorial winds were from the east.

It is also observed that seasonal hurricane activity is related to the temporal changes of zonal wind during the hurricane season. Irrespective of wind direction, seasonal hurricane activity is enhanced when 30 mb winds are becoming more westerly, and suppressed when they are becoming more easterly. Figures 34 and 35 portray the tracks of hurricane intensity storms for 12 non-El Nino years between 1950-1982 when 30 mb zonal winds were increasing with time during the hurricane season vs. 12 non-El Nino years when 30 mb zonal winds were decreasing with time during the hurricane season. There were 42 percent more hurricanes and 60 percent more hurricane days in non-El Nino seasons (13 cases) with increasing 30 mb westerly winds (or decreasing easterly winds) than in seasons (12 cases) of increasing 30 mb easterly winds.

A more detailed analysis of the stratospheric winds indicates that when 30 mb winds are from the west and are also increasing in velocity from the west, hurricane activity is even greater than for the average of all the westerly wind cases by themselves or of all increasing westerly wind cases by themselves. The opposite is also true. When 30 mb winds are from the east and are also increasing in velocity from the east, hurricane activity is more suppressed than it is for the average of all east wind cases or the average of all increasingly east wind cases. Those non-El Nino seasons in which 30 mb winds were from the west and increasing with time from the west (9 cases in 1950-1982 period) had 62 percent more hurricanes and 205 percent more hurricane days than seasons with 30 mb winds from the east and increasing in speed from the east (7 cases in 1950-1982 period). Figures 36 and 37 show the hurricane intensity tracks in these two situations. Years of westerly

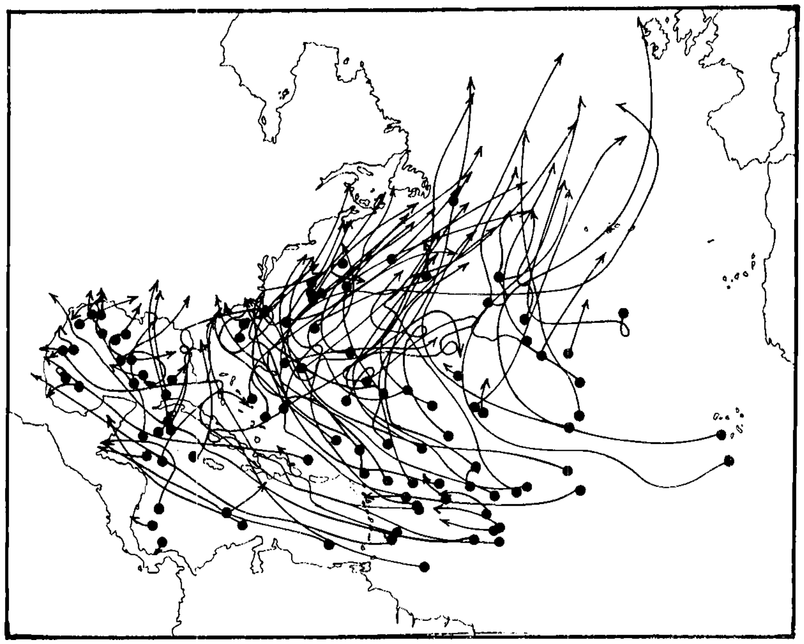

Fig. 34. Composite tracks of hurricane intensity storms during 12 non-El Nino years when 30 mb equatorial zonal winds were increasing during the hurricane season. The twelve years are: 1950, 1952, 1955, 1959, 1961, 1963, 1966, 1969, 1971, 1975, 1979, 1980.

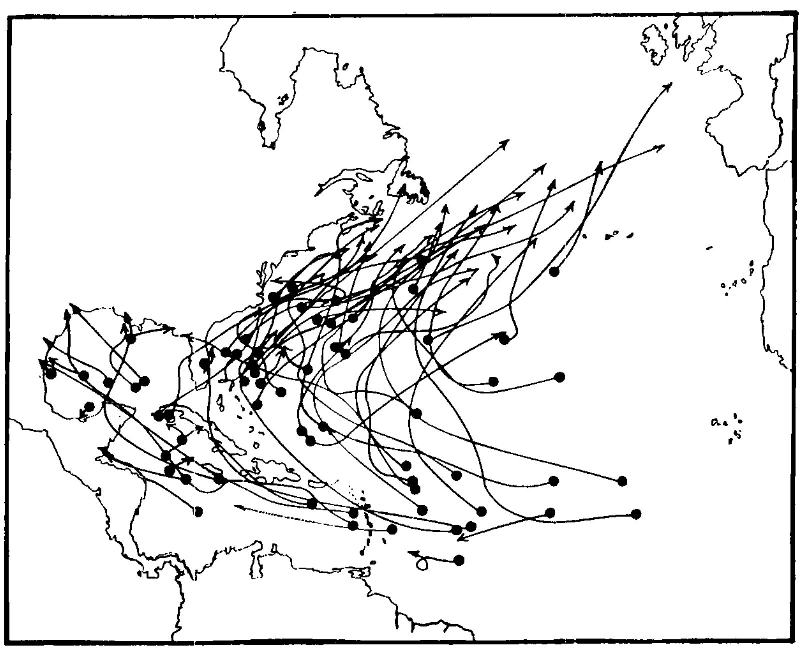

Fig. 35. Composite tracks of hurricane intensity storms during 12 non-El Nino years when 30 mb equatorial zonal winds were decreasing during the hurricane season. The twelve years are: 1951, 1956, 1958, 1962, 1964, 1967, 1968, 1970, 1973, 1974, 1978, 1981.

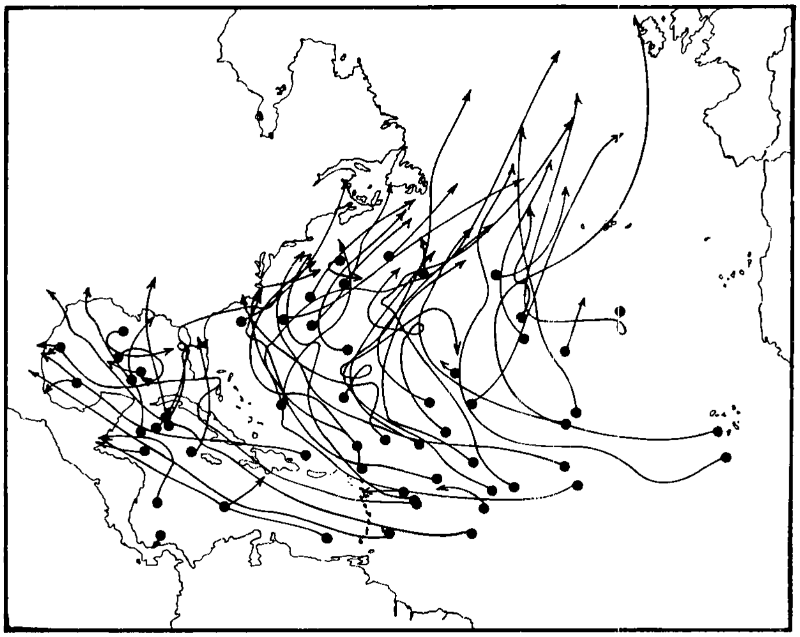

Fig. 36. Tracks of all hurricane intensity storms for the nine seasons when 30 mb equatorial zonal winds were westerly and increasing in westerly strength during the hurricane season.

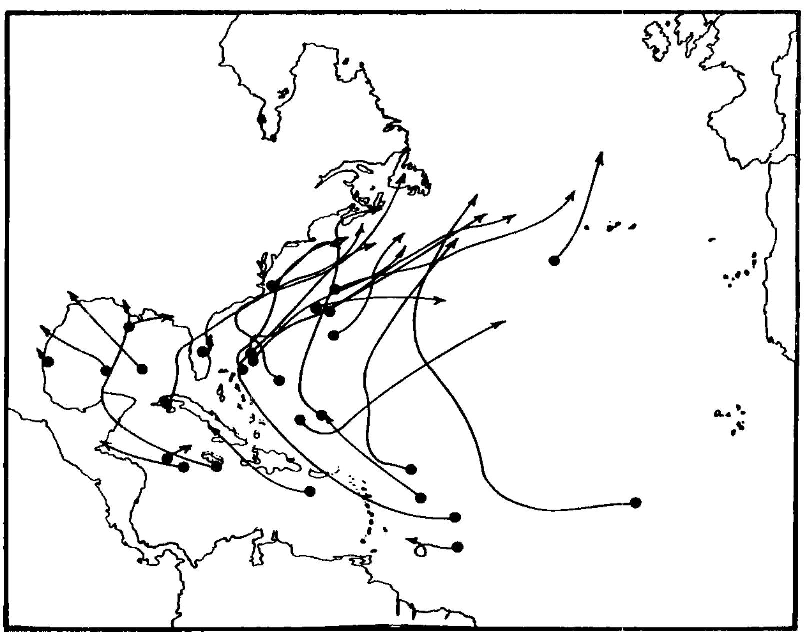

Fig. 37. Tracks of all hurricane intensity storms for the seven seasons when 30 mb equatorial zonal winds were easterly and increasing in easterly strength during the hurricane season. For an equivalent number of seasons with Fig. 36 the two additional seasons of 1954 and 1967 have been added. 1954 has east winds and no appreciable change of wind speed. 1967 has only small zonal wind but easterly winds were increasing.

wind cases are observed to have a much larger number of hurricane track storms.

Table 10 gives summary data on the association of seasonal hurricane numbers, total seasonal number of hurricanes and tropical storms, and seasonal hurricane days for various phases of the 30 mb QBO signal for all 27 years of the period of 1950-1982 that were not El Nino years. Note that quite systematic frequency differences occur for these various wind direction, wind speed change, and combination of wind direction and wind speed change categories. This table also gives P-values of the Wilcoxon two-rank statistical test of the null hypothesis that no relationship exists between these various wind categories and hurricane activity. In all but one case P-values are less than .05.

The general importance of monitoring such 30 mb QBO zonal wind patterns and their tendency is apparent. Information on wind speed changes appear nearly as important as the direction of the equatorial zonal wind itself.

Depth of Wind Oscillation. The explanation for these storm variations due to temporal 30 mb wind changes appears to be related to the changing depths of the stratospheric west and east winds. The greater the thickness of the stratospheric layer of west winds (or thinness of the layer of east winds) the greater the amount of hurricane activity. Because of the downward progressing vertical slope of the zonal wind phase lines with time, a 30 mb westerly or easterly wind increase with time brings about a progressively larger vertical extent of stratospheric westerly or easterly winds. For example, in the nine non-El Nino seasons of 1950, 1955, 1959, 1961, 1966, 1969, 1971, 1975, and 1980 (Fig. 36 gives tracks) 30 mb west winds were increasing with

TABLE 10

Comparison of seasonal average number of hurricanes, number of hurricanes and tropical storms, and number of hurricane days for various phases of the QBO for the 27 non-El Nino years in the period of 1950-1982. Information pertains to 30 mb zonal winds of Fig. 30. The number of years involved in each average is shown in parenthesis.

30 mb Zonal Wind	Number of Hurricanes	Seasonal Number of Hurricanes and Tropical Storms	Seasonal Number of Hurricane Days
West Wind	7.4(13)	11.1(13)	33.6(13)
East Wind	5.2(12)	8.2(12)	17.7(12)
% Difference	42	35	90
P-value of no difference	(.0045)	(.0016)	(.0045)
Cases of $\partial u/\partial t$ Positive	7.4(13)	10.3(13)	32.6(13)
Cases of $\partial u/\partial t$ Negative	5.2(12)	8.9(12)	20.4(12)
%Difference	42	16	60
P-value of no difference	(.0065)	(.0446)	(.0158)
West Wind and Increasing from West	8.1(9)	11.5(9)	37.2(9)
East Wind and Increasing from East	5.0(7)	8.4(7)	12.2(7)
%Difference	62	37	205
P-value of no difference	(.0038)	(.0048)	(.0024)

time during the hurricane season and stratospheric winds from 10 mb to 50 mb were almost all from the west - see Fig. 38. The reverse situation occurred with increases of 30 mb easterly winds during the seven seasons of 1956, 1958, 1962, 1968, 1970, 1974, and 1979 when easterly winds during the hurricane season occupied nearly the whole vertical extent of the stratosphere from 10 to 50 mb. The situation is quite different with decreasing 30 mb winds from either east or west. In these cases, the sloping directional phase lines cause

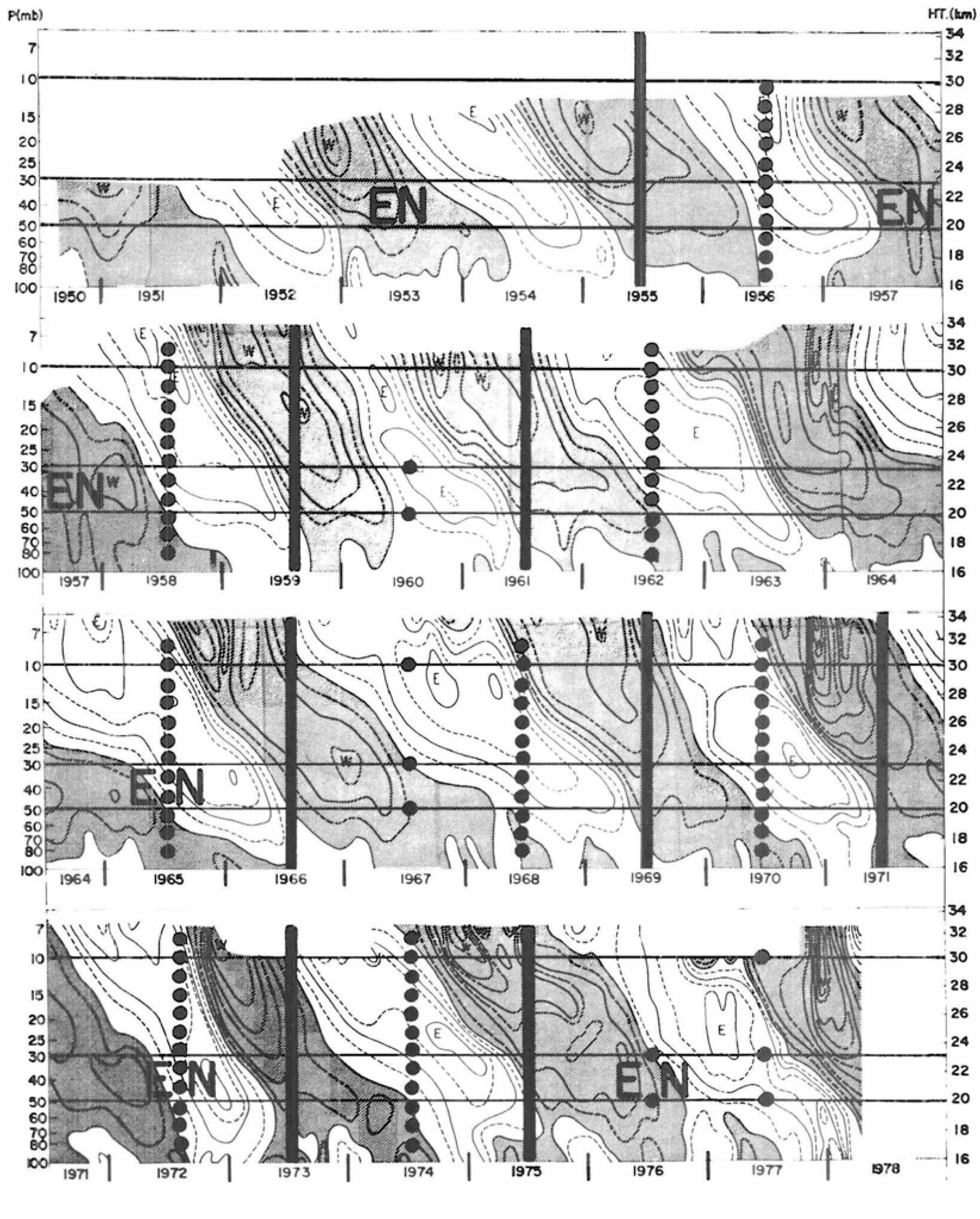

Fig. 38. Designation of non-El Nino seasons when deep zonal westerly winds exist (vertical solid lines) and are increasing with time vs. non-El Nino seasons when deep easterly winds exist (vertical dotted lines) and are increasing with time. El Nino years are indicated by EN.

a change of sign of the zonal wind between 10 and 50 mb. This results in a decreasing thickness of unidirectional 10-50 mb zonal winds.

Figure 39 portrays in idealized form the relative positions of these different phases of the biennial oscillation in terms of maximum depth of stratospheric easterly and westerly winds and associated position of 30 mb wind changes relative to typical maximum and minimum seasonal hurricane activity.

<u>QBO Relationship with Other Parameters</u>. A careful analysis of the tropospheric temperature and precipitation information from Caribbean Basin stations for all the non-El Nino years since 1950 (for precipitation) and since 1957 (for temperature) shows almost no differences between the various classes of 30 mb QBO zonal wind

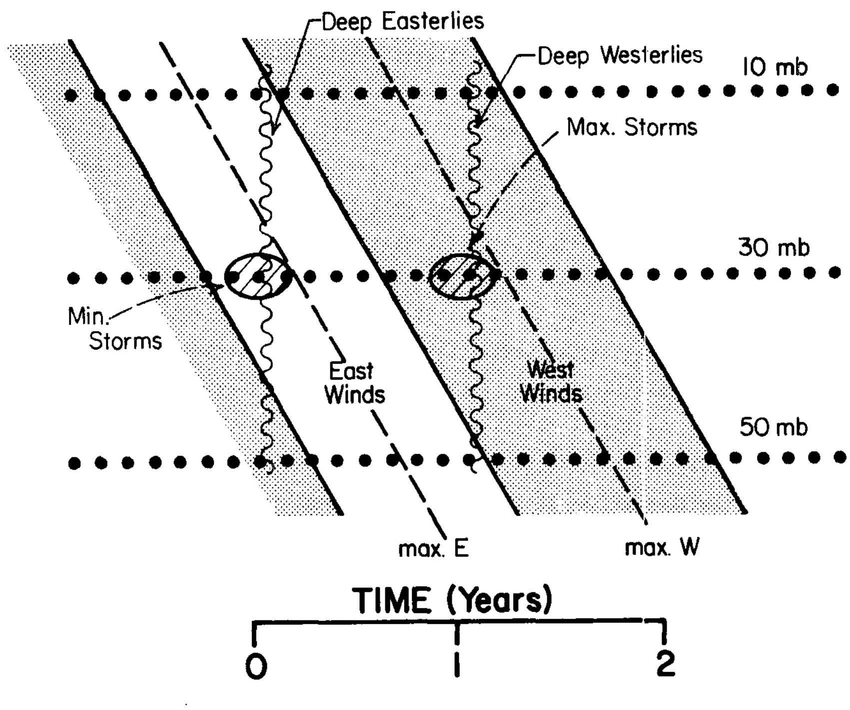

Fig. 39. Portrayal of the typical variation of 10 to 50 mb stratospheric zonal wind events when the 30 mb west winds are increasing in strength (vertical wavy lines in shaded region) and in other cases when 30 mb east winds are increasing in strength (vertical wavy lines in unshaded area). These are the times when the enhancement and suppression of the QBO influence on seasonal hurricane activity is observed to be the greatest.

categories. For instance, Table 11 gives information on the percentage precipitation differences between 9 of the 27 non-El Nino hurricane seasons when 30 mb stratospheric winds were from the west and increasing in westerly direction with time and the 9 other non-El Nino seasons when 30 mb winds were from the east and increasing in easterly speed with time or no change in speed (2 cases). The 9 other non-El Nino years of this 1950-1982 period are also shown. Note that mean precipitation differences between these three categories of 30 mb QBO zonal wind differ by less than ± 5 percent. Individual monthly mean precipitation differences are less than ± 10 percent. As with the El Nino information of the previous section, it appears that it is not the number or rain intensity of the individual weather systems which are altered between the different phases of the QBO zonal wind signal. Instead it is the existence of these rain producing weather systems in a more favorable large-scale environment when 30 mb winds are from a westerly direction in comparison with environmental conditions when 30 mb winds are from an easterly direction.

Surface Pressure Anomaly and QBO Association. The 30 mb zonal wind oscillation is best detected in surface pressure. An analysis of the August-September mean sea level pressure anomaly (SLPA) differences with the different phases of the QBO for the 6-station Caribbean Basin average is given in Table 12. Note the consistent August-September pressure anomaly differences of about 0.2-0.5 mb which are associated with the different west wind minus east wind and west wind increase minus east wind increase QBO signals. The P-value for the Wilcoxon two-rank test of the null hypothesis that August-September SLPA is not related to seasonal hurricane activity is .007.

TABLE 11

Monthly mean percentage precipitation departures from the average of 15-20 Caribbean Basin stations for 27 non-El Nino years divided into three classes of 30 mb QBO zonal wind.

30 mb QBO Wind Category	Month JUN.	JUL.	AUG.	SEPT.	OCT.	5-MONTH AVE.
9 Non-El Nino Seasons of West Winds and West Winds Increasing	-8	-4	-1	-4	+8	-2
9 Non-El Nino Seasons of East Winds and East Winds Increasing	+10	+9	+1	+2	0	+4
Other 9 Non-El Nino Seasons	-2	-5	+1	+2	-8	-2

TABLE 12

Mean August-September sea level pressure anomaly (SLPA) for the 6-station Caribbean Basin average for the various phases of the 30 mb QBO zonal wind oscillation in non-El Nino years. The number of years involved in each average is shown in parenthesis.

30 mb Zonal Wind (u)	SLPA (in mb)
West Wind	-.14 (12)
East Wind	+.07 (12)
Difference (W-E)	-.21
Cases of $\partial u/\partial t$ Positive	-.29 (12)
Cases of $\partial u/\partial t$ Negative	+.10 (12)
Difference (Positive-Negative)	-.39
West and $\partial u/\partial t$ Positive	-.26 (9)
East and $\partial u/\partial t$ Negative	+.23 (7)
Difference (W-E)	-.49

Even though these surface pressure anomalies are not very large, they are the most detectable meteorological element difference that can be found to help explain such a QBO and seasonal hurricane activity association. It is well known that seasonal hurricane activity is negatively correlated with seasonal SLPA.

Speculative Physical Linkage for QBO-Hurricane Activity Association. Our analysis shows that equatorial stratospheric temperatures are typically 3-4^{o}K warmer in west wind than in east wind cases. These type of temperature changes associated with the stratospheric QBO have also been analyzed by Van Loon and Rogers (1983) - see Fig. 40. Such warmer stratospheric temperatures as occur with 30 mb west wind cases would (other factors remaining constant) lead to a general lowering of equatorial surface pressure even though tropospheric temperature conditions are (as observed) little affected by such 30 mb equatorial zonal wind alterations. Conversely, equatorial surface pressure should (other factors remaining constant) be higher than normal when equatorial 30 mb zonal winds are from an easterly direction. This type of QBO induced surface pressure alteration will be primarily evident at equatorial latitudes and little noticed at sub-tropical locations where the QBO signal faces away. Due to asymmetry of the QBO signal in summer, and the lack of earth vorticity and the inability to sustain balanced wind-pressure gradients near the equator, the maximum west vs. east wind QBO induced SLPA differences should be located 5-8 degrees or more away from the equator.

Such temperature induced pressure alterations should cause (in west wind cases) a general relaxation of the normal North-South (N-S) pressure gradient between the latitude belts of 0-10^{o}N but a

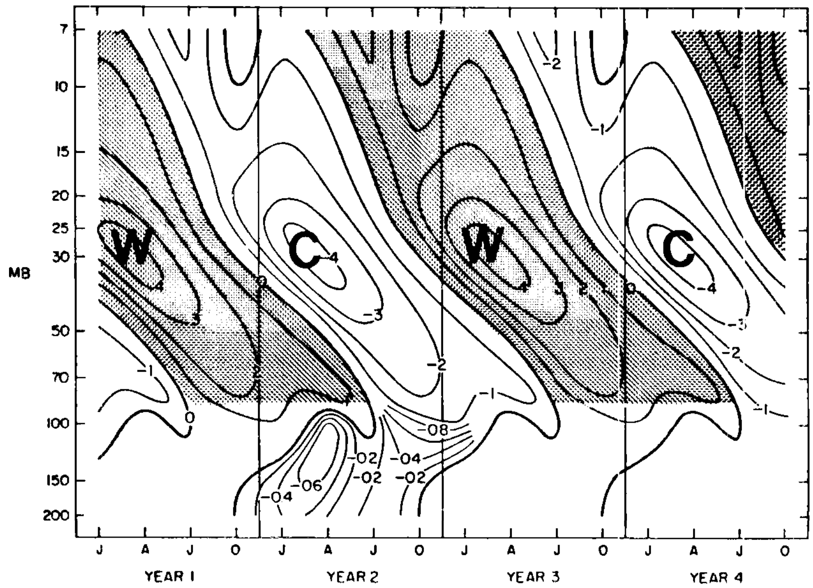

Fig. 40. Typical variation of stratospheric temperature anomaly (^{o}C) associated with the different phases of QBO signal (from Van Loon and Rogers, 1983). Positive values are shaded. W and C stand for Warm and Cold.

strengthening of the N-S pressure gradient between 10-20^{o}N - see the left diagram of Fig. 41. When such 30 mb equatorial west wind induced pressure alterations are superimposed upon the normal west Atlantic-Caribbean Basin hurricane season N-S pressure gradient (solid line of this figure), a general reduction in EQ-10^{o}N low level east wind and enhancement of 10-20^{o} trade winds should occur. These wind alterations will cause a general increase in 850 mb N-S zonal wind shear and low level vorticity in the 8-18^{o} latitude belt. This is the latitude belt of maximum tropical cyclone development. A similar pressure or height change at upper tropospheric levels will act to increase east winds at 5-10^{o}N and cause a general reduction of upper level vorticity between 8-18^{o}N. These alterations of lower and upper tropospheric vorticity associated with 30 mb west wind situations should (other factors remaining constant) lead to a general increase in seasonal hurricane activity.

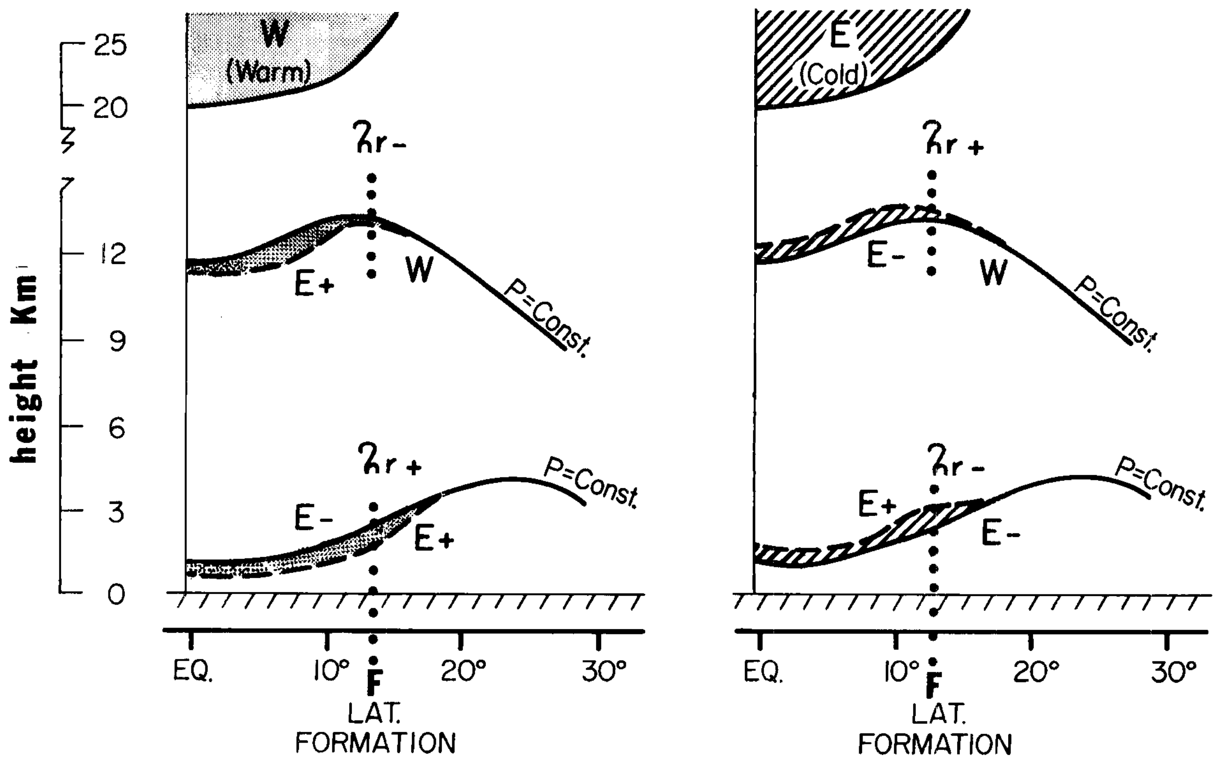

Fig. 41. North-South vertical cross section of the hypothesized meridional slope of constant pressure surfaces which occur in 30 mb west wind situations - left diagram vs. 30 mb east wind situations - right diagram. Solid lines portray the hurricane season climatological slope of constant pressure surfaces. Dashed lines show the altered slope of pressure surfaces in 30 mb west (left) and 30 mb east (right) QBO wind phases. E, W, and ζr stand for East wind, West wind, and relative vorticity respectively. + and - stand for increase or decrease of wind or vorticity field from seasonal climatology.

In the opposite situation when 30 mb winds are from an easterly direction, cold stratospheric temperatures will lead to a general positive pressure anomaly at equatorial latitudes - see the right diagram of Fig. 41. By analogous reasoning this should cause a general reduction in the N-S shearing vorticity at lower levels but an increase in the upper level vorticity. These changes would (other factors remaining constant) lead to a general reduction in seasonal hurricane activity.

Figures 42-43 show 850 mb and 200 mb mean August-September zonal wind speed differences in m/s for West minus East 30 mb wind direction categories. These zonal wind differences indicate that there is a generally greater cyclonic wind shear between 8-18°N at 850 mb and greater negative wind shear at 200 mb in 30 mb west wind as opposed to east wind conditions. Such 850 and 200 mb zonal wind speed differences between QBO west and east wind situations, although of rather small magnitude, are still of the right sign as to produce a more favorable climatology for cyclone formation in 30 mb west wind situations. Note that the five lowest latitude stations of these figures have greater 850 mb west winds and greater 200 mb east winds in the situation when 30 mb winds are from a westerly direction. And opposite wind patterns are found at higher latitudes. Such wind changes cause a more favorable climatological environment for cyclone formation. It is in this latitude belt of 8-18° that cyclone genesis is most prevalent. A similar analysis of the variation in the N-S pressure gradient in West minus East wind situations cannot be accomplished due to the general noisiness (and some unreliability) of the N-S surface pressure gradient observations. Although lower SLPA is distinctly observed in QBO west wind situations, the horizontal gradients of such SLPA cannot be reliably measured.

This is admittedly a rather tenuous argument for the QBO-hurricane activity association. It is based on the premise that small seasonal alterations in the N-S pressure field of only $\pm$ 0.3-0.5 mb can exert a noticeable influence on the lower and upper tropospheric vorticity fields and thus on seasonal hurricane activity variation. The precise physical linkage between such seasonal pressure changes and individual

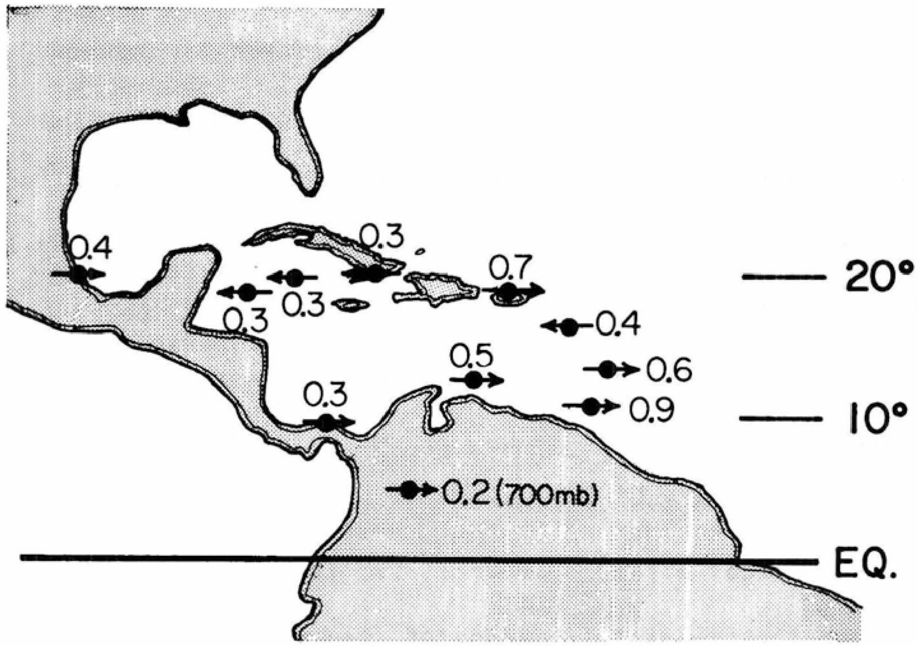

Fig. 42. August-September 850 mb zonal wind differences (m/s) between equatorial 30 mb winds from the west minus 30 mb winds from the east.

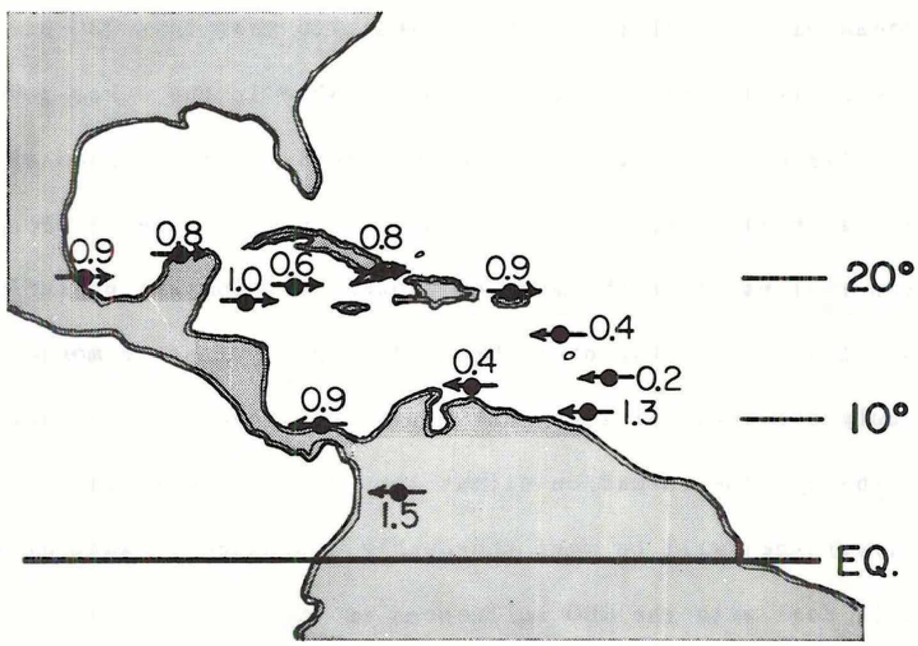

Fig. 43. Same as Fig. 42 but for the 200 mb level.

case storm genesis is not well understood. There is, however, a great deal of meteorological evidence which indicates that a more positively favorable climatological environment, even if of small magnitude, will nevertheless lead to a seasonal increase in the number of the infrequent but intense weather system events.

Thus, even though the N-S tropospheric pressure gradient modulation by the different phases of the QBO is small in comparison with the magnitude of the average pressure gradient, such small seasonal pressure gradient variations appear, nevertheless, to have a significant influence on the seasonal frequency of the occassional and intense (hurricane) event.

<u>QBO-Tropical Cyclone Relationship in Other Regions</u>. Research is also progressing on the association of tropical cyclone activity in the other ocean basins. Initial results indicate that this QBO-hurricane frequency relationship is much less detectable in the other regions. This is believed to be due to the climatological differences of the west Atlantic-Caribbean Basin hurricane basin from most other cyclone formation regions where the monsoon trough is a dominating influence. The west Atlantic and Caribbean Basin does not possess a monsoon trough. The speculative physical link just described above will not act to enhance the cyclone formation climatology of monsoon trough regions. These differences will be more thoroughly discussed in another paper which will deal with the QBO influences in the other formation basins.

5. Discussion

It is hoped that this paper has demonstrated the importance of the large global circulation component to the more regional problem of seasonal hurricane variability. These linkages of the El Nino and stratospheric QBO with seasonal hurricane activity open up a new dimension to the understanding of west Atlantic hurricane variability. This is particularly the case if one combines the effects of the QBO and El Nino signals. It is interesting to note the very low degree of seasonal hurricane activity that occurred in the strong El Nino (very low SOI) years of 1972 (only 6 hurricane days) and 1982 (5 hurricane days) when a 30 mb easterly stratospheric QBO regime was simultaneously present with a strong El Nino event. It is likely that other meteorological phenomena also respond to such combinations of modulating global circulation influence.

A growing awareness is taking place concerning the biennial variability of a number of tropospheric phenomena (Angel, et al., 1969; Wright, 1968; Trenberth, 1980; Rasmusson, et al., 1981 and others). Brier (1978) has hypothesized that a tropospheric QBO response should be an expected consequence of the basic differences in atmospheric-ocean energy exchange processes between successive Northern Hemisphere summer seasons. It should thus not be completely unexpected that a QBO-seasonal hurricane activity modulation relationship might be present. What is surprising is the very large amount of explained seasonal hurricane variance associated with these oscillations.

QBO and El Nino influences on Atlantic storm frequency are likely to be more pronounced than in the other ocean basins because the western Atlantic hurricane area is located at a somewhat higher latitude and is a more marginal region for hurricane activity. The usual type of storm development within a monsoon trough does not typically take place in the Atlantic. Atlantic hurricane activity can vary from zero (as in 1907 and 1914) or 1 (as in 1906, 1919, and 1925) to 11 (as in 1916 and 1950) or 10 as in 1933 and 1969. Such large variability indicates that the Atlantic region has, in general, a greater sensitivity to large scale general circulation modulation influences than most other tropical cyclone basins. Thus, the places where tropical cyclone activity is typically the lowest will likely be the places most influenced by general circulation alterations. In El Nino years (and low SOI situations) hurricane activity in the Australian region (Nicholls, 1979) is also somewhat suppressed, particularly in the early part of the season.

Regional influences on tropical cyclone activity such as sea surface temperature, surface pressure, tropospheric temperature-height, etc. may often not be the most important influences to seasonal cyclone frequency.

Other global circulation features that have yet to be investigated for relationships to hurricane activity are the 40-50 day oscillation of zonal wind as discussed by Madden and Julian (1971, 1972), and the global influences to wind changes of the yearly fluctuations in the strength of the Asian summer monsoon. Future papers will deal with these topics.

The next paper (Part II) discusses how information on the El Nino and QBO can be used in conjunction with other West Indies regional meteorological parameters to make seasonal forecasts of the variability of West Atlantic seasonal hurricane activity.

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ATLANTIC SEASONAL HURRICANE FREQUENCY

PART II: FORECASTING ITS VARIABILITY

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ABSTRACT

This is the second (Paper II) of two reports on Atlantic seasonal hurricane activity. Paper I discussed the association of the El Nino and the phases of the stratospheric QBO of equatorial zonal wind with Atlantic seasonal hurricane variability. This paper is an extension of Paper I. It shows how the addition of regional sea level pressure data from Caribbean Basin meteorological stations can be combined with the more global El Nino and QBO information to form a rather skillful forecast scheme for Atlantic seasonal hurricane activity. Seasonal forecasts could be issued on 1 June of each year and updated prior to the commencement of the most active part of the hurricane season on 1 August. It appears possible to predict between half and two-thirds of the variance of seasonal hurricane activity.

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1. Background

Forecasts of the yearly hurricane activity in the western Atlantic are not being made. This is because forecast techniques which show skill have yet to be developed. Attempts to link hurricane activity with the large scale Atlantic wind and pressure field patterns (Ballenzweig, 1959; Namias, 1955, 1969, 1973; Shapiro, 1981a, 1981b; Ding and Reiter, 1981, 1983) have so far proven only marginally beneficial as far as seasonal forecasting is concerned. Although a number of broad-scale hurricane frequency correlations have been found to exist and have been shown to be statistically significant with many years of data, such associations usually show a rather low correlation. They typically do not offer much assistance in seasonal hurricane activity forecasting. Any simultaneous association of monthly and/or seasonal surrounding flow, sea surface temperature, or pressure patterns with hurricane activity does not by itself indicate a useful predictive skill. How does one predict the monthly or seasonal large-scale flow or pressure patterns from which a hurricane season forecast can be made?

This study presents a technique whereby western Atlantic seasonal hurricane activity might be forecast with some degree of useful skill. This forecasting technique is based on the observed decrease of Atlantic hurricane activity associated with El Nino years and with the observed alteration of hurricane activity with different phases of the stratospheric Quasi-Biennial Oscillation (QBO) of zonal wind as discussed in the preceding Paper I (Gray, 1983). This forecasting technique is also based on the observed association of seasonal hurricane activity with Caribbean Basin springtime and early summer mean monthly sea level pressure anomaly.

2. Monthly Caribbean Basin Sea Level Pressure Anomaly (SLPA) and Seasonal Hurricane Activity

Although the influence of QBO and El Nino events on hurricane frequency are of primary importance, regional influences of springtime monthly Sea Level Pressure Anomaly (SLPA) also appear to exert a detectable and significant influence on seasonal hurricane modulation.

Figures 1-4 show the yearly variation of SLPA for the month of May, and the average for the months of April-May, June-July, and August-September for the period 1950-1982. The solid line in these figures represents a special 6-station average. The dashed line represents the SLPA that was determined by averaging all available (15-20 stations) individual Caribbean Basin stations. Anomalies were determined for each month by obtaining each station's individual month SLP difference from that station's long term (1950-1982) mean for that month. Note that month to month SLPA variations range between ± 1.5 mb.

Some Caribbean Basin station pressure data was not available for the entire 1950-1982 period and some station pressures appeared somewhat less reliable than other first order stations. To standardize the monthly pressure records as much as possible and to reduce the need for too many calculations if applied in real forecast situations it was decided to perform SLPA calculations for just six of the more representative and more reliable stations of Barbados, Curacao, San Juan, Merida, Miami and Brownsville as shown in Fig. 5. The other stations used for the calculation of the all Caribbean Basin monthly SLPA are shown in Fig. 6. Figures 1-4 show that there is not much SLPA difference between the 6-station and the all station Caribbean Basin monthly means.

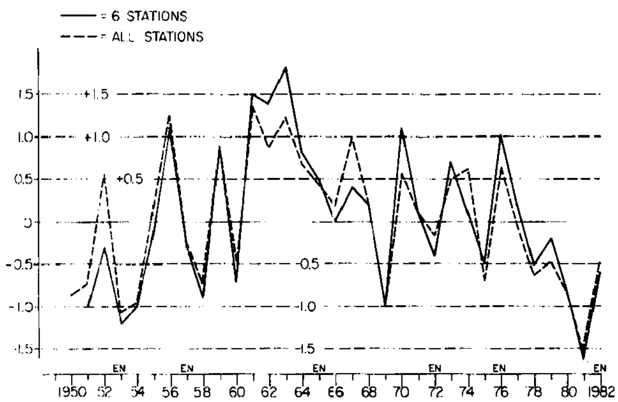


Fig. 1. Six-station average of Caribbean Basin SLPA for May (solid line). All station average is given by the dashed curve.

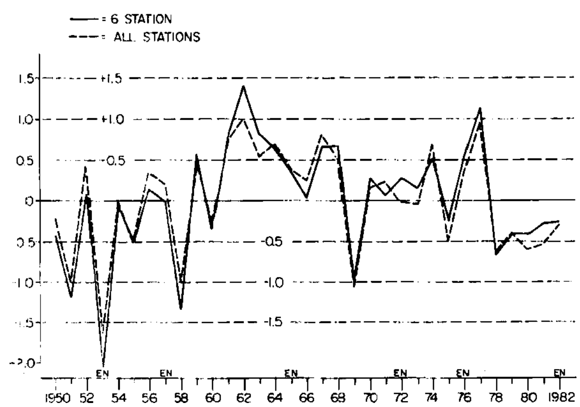


Fig. 2. Same as Fig. 1 but for average of April-May data.

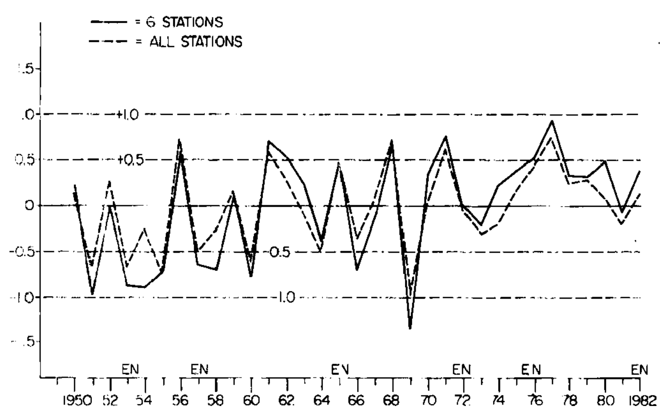


Fig. 3. Same as Fig. 1 but for average of June-July data.

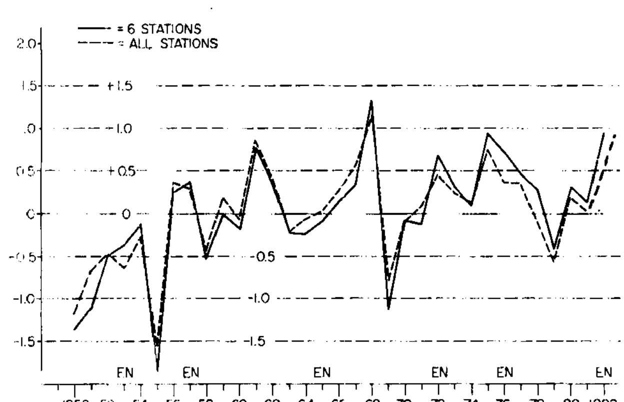


Fig. 4. Same as Fig. 1 but for average of August-September data.

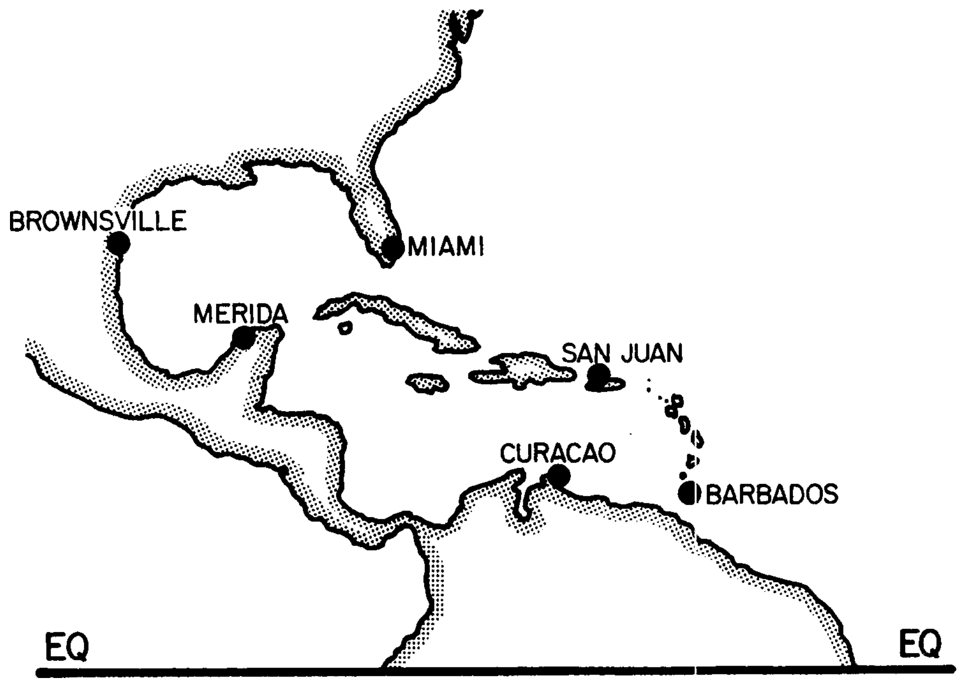


Fig. 5. Location of meteorological stations used for determining the 6-station mean monthly SLPA for the Caribbean Basin region.

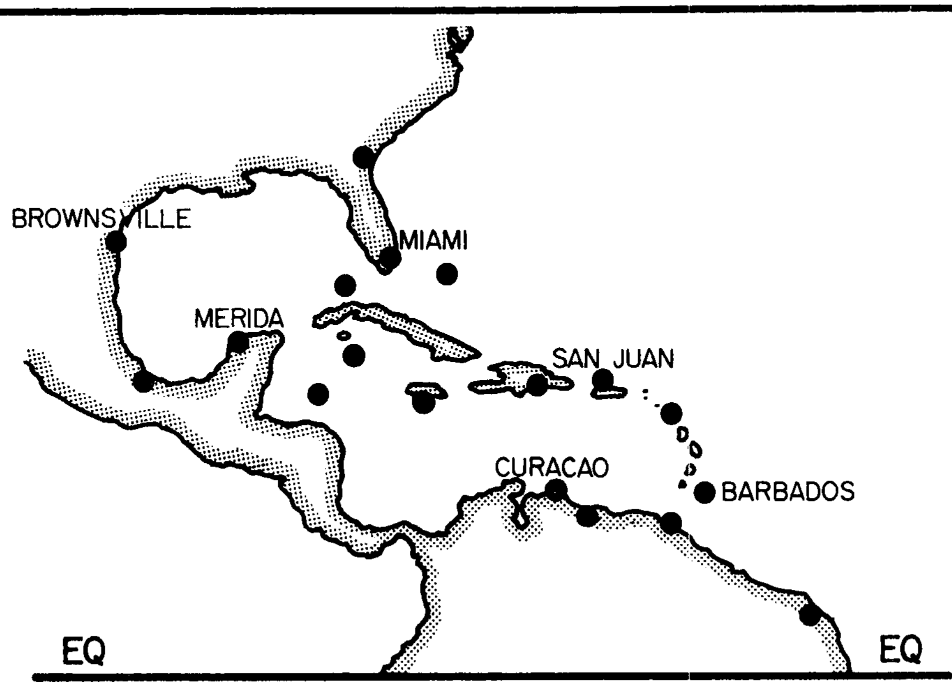


Fig. 6. Location of meteorological stations used to determine the all station mean monthly SLPA for the Caribbean Basin region.

As the SLPA for both data sets were quite similar, most of the results to follow will employ only the 6-station data.

a. Lag-correlation of SLPA between Different Months

Springtime Caribbean Basin SLPA has a significant correlation with the following summer SLPA. Table 1 shows these various monthly lag correlations for the special 6 Caribbean Basin stations for the 33 year period of 1950-1982. Data are correlated for all 33 years and also for the 27 non-El Nino years of this period which are shown in parentheses. Adjacent monthly SLPA are correlated at about the 0.5-0.6 level. Months two or more apart correlate at a level of about 0.3-0.5. Note that April-May SLPA correlates with August-September SLPA at about the 0.5 level. June-July SLPA shows a correlation with August-September SLPA of about 0.55-0.60. These month to month pressure anomaly correlations may be higher than some readers would suspect and, because SLPA is known to correlate directly with hurricane activity in the month in which such activity occurs, the existence of statistically significant one to five month lag relationships between SLPA and hurricane frequency should be expected.

b. Shapiro's Analysis of Seasonal Hurricane Activity as Related to SLP

Shapiro (1982a, 1982b) has recently performed a detailed analysis of West Atlantic seasonal hurricane activity for the period 1899 to 1978. He has made an extensive analysis of the association of seasonal hurricane activity with sea level pressure (SLP), 500 mb height, and sea surface temperature (SST) fields in the Atlantic region poleward of 20°N from analyzed National Meteorological Center (NMC) grid point data. Shapiro finds that August-September-October (ASO) sea level pressure

TABLE 1

Correlation array of Caribbean Basin SLPA between different months for the period 1950-1982. Correlations involving only the 27 non-El Nino years are shown in parentheses.

	May	April-May	June-July	August-September
May	- -	- -	.49 (.45)	.30 (.34)
April-May	- -	- -	.60 (.57)	.48 (.53)
June-July	.49 (.45)	.60 (.57)	- -	.58 (.61)
August-September	.30 (.34)	.48 (.53)	.58 (.61)	- -

poleward of 20^{o}N is negatively correlated with seasonal hurricane activity. At some Atlantic locations this correlation is as high as -0.6 in the hurricane months of ASO. SST also shows correlations nearly as high as SLP. But SST and SLP are not independent parameters. Overall, Shapiro shows that SLP is a slightly better predictor than SST. Very little additional skill is obtained by treating both parameters together.

Shapiro further shows that at the best location points, pre-season May-June-July (MJJ) SLP is correlated with hurricane activity at about the 0.3 to 0.4 level. Such correlations explain about 17% or less of the variance in the following ASO hurricane activity (significant level of 1%) - see Fig. 7. This paper's SLP analysis using individual station data from all available Caribbean Basin stations (many south of 20^{o}N) substantiates Shapiro's analysis. Such a pre-season SLP-hurricane activity relationship, even if at a rather low level of 0.3 to 0.4, may

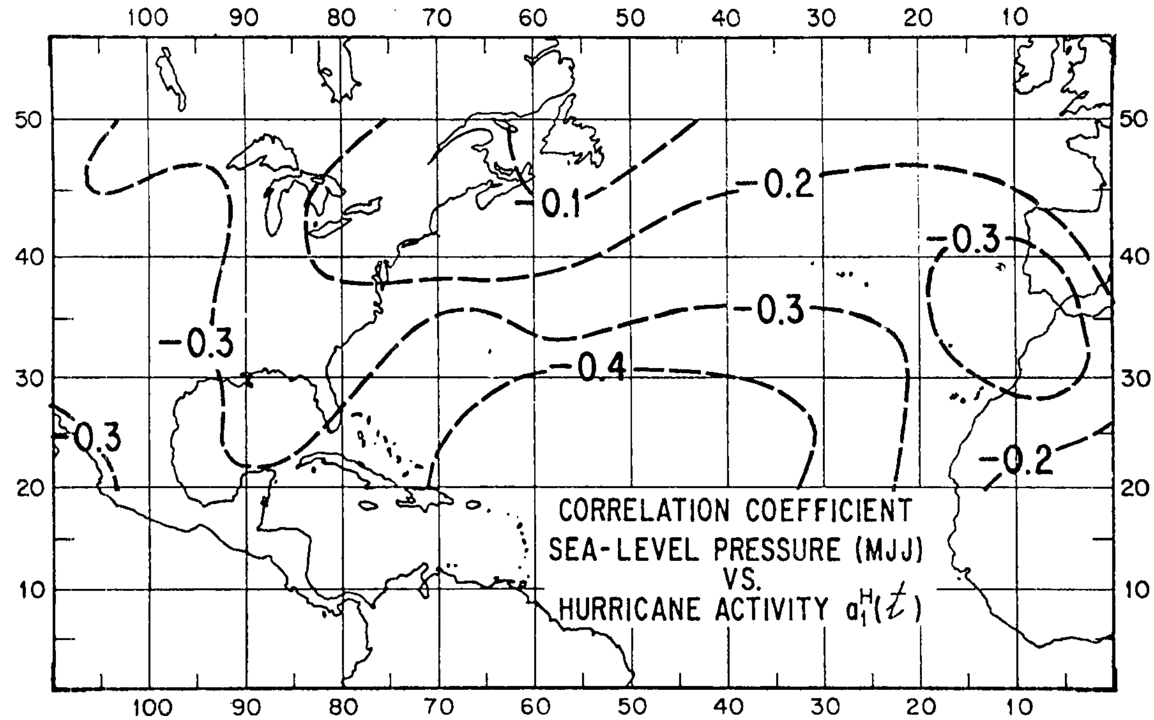


Fig. 7. Shapiro's (1982b) correlation of May-June-July SLP with the following August-September-October hurricane activity.

still prove useful if it can be shown that there is little association of such pre-season SLP with the El Nino (EN) and 30 mb QBO zonal wind events as discussed in Paper I. Such a quasi-independence of pre-season monthly SLP with EN and QBO phenomena, as appears to be the case, offers a unique possibility for combining the global scale EN and QBO hurricane relationships with the more regional Caribbean Basin SLP and hurricane association. This will allow a more skillful seasonal prediction scheme than would be possible with either the global or regional relationships by themselves.

c. El Nino and QBO Influences on Caribbean Basin SLP

There is only a small difference in monthly SLPA between springtime El Nino years and the other non-El Nino years. Also there is not such a large difference (< 0.3 mb) in springtime (April-May) SLPA between the different east and west wind phases of the 30 mb QBO signal. Table 2 shows mean monthly SLPA differences between the last six moderate and strong El Nino (EN) years of 1953, 1957, 1965, 1972, 1976, 1982 and the other last 27 non-EN years. Note that SLPA differences of El Nino minus non-El Nino years, although of the order of +0.2 mb for the August-September period, are generally of opposite sign and of magnitude 0 to -0.2 mb in the earlier pre-hurricane season months. SLPA in El Nino and non-El Nino years thus shows little difference in the 3-4 month period prior to the hurricane season. Paper I contains more individual station information on these SLPA differences between EN and non-EN years.

TABLE 2

El Nino minus Non-El Nino year SLPA differences (in mb) by month for the 6-station Caribbean Basin average.

	May	April-May	June-July	August-September
6 Station Average	-.17	-.19	-.02	.18

Table 3 is similar to Table 2. It shows the same monthly SLPA differences between the various components of the 30 mb equatorial QBO zonal wind for the last 27 non-El Nino years. Slightly greater SLPA differences are noted than with the EN vs. non-EN cases. However, such springtime SLPA differences associated with the different east and west QBO zonal wind categories are still small (0 to 0.3 mb) in comparison with the observed year to year variations of springtime SLPA of $\pm$ 1.5 mb.

These pre-season SLPA differences of less than 0.3 mb indicate that the EN and QBO oscillations are quasi-independent of such springtime SLPA. This being the case, it is likely that the larger year to year monthly variations of SLPA of ± 0-1.5 mb (which by themselves have been shown to be correlated with seasonal tropical cyclone frequency) can be utilized as an additional and somewhat independent predictive parameter.

TABLE 3

Sea Level Pressure Anomaly by month for various phases of the 30 mb equatorial QBO zonal wind for the Caribbean Basin region 6-station average (in mb). Data include the 27 non-El Nino years of 1950-1982. The number of years in each average are given in parentheses.

Phases of QBO Signal	May	April-May	June-July	August-September
West Wind (W) Cases (12)	.01	-.14	-.12	-.14
East wind (E) Cases (12)	-.05	.15	.10	.07
(W)-(E)	.06	-.29	-.22	-.21
West Wind Increase (W+) Cases (12)	.03	-.05	.03	-.29
East Wind Increase (E+) Cases (12)	.15	.08	.03	.10
(W+)-(E+)	-.12	-.13	.0	-.39
W + W+ Cases (9)	-.10	-.12	-.01	-.26
E + E+ Cases (7)	-.20	.20	.23	.23
(W+W+)-(E+E+)	.10	-.32	-.24	-.49

Table 4 shows the monthly correlation of SLPA with seasonal numbers of hurricanes, hurricanes and tropical storms, and hurricane days for all 33 years and for the 27 non-El Nino years. Non-El Nino years correlate best. It was expected that August-September SLPA would show the best correlation with hurricane activity. In a predictive sense, however, August-September cannot be used. It is of interest that May and April-May's SLPA correlate almost as well with seasonal hurricane activity as does the June-July SLPA. Note that the correlation of April-May SLPA with hurricanes and with hurricane and tropical storm activity for non-El Nino years is as high as -.45 to -.48.

TABLE 4

Correlation of 6-station average Caribbean Basin region SLPA and seasonal hurricane activity by month for the period 1950-1982. The correlation of the 27 non-El Nino years of this period with hurricane activity is shown in parentheses.

	May	April-May	June-July	August-September
No. of Hurricanes	-.28 (-.45)	-.34 (-.48)	-.34 (-.40)	-.39 (-.61)
No. of Hurricanes and Tropical Storms	-.31 (-.36)	-.50 (-.45)	-.40 (-.34)	-.52 (-.51)
No. of Hurricane Days	-.12 (-.24)	-.20 (-.32)	-.36 (-.42)	-.61 (-.59)

The fact that the hurricane activity correlation of May and April-May's SLPA is as high as June-July SLPA is fortunate because of the longer lead time forecast which is possible. All information needed to make a seasonal forecast of hurricane activity could be made available on 1 June, the official start of the hurricane season. For these reasons it was decided to give primary attention to the year to year variation of the May and the April-May SLPA.

The level of significance of these correlation coefficients for the 33-year and 27-year non-El Nino calculations depends on the value of the correlation coefficient. For correlation coefficients of 0.2, 0.3, 0.4, 0.5 and 0.6 the levels of significance are respectively .14, .05, .012, .003, and .000+ for the 33 year calculations and .19, .07, .02, .004, and .000+ respectively for the 27 year period of non-El Nino year calculations.

d. Association of April-May SLP Anomaly with Seasonal Hurricane Frequency

Inspection of the April-May SLPA (as shown in Fig. 8) and tropical hurricane frequency shows that SLPA seems to alter seasonal cyclone frequency by about one cyclone for every 0.4 mb of mean pre-season anomaly. In seasons where the SLPA is between -0.4 mb and -0.8 mb hurricane activity can be expected to increase by about one cyclone; when SLPA is less than -0.8 mb then seasonal hurricane activity (all other factors remaining constant) can be exected to be greater than the multi-year seasonal average by about two hurricanes. The reverse situation occurs with SLPA > +0.4 mb and > +0.8 mb respectively. No alteration of cyclone frequency should be considered if monthly SLPA is between ± 0.4 mb.

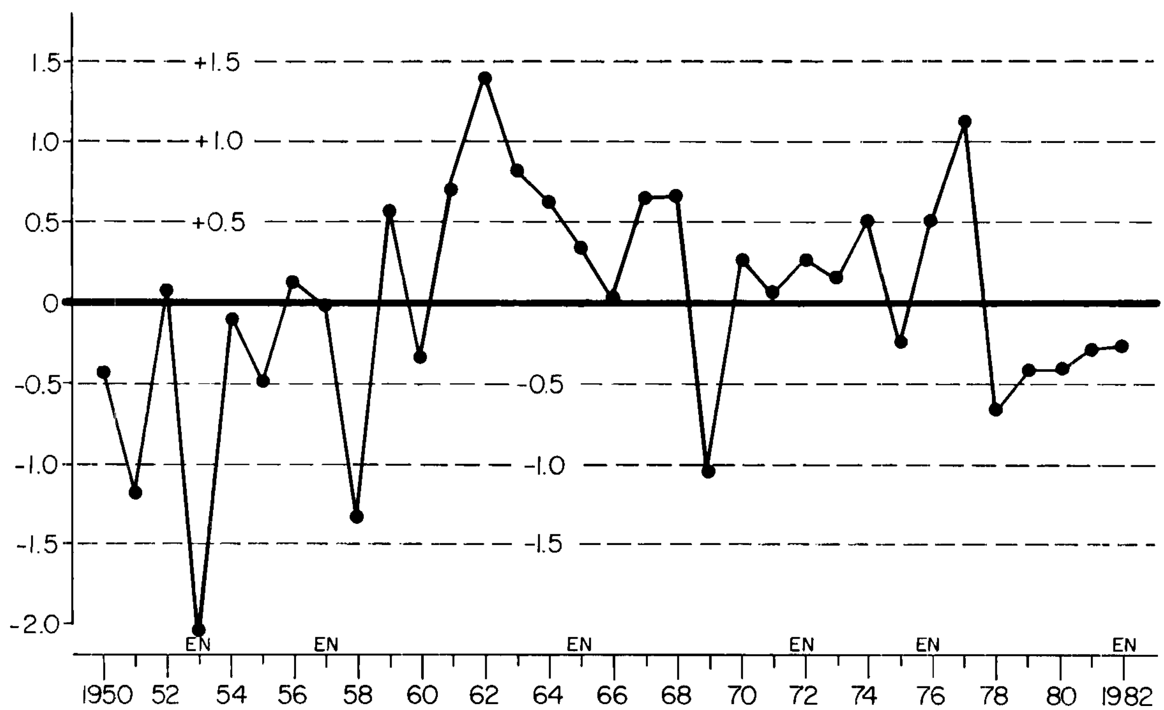


Fig. 8. Yearly variation of April-May mean Caribbean Basin SLPA for the 6 stations of Fig. 1.

Such a multi-month lag in hurricane activity with springtime SLPA is similar to observations by Nicholls (1979) of Australian region seasonal hurricane variation. Nicholls showed that when the Darwin, Australia surface pressure is higher than normal during the winter-spring season, the following summer Australian tropical cyclone activity (particularly in the early part of the season) was supressed. Such positive winter-springtime SLPA appears to be related to a later establishment of the monsoon trough over northern Australia and a generally weakened trough when established. Such conditions lead to a quite noticeable reduction in early season hurricane activity.

The next section will attempt to study the inter-relationship between springtime SLPA, the QBO, the EN and seasonal hurricane activity through multiple linear regression analysis.

3. Multiple Linear Regression Analysis of QBO, EN, and SLPA Association with Seasonal Hurricane Activity

To try to better understand the relationships between these combinations of predictors and seasonal hurricane activity a multiple linear regression analysis was made. This multiple regression analysis was performed on the four prediction parameters shown on the left side of Table 5 and the three measures of seasonal hurricane activity as shown on the right side of this table.

QBO activity was broken into two categories by 30 mb wind direction and 30 mb wind speed change. 30 mb west winds and increasing west wind speed during the hurricane season are each denoted by +1, east winds and increasing east wind speed are each denoted by -1. 0 is used when 30 mb wind direction or speed acceleration are changing sign during the hurricane season.

EN activity is denoted by -2 and -4 in moderate and strong EN years and 0.7 in non-EN years. SLPA is given in millibars for the 6-station Caribbean Basin for the months of April-May.

Table 6 shows the correlation coefficient arrays which relate each of these four predictors to seasonal number of hurricanes, number of hurricanes and tropical storms, and number of hurricane days.

Note that the QBO wind direction is better related to hurricane activity than QBO wind change but this relationship can vary for the three activity parameters. This is also true of the EN and SLPA predictors. The large dominance of the QBO direction influence is to be noted. This is the single best predictor of hurricane activity.

The low internal correlation between each of the QBO, EN, and SLPA predictors is evident. EN and SLPA correlate at only .09. EN and QBO

TABLE 5

Yearly distribution of QBO direction, QBO change, EN, and April-May SLPA factors which went into the multiple linear regression analysis.

Year	(1) QBO Direction	(2) QBO Change	(3) EN	(4) April-May SLPA Correct. Factor	Observed Seasonal No. of Hurricanes	Hurricanes and Tropical Storms	Hurricane Days
1950	1	1	.7	-.43	11	13	57
1951	1	-1	.7	-1.18	08	10	37
1952	-1	1	.7	.07	06	07	23
EN1953	1	-1	-2.0	-2.06	06	14	18
1954	-1	0	.7	-.06	08	11	33
1955	1	1	.7	.51	09	12	46
1956	-1	-1	.7	.15	04	08	12
EN1957	1	0	-4.0	-.01	03	08	20
1958	-1	-1	.7	-1.35	07	10	33
1959	1	1	.7	.57	07	11	22
1960	-1	0	.7	-.36	04	07	18
1961	1	1	.7	.82	08	11	46
1962	-1	-1	.7	1.40	03	05	10
1963	0	1	.7	.82	07	09	36
1964	1	-1	.7	.64	06	12	43
EN1965	-1	-1	-2.0	.37	04	04	27
1966	1	1	.7	.05	07	11	41
1967	0	-1	.7	.65	06	08	35
1968	-1	-1	.7	.67	04	07	09
1969	1	1	.7	-1.00	10	14	39
1970	-1	-1	.7	.28	05	10	07
1971	1	1	.7	.07	06	13	28
EN1972	-1	-1	-4.0	.27	03	04	06
1973	1	-1	.7	.15	04	07	09
1974	-1	-1	.7	.52	04	07	16
1975	1	1	.7	-.25	06	08	18
EN1976	0	-1	-2.0	.54	06	08	24
1977	-1	1	.7	1.14	05	06	06
1978	1	-1	.7	-.66	05	11	13
1979	-1	1	.7	-.41	05	08	23
1980	1	1	.7	-.41	09	11	38
1981	-1	-1	.7	-.28	07	12	23
EN1982	-1	1	-4.0	-.27	02	05	05

TABLE 6

Correlation coefficient array relating each of the four predictors and seasonal hurricane activity.

a. Seasonal Number of Hurricanes

	QBO Direction	QBO Change	EN	SLPA
QBO Direction	1.00			
QBO Change	.30	1.00		
EN	.10	.14	1.00	
SLPA	-.28	.01	.09	1.00
HUR. NO.	.51	.42	.49	-.34

b. Seasonal Number of Hurricanes and Tropical Storms

	QBO Direction	QBO Change	EN	SLPA
QBO Direction	1.00			
QBO Change	.30	1.00		
EN	.10	.14	1.00	
SLPA	-.28	.01	.09	1.00
HUR. AND TROP. STORM NO.	.63	.23	.39	-.50

c. Seasonal Number of Hurricane Days

	QBO Direction	QBO Change	EN	SLPA
QBO Direction	1.00			
QBO Change	.30	1.00		
EN	.10	.14	1.00	
SLPA	-.28	.01	.09	1.00
HUR. DAYS	.52	.36	.33	-.20

direction, and EN and QBO change correlate at only .10 and .14 respectively. SLPA and QBO change have only a .01 correlation. SLPA and QBO direction, however, correlate at -.28. These low internal correlations of predictors allow for a significant forecast improvement when all four predictors are used in combination.

Table 7 gives the Wilcoxon two sample rank test of the probablities (or P values) of the null hypothesis that no relationships exist between these four predictors and seasonal hurricane activity. P-values are observed to be quite low except for QBO wind change and hurricane and tropical storms, and for SLPA and hurricane days. The P-values (of the null hypothesis) using the 4 predictors in combination is, of course very much lower. The level of confidence that a relationship exists between these combined predictors and hurricane activity is higher than 99.9 percent for hurricanes and hurricanes and tropical storm activity, and about 99.5 percent for hurricane days.

TABLE 7

Probability (or P value) of the null hypothesis that no relationship exists between each of the four predictors and seasonal hurricane activity. The null hypothesis for the combination of parameters is also given on the bottom line.

	No. of Hurricanes	No. of Hur. and Tropical Storms	No. of Hur. Days
QBO Direction	.0312	.0007	.0192
QBO Change	.0478	.7287	.1987
EN	.0013	.0028	.0833
SLPA(April-May)	.0271	.0021	.4738
Combination of 4 Predictors	.000	.000	.006

The sum of the four parameter predictors of Table 5 is correlated with seasonal number of hurricanes, number of hurricanes and tropical storms, and hurricane days at levels of .77, .81, and .63 respectively, or a consequent explanation of hurricane activity variance of 59, 65 and 40 percent. This is a surprisingly high amount of seasonal hurricane activity variance to be explained as early as 1 June of each hurricane season.

This information will now be used to develop predictive equations for the seasonal number of hurricanes, number of hurricanes and tropical storms, and seasonal number of hurricane days.

4. The Rationale for Developing an Atlantic Seasonal Hurricane Activity Forecast

A forecast scheme using the previously discussed QBO, EN, and SLPA information would be based on the premise that:

1) the phases of the QBO of zonal wind which have such a long period (~ 26 months) and change in such a uniform manner will be known and can be extrapolated for 3 to 5 months into the future.

2) the oceanography community will be able to detect an EL Nino year by June 1 or August 1 at the latest and notify hurricane forecasters of such an event. Alternately, in ambiguous situations, the Caribbean Basin pre-season 200 mb zonal wind speed can be monitored. If Caribbean Basin monthly average zonal wind speeds are much stronger than normal at a number of stations by 3 m/s or so, it can be assumed that an El Nino or a similar influence event is occurring.

3) information on the Caribbean Basin monthly average SLPA for the four pre-hurricane months of April to July would be readily available to the forecaster at the end of each month.

Of the above three data requirements, knowledge of the onset of an El Nino event is likely the most uncertain.

Figure 9 shows the average distribution of hurricane and tropical storm activity by calendar date. 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.

Recent information of Rasmusson and Carpenter (1982) on the most recent El Nino events prior to 1982 indicates that a pre-hurricane season detection of a typical El Nino event starting around the first of the year should be able to be made by early June. The unusually strong and unusually late starting El Nino of 1982 could also likely have been detected by 1 June. Figure 10 shows Eastern Tropical Pacific Sea Surface Temperature Anomaly (SSTA) for the months of April and May in

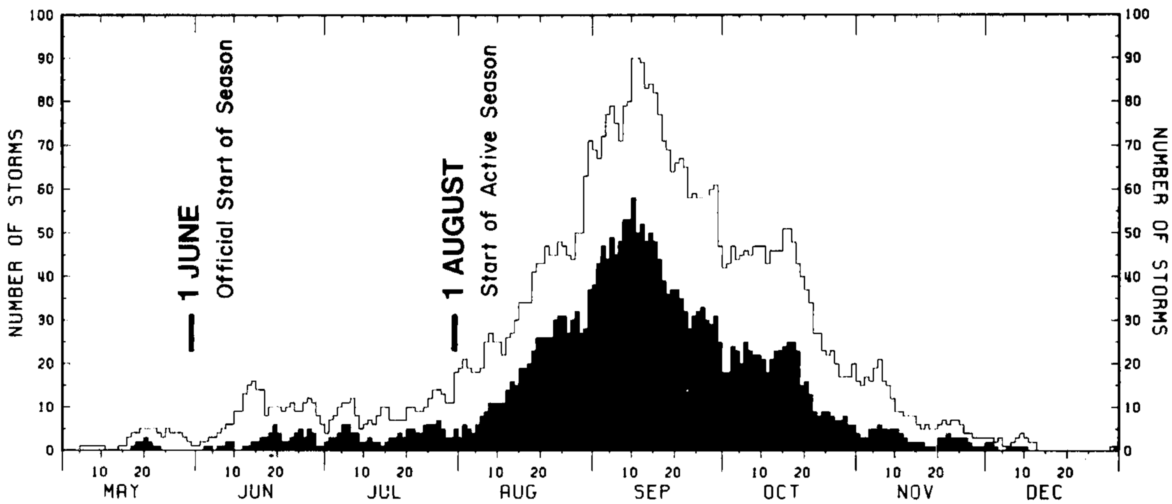
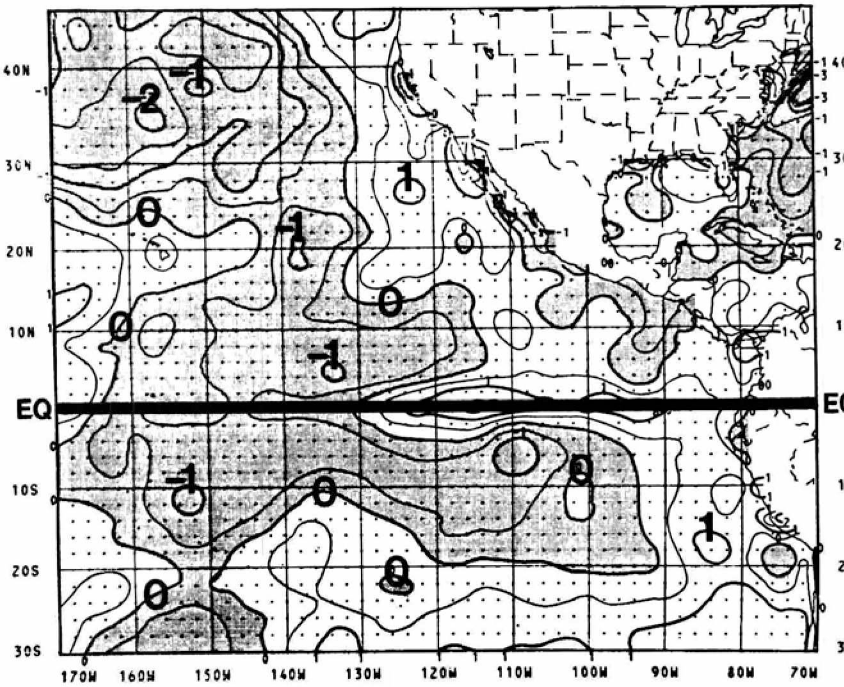


Fig. 9. Number of tropical storms and hurricanes (open curve) and hurricanes (solid curve) observed on each day, May 1-December 31, 1886 through 1980 (from Neumann, et al., 1981).

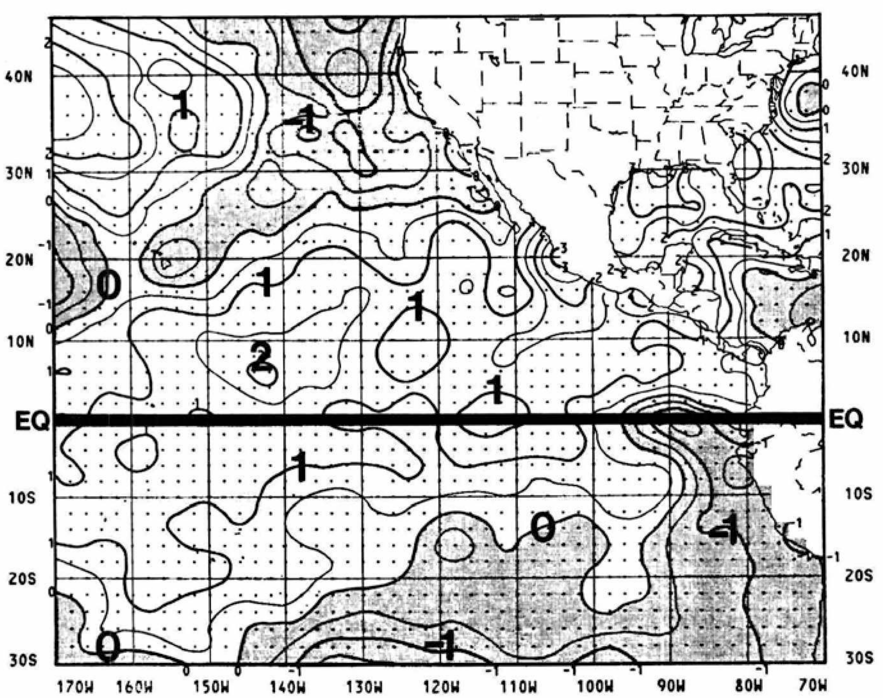
1981 and 1982. In comparison with April and May 1981, the months of April and May 1982 showed distinctly warmer SSTA at the typical places where warm SSTA occurs in El Nino years. If the 1982 El Nino event could not have been detected with confidence by early June, it almost surely should have been detected by early August even though it was an unusually late starting El Nino event.

Assuming such information on the QBO, El Nino, and pre-season SLPA will be available to the forecaster, an attempt has been made to develop a skillful seasonal hurricane activity forecast scheme. This forecast scheme is based solely on the 33 year data sample of 1950 through 1982 - the only period when QBO information is available.

Table 8 contains individual season information on the QBO, El Nino, and April-May SLPA together with the associated seasonal hurricane activity. This table shows that the most active hurricane seasons are

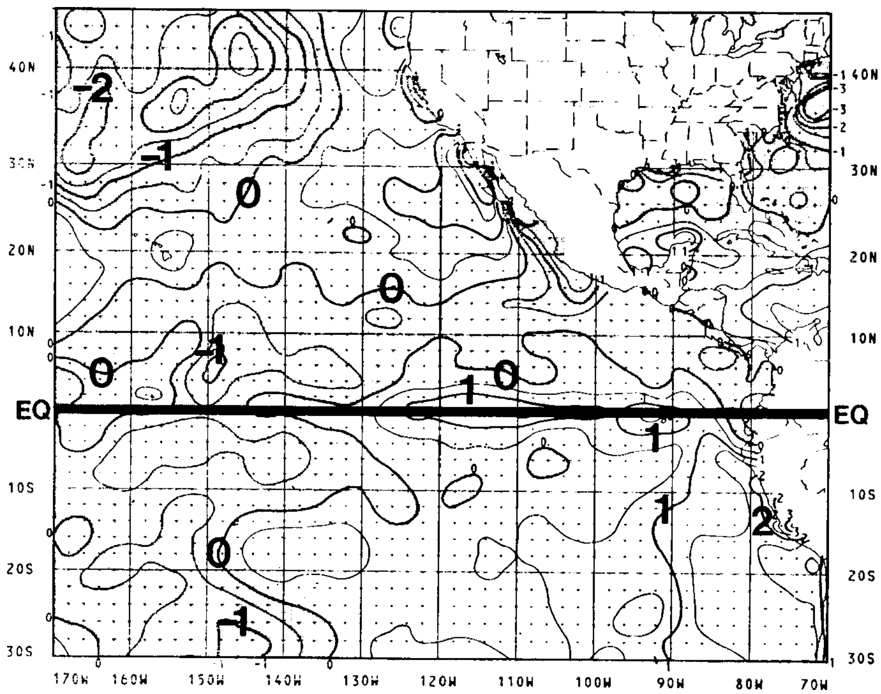


April 1981

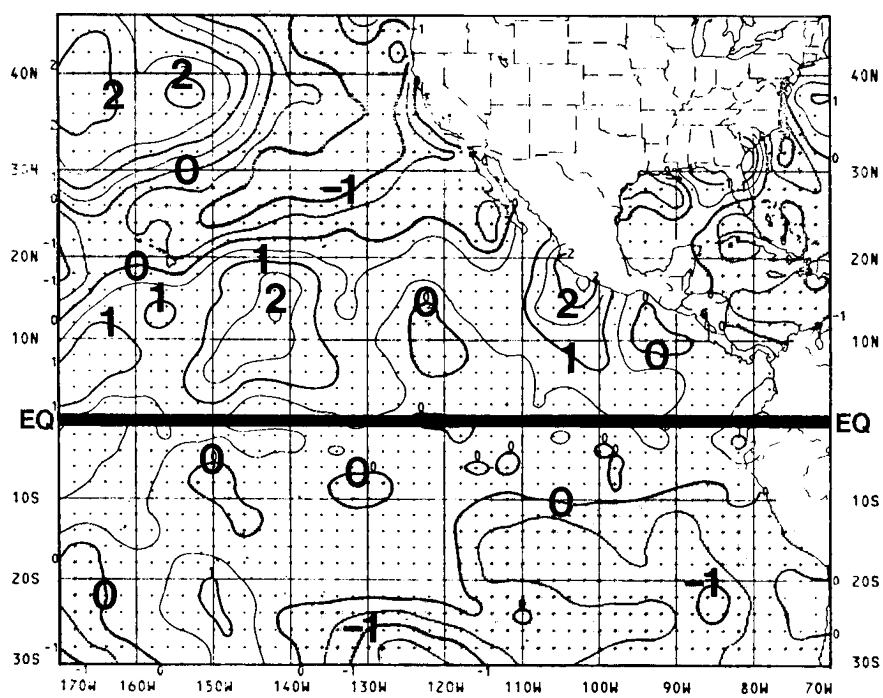


April 1982

Fig. 10a. SSTA (in ^{o}C) for months of April 1981 in comparison with April of 1982. Isolines are drawn every 0.5^{o}C. Shaded values indicate negative values of SSTA. (From NOAA Oceanographic Monthly Summary Reports of 1981, 1982).



May 1981



May 1982

Fig. 10b. SSTA (in ^{o}C) for months of May 1981 in comparison with May of 1982. Isolines are drawn every $0.5^{o}C$. Shaded values indicate negative values of SSTA. (From NOAA Oceanographic Monthly Summary Reports of 1981, 1982).

TABLE 8

West Atlantic Seasonal Tropical Cyclone Activity for the period 1950-1982 with the associated 30 mb wind direction, direction changes, El Nino (EN) years, and April-May Caribbean Basin SLPA. Also shown are seasonal numbers of hurricanes, seasonal number of hurricanes and tropical cyclones, and seasonal number of hurricane days.

Year	Hurri- canes	Hurri- canes and Tropical Storms	Hurri- icane Days	30 mb Wind	30mb Wind Increase	6-station April-May SLPA (mb)
1950	11	13	57	W	W increase	-.43
1951	08	10	37	W	E increase	-1.18
1952	06	07	23	E	W increase	.07
1953EN	06	14	18	W	E increase	-2.06
1954	08	11	33	E	no change	-.06
1955	09	12	46	W	W increase	-.51
1956	04	08	12	E	E increase	.15
1957EN	03	08	20	W	no change	-.01
1958	07	10	33	E	E increase	-1.35
1959	07	11	22	W	W increase	.57
1960	04	07	18	E	no change	-.36
1961	08	11	46	W	W increase	.82
1962	03	05	10	E	E increase	1.40
1963	07	09	36	-	W increase	.82
1964	06	12	43	W	E increase	.64
1965EN	04	04	27	E	E increase	.37
1966	07	11	41	W	W increase	.05
1967	06	08	35	-	E increase	.65
1968	04	07	09	E	E increase	.67
1969	10	14	39	W	W increase	-1.00
1970	05	10	07	E	E increase	.28
1971	06	13	28	W	W increase	.07
1972EN	03	04	06	E	E increase	.27
1973	04	07	09	W	E increase	.15
1974	04	07	16	E	E increase	.52
1975	06	08	18	W	W increase	-.25
1976EN	06	08	24	-	E increase	.54
1977	05	06	06	E	W increase	1.14
1978	05	11	13	W	E increase	-.66
1979	05	08	23	E	W increase	-.41
1980	09	11	38	W	W increase	-.41
1981	07	12	23	E	E increase	-.28
1982EN	02	05	05	E	W increase	-.26
Ave.	5.9	9.2	24.9			

usually those in which an El Nino event does not occur, 30 mb equatorial winds are from a westerly direction and are increasing in westerly direction, and/or the April-May Caribbean Basin SLPA is negative. Seasons with fewest hurricanes are either El Nino years, seasons in which 30 mb equatorial winds were from the east and/or were increasing in easterly direction, and/or April-May SLPA was positive.

Other Parameters Related to Seasonal Hurricane Activity. As discussed in Paper I, other monthly pre-hurricane season meteorological parameters such as rainfall, temperature, upper level heights, etc. do not appear to contain a predictive signal. Despite extensive analysis we have also not been able to detect any pre-hurricane season Caribbean Basin wind pattern features which have a predictive signal that is at all comparable to either the QBO, EN and SLPA predictive signals. For these reasons the seasonal hurricane forecast proposed in the next section will rely solely on information of the QBO, EN and SLPA.

5. Seasonal Hurricane Activity Forecasts

The following seasonal hurricane activity forecast equations have been developed from the information of Paper I and the previous chapters. These equations predict the number of hurricanes per year, the number of hurricanes and tropical storms per year, and the number of hurricane days per year from QBO, EN and April-May SLPA information available on 1 June.

a. Number of Hurricanes

Equation (1) gives a simple formula to predict the seasonal number of hurricanes

$$\begin{pmatrix}\text{Predicted No.}\\ \text{of Hurricanes}\\ \text{per season}\end{pmatrix} = 6 + (QBO_1 + QBO_2) + EN + SLPA \qquad (1)$$

where

QBO_1 = 30 mb equatorial wind direction correction factor – if westerly add <u>one</u>, if easterly subtract <u>one</u>. Set to zero if zonal wind direction during the season is in a change over phase from east to west or west to east.

QBO_2 = correction factor for change in 30 mb equatorial zonal winds (u) during the hurricane season – if uniformally increasing westerly (positive $\partial u/\partial t$) then add <u>one</u>, if uniformally decreasing westerly (negative $\partial u/\partial t$) then subtract <u>one</u>. Set to zero if there is a change of sign of $\partial u/\partial t$ during the season. The total QBO correction represents the sum of QBO_1 and QBO_2 and varies between $\pm$ 2.

EN = El Nino influence. If present subtract two <u>for</u> a moderate El Nino event, <u>four</u> for a strong El Nino event, otherwise set to zero.

SLPA = average SLPA for April-May, from the six-Caribbean Basin stations shown in Fig. 6. Add <u>one</u> or <u>two</u> if SLPA is $<$ –0.4 mb or $<$ –0.8 mb respectively. Subtract <u>one</u> or <u>two</u> if SLPA is 0.4–0.8 mb or $>$ 0.8 mb respectively. Make no correction for SLPA between –0.4 and 0.4 mb. Do not accept any pressure correction greater or less than $\pm$ 2.

Special Correction. If Eq. (1) should indicate a value less than three during an El Nino year, then disregard and make a seasonal forecast for at least three hurricanes. If Eq. 1 indicates a value less than four for a non-El Nino year, then disregard and make the forecast for four hurricanes.

Table 9 lists each of the correction terms of Eq. (1) by year and gives predicted vs. observed number of hurricanes per season for each year for the 33 year period of 1950-1982.

b. Number of Hurricanes and Tropical Storms

Equation (2), similar to Eq. 1 gives the formula for the prediction of the number of hurricanes and tropical storms

$$\begin{pmatrix}\text{Predicted No. of} \\ \text{Hurricanes and} \\ \text{Tropical Storms} \\ \text{per season}\end{pmatrix} = 9 + QBO + EN + SLPA \qquad (2)$$

where

QBO = 30 mb equatorial wind direction correction factor – if westerly add 1.5, if easterly subtract 1.5. In El Nino years add 2 for west winds and subtract 2 for east winds. Set to zero if zonal wind direction is in change over phase from east to west or west to east during the season. Make no correction for the change in QBO wind speed during the season.

EN = El Nino influence. If present subtract two for a moderate El Nino event, four for a strong El Nino event, otherwise add 0.7.

SLPA = average SLPA for April-May, from the six-Caribbean Basin stations shown in Fig. 6. Add one or two if SLPA is < -0.4 mb or < -0.8 mb respectively. Subtract one or two if SLPA is 0.4-0.8 mb or $>$ 0.8 mb respectively. Make no correction for SLPA between -0.4 and 0.4 mb. Do not accept any pressure correction greater or less than $\pm$ 2.

Special Correction. If Eq. 2 gives a value less than five in a non-El Nino year then disregard and make a prediction of 5. Accept no value less than 4 in an El Nino year.

TABLE 9

Predicted number of hurricanes per year from QBO, EN and April-May SLPA correction factors vs. observed number of hurricanes per year.

Year	QBO Correct.	EN Correct.	April-May SLPA Correct.	Total QBO+EN SLPA Correct.*	Predicted No. of Hurr. Eq. 1	Observed No. of Hurr.	Predicted Minus Observed
1950	+2	0	+2	+4	10	11	-1
1951	0	0	+2	+2	8	8	0
1952	0	0	0	0	6	6	0
1953EN	0	-2	+2	-2	6	6	0
1954	-1	0	+1	+1	5	8	-3
1955	+2	0	+1	+2	9	9	0
1956	-2	0	0	-2	4	4	0
1957EN	+1	-4	0	-3	3	3	0
1958	-2	0	+2	-1	6	7	-1
1959	+2	0	-1	+1	7	7	0
1960	-1	0	0	0	5	4	1
1961	+2	0	-2	0	6	8	-2
1962	-2	0	-2	-4(-2)	4	3	1
1963	+1	0	-2	-1	5	7	-2
1964	0	0	-1	-1	5	6	-1
1965EN	-2	-2	0	-4(-3)	3	4	-1
1966	+2	0	0	+2	8	7	1
1967	-1	0	-1	-2	4	6	-2
1968	-2	0	-1	-3	4	4	0
1969	+2	0	+2	+4	10	10	0
1970	-2	0	0	-2	4	5	-1
1971	+2	0	0	+2	8	6	2
1972EN	-2	-4	0	-6(-3)	3	3	0
1973	0	0	0	0	6	4	2
1974	-2	0	-1	-3	4	4	0
1975	+2	0	0	+2	8	6	2
1976EN	-1	-2	-1	-4(-3)	3	6	-3
1977	0	0	-2	0	4	5	-1
1978	0	0	+1	+1	7	5	2
1979	0	0	+1	0	7	5	2
1980	+2	0	+1	+3	9	9	0
1981	-2	0	0	0	4	7	-3
1982EN	0	-4	0	-4(-3)	3	2	1

*Correction factor must never be less than -2 in a non-El Nino year or less than -3 in an El Nino year. Applicable correction factors in parentheses.

TABLE 10

Predicted number of hurricanes and tropical storms per year from QBO, EN and April-May SLPA correctional factors vs. observed number of hurricanes and tropical storms per year.

Year	QBO Correc.	EN Correc.	April-May SLPA Correc.	Total QBO+ EN+ SLPA Correc.	Round Off of Total Correc.*	Predicted No. of Hurr. and Trop.St.	Obs. No. of Hurr. and Trop.St.	Predicted Minus Obs.
1950	1.5	.7	+2	4.2	+4	13	13	0
1951	1.5	.7	+2	4.2	+2	11	10	+1
1952	-2.0	.7	0	-1.3	-1	8	7	+1
1953EN	1.5	-2	+2	1.5	-2	11	14	-3
1954	1.5	.7	+1	3.2	+3	12	11	1
1955	1.5	.7	+1	3.2	+3	12	12	0
1956	-1.5	.7	0	-.8	-1	8	8	0
1957EN	2.0	-4	0	-2.0	-2	7	8	-1
1958	-1.5	.7	+2	1.2	1	10	10	0
1959	1.5	.7	-1	1.2	+1	10	11	-1
1960	-1.5	.7	0	-0.8	-1	8	7	+1
1961	1.5	.7	-2	0.2	0	9	11	-2
1962	-1.5	.7	-2	-2.8	-3	6	5	+1
1963	0	.7	-2	-1.3	-1	8	9	-1
1964	1.5	.7	-1	1.2	+1	10	12	-2
1965EN	-2.0	-2	0	-4.0	-4	5	4	+1
1966	1.5	.7	0	2.2	+2	11	11	0
1967	0	.7	-1	0.3	0	9	8	1
1968	-1.5	.7	-1	-1.8	-2	7	7	0
1969	1.5	.7	+2	+4.2	+4	13	14	-1
1970	-1.5	.7	0	-0.8	-1	8	10	-2
1971	1.5	.7	0	2.2	+2	11	13	-2
1972EN	-2.0	-4	0	-6.0	-6(-5)	4	4	0
1973	1.5	.7	0	2.2	+2	11	7	+4
1974	-1.5	.7	-1	-1.8	-2	7	7	0
1975	1.5	.7	0	2.2	+2	11	8	+3
1976EN	0	-2	-1	-3.0	-3	6	8	-2
1977	-1.5	.7	-2	-2.8	-3	6	6	0
1978	1.5	.7	+1	3.2	+3	12	11	1
1979	-1.5	.7	+1	.2	0	9	8	1
1980	1.5	.7	+1	3.2	+3	12	11	1
1981	-1.5	.7	0	-0.8	-1	8	12	-4
1982EN	-2.0	-4	0	-6.0	-6(-5)	4	5	-1

*Correction factor must not be less than -4 in a non-El Nino year or less than -5 in an El Nino year. Applicable correction factors in parentheses.

Table 10 is similar to Table 9. It lists the correction terms of Eq. (2) by year and gives predicted vs. observed number of hurricanes and tropical storms per season in each of the last 33 years.

c. Number of Hurricane Days

Equation (3) gives a prediction of the number of hurricane days per season,

$$\begin{pmatrix}\text{Predicted No. of} \\ \text{Hurricane Days} \\ \text{per season}\end{pmatrix} = 25 + (QBO_1 + QBO_2) + EN + SLPA \qquad (3)$$

where the meaning of the symbols are similar to Eq. 1 but each unit of correction factor will be multiplied by 5 instead of 1 as with the two previous determinations, thus

QBO_1 = QBO correction factor due to 30 mb wind direction - if westerly add two, if easterly subtract two. Set to zero if wind direction is in a change over phase from east to west or west to east during the season.

QBO_2 = QBO correction factor due to uniform change in 30 mb zonal wind (u) speed during the hurricane season - if increasing westerly (positive $\partial u/\partial t$) then add one, if decreasing westerly (negative $\partial u/\partial t$) then subtract one. Set to zero if there is a change of sign of $\partial u/\partial t$ during the season.

EN = El Nino correction factor. If El Nino year then subtract two for moderate El Nino or four for a strong El Nino. Add one in all non-El Nino years.

SLPA = April-May Sea Level correction factor. Add 2, 1, 0, or -1, -2 depending upon whether the 6-station Caribbean Basin SLPA is $<$ -0.8 mb, between -0.4 to -0.8 mb, -0.4 to 0.4 mb, or $>$ 0.4 mb, $>$ 0.8 mb respectively.

Special Correction. If correction factor is 3 or greater subtract one, if less than -3, then set equal to -3.

Table 11 lists the correction terms of Eq. (3) by year and gives predicted vs. observed number of hurricane days for 1950-1982.

TABLE 11

Predicted number of hurricane days per season from QBO, EN and April-May SLPA correction values vs. observed number of hurricane days per year.

Year	QBO Correc. Factor	EN Correc. Factor	April-May SLPA Correc. Factor 6 Station	Total QBO+EN +SLPA Correc. Factor*	Total Correc. x 5	Predicted No. of Hurr. Days	Observed No. of Hurr. Days	Predicted Minus Observed
1950	3	1	+2	6(5)	25	50	57	-7
1951	1	1	+2	4(3)	20	40	37	3
1952	-1	1	0	0	0	25	23	2
EN1953	1	-2	+2	0	+1	30	18	12
1954	-2	1	+1	0	0	25	33	-8
1955	3	1	+1	5(4)	20	45	46	-7
1956	-3	1	0	-2	-10	15	12	3
1957EN	3	-4	0	-1	-5	20	20	0
1958	-3	1	+2	0	0	25	33	-8
1959	3	1	-1	3(2)	10	35	22	13
1960	-1	1	0	0	0	25	18	7
1961	+2	1	-2	1	+5	30	46	-16
1962	-3	1	-2	-4	-15	10	10	0
1963	1	1	-2	0	0	25	36	-11
1964	1	1	-1	1	5	30	43	-13
1965EN	-3	-2	0	-5(-3)	-15	10	27	-17
1966	3	1	0	4(3)	15	40	41	-1
1967	-1	1	-1	-1	-5	20	35	-15
1968	-3	1	-1	-3	-15	10	9	1
1969	3	1	+2	6(5)	25	50	39	11
1970	-3	1	0	-2	-10	15	7	8
1971	3	1	0	4(3)	15	40	28	12
1972EN	-3	-4	0	-7(-3)	-15	10	6	4
1973	1	1	0	2	10	15	9	6
1974	-3	1	-1	-3	-15	10	16	-6
1975	3	1	0	4(3)	15	40	18	22
1976EN	-1	-2	-1	-4(-3)	-15	10	24	-14
1977	-1	1	-2	-2	-10	15	6	9
1978	1	1	+1	3(2)	10	35	13	22
1979	-1	1	1	1	5	30	23	7
1980	3	1	+1	5(4)	20	45	38	7
1981	-3	1	0	-2	-10	15	23	-8
1982EN	-1	-4	0	-5(-3)	-15	10	5	5

*Total negative correction factor should not be more than -3. Subtract 1 from all correction factors greater than 3. Applicable correction factors in parentheses.

6. Forecast Verification

The right hand column of Tables 9-11 give the predicted minus observed season number of hurricanes, hurricanes and tropical storms, and hurricane days for this 33 year forecast period. The predicted to observed number of hurricanes was within ± 2 in all years but three when the errors were 3. Predicted number of hurricanes and tropical storms was in error by more than ± 2 in 4 of 33 years when errors were 3(2 years) and 4(2 years). Errors in predicted to observed number of hurricane days exceeded ± 15 days in 4 seasons.

Figure 11 shows a plot of predicted vs. observed number of hurricanes per season. The correlation is .77 or a 59% reduction in variance.

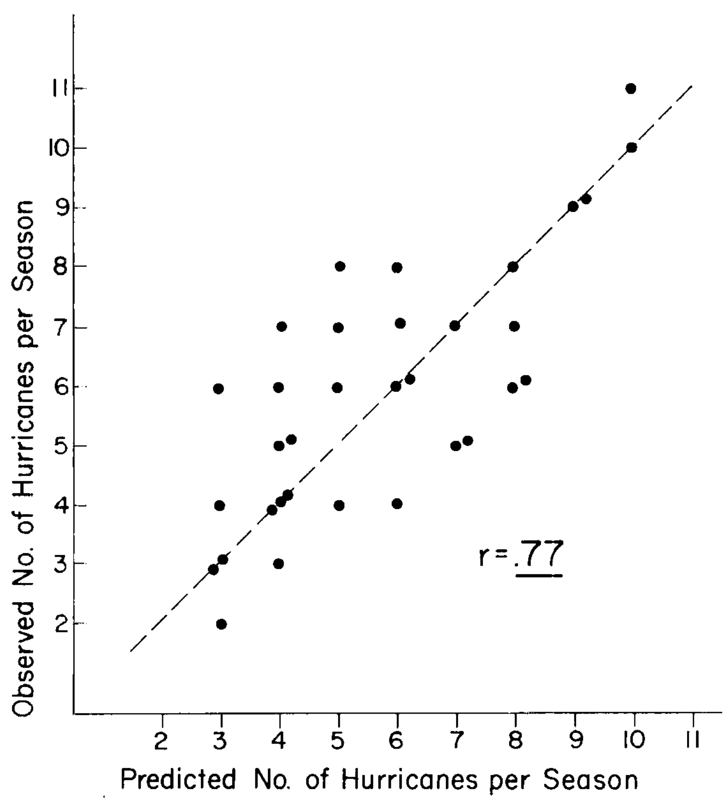


Fig. 11. Regression analysis of predicted vs. observed number of hurricanes per season for the period of 1950-1982 from the use of Eq. (1). The correlation coefficient is .77.

Figure 12 shows a plot of the predicted vs. observed number of hurricanes and tropical storms per season that one would have obtained by applying Eq. 2 during the past 33 year period. The correlation coefficient is .82 or an explanation of 67% of the inter-year variance.

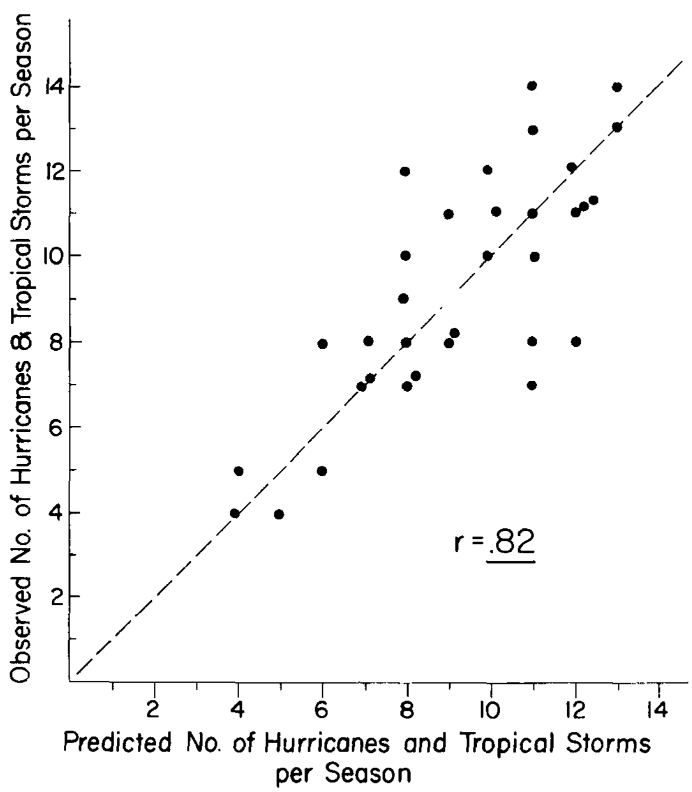


Fig. 12. Regression analysis of the predicted vs. observed number of hurricanes and tropical storms per season for the period of 1950-1982 from Eq. (2).

Figure 13 shows a plot of the predicted vs. observed number of hurricane days per season from the use of Eq. (3). The correlation of these points is .68 or an explanation of about 46% or nearly half of the seasonal variance.

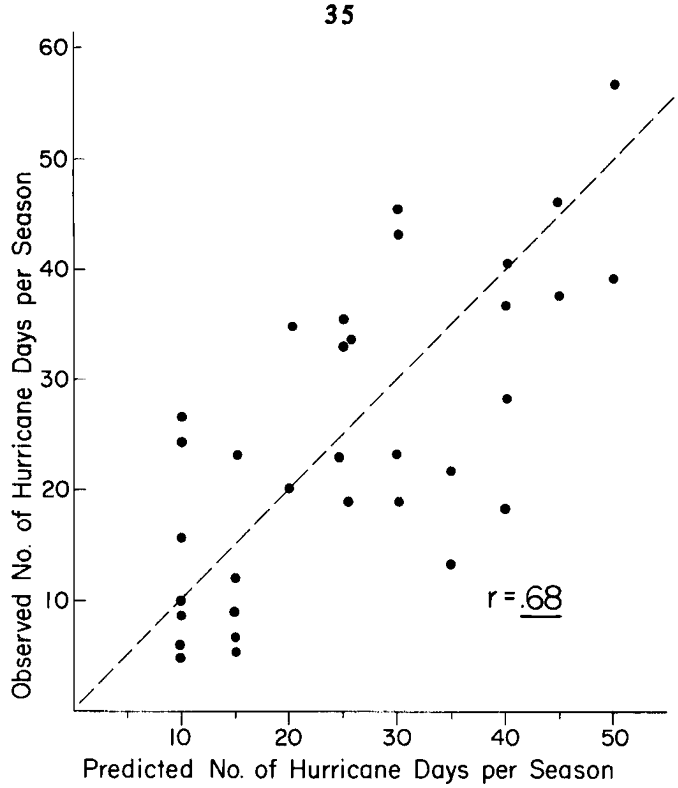


Fig. 13. Regression analysis of the predicted vs. observed number of hurricane days per season for the period of 1950-1982 from the use of Eq. (3).

Determining Skill of Forecasts. These forecasts might be further tested by determining their ability to predict seasonal number of hurricanes above normal (8 or more), normal (5-7) or below normal (4 or less) from the 1950-1982 average.

Of the 33 forecasts of seasonal hurricane number, 8 seasons were forecast to be above normal, 13 seasons were forecast to be below normal, and 12 forecasts predicted a normal number (or 5 to 7).

Of the 8 seasonal forecasts of above normal number of hurricanes 6 seasons were observed to be above normal and the other 2 observed to be normal. Of the 13 forecasts of below normal hurricane number, 8 were observed to be below normal and the other 5 years were normal. Of the 12 forecasts of normal hurricane activity 8 were normal, 2 above normal, and 2 below normal. In none of the 33 years were seasonal forecasts in error by two categories, that is an above normal forecast made when a below normal season was observed or vice-versa.

If one considers a forecast to be half in error (or only half correct) when above or below normal activity occurs when normal activity has been predicted or normal activity occurs when a forecast of above or below activity has been forecast,[1] then the skill score (Eq. 4) for the forecast (Panofsky and Brier, 1958) of seasonal above or below normal hurricane number would be

$$S = \frac{C-E}{T-E} \times 100 = \frac{25.5 - 16.5}{33 - 16.5} \times 100 = 67 \qquad (4)$$

where C = number of correct forecasts

T = number of forecasts made

E = expected number of correct forecasts taken to be half the number of forecasts made (i.e., there is no known method for such a seasonal forecast. By random chance one should be correct half of the time).

A contingency table of the distribution of all these above, normal, and below normal seasonal forecasts is given in Table 12.

The contingency tables of Tables 13 and 14 are similar to Table 12 but for the distribution of above, below, and normal forecasts vs. observations of number of hurricanes and tropical storms per season and number of hurricane days per season. Skill scores for these latter two prediction categories are 61 and 48 respectively.

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(1) For instance a forecast of normal hurricane activity in all years which were either above or below normal would result in a zero skill score despite the counting of each year as only half correct or half in error.

TABLE 12

Distribution of 33 forecasts of predicted vs. observed seasonal number of hurricanes by categories of above normal, normal and below normal.

PREDICTED \ OBSERVED	Above Normal (8 or more)	Normal (5-7)	Below Normal (4 or less)
Above Normal (8 or more)	6	2	0
Normal (5-7)	2	8	2
Below Normal (4 or less)	0	5	8

TABLE 13

Same as Table 12 but for above normal, normal and below normal predicted vs. observed number of hurricanes and tropical storms.

PREDICTED \ OBSERVED	Above Normal (11 or more)	Normal (8-10)	Below Normal (7 or less)
Above Normal (11 or more)	9	2	1
Normal (8-10)	5	5	2
Below Normal (7 or less)	0	2	7

TABLE 14

Same as Table 12 but for above normal, normal and below normal predicted vs. observed number of hurricane days per season.

		OBSERVED		
		Above Normal (more than 30)	Normal (20-30)	Below Normal (less than 20)
PREDICTED	Above Normal (more than 30)	6	2	2
	Normal (20-30)	6	3	2
	Below Normal (less than 20)	0	3	9

The years when this forecast scheme was in major error were those years in which below normal hurricane activity was predicted and above normal activity occurred or vice-versa. This type of forecast error was not made for any of the 33 forecasts of the number of hurricanes. It was made only once (1973 when 11 systems were forecast and only 7 were observed) for the forecast of the number of hurricanes and tropical storms. This type of error was made only twice (1975, 1978) in 33 years for the forecast of the number of hurricane days per season.

These various analyses of forecast verification show that Atlantic seasonal hurricane activity predictions can be made with a quite respectable degree of skill and also with quite a high and quite an unexpected degree of reliability.

Discussion. Fairness requires that the reader be reminded of two well established meteorological truths:

1) most forecast schemes work better on past than future data sets,

2) all forecast schemes break down in some years.

Nevertheless, the author recommends this forecast method for the following reasons:

1) no other very skillful and objective forecast schemes for seasonal hurricane activity are available

2) the reliability of the forecast scheme as indicated by the small number of prediction reversal errors of above and below normal activity appears to be good.

One of the strengths of this forecast scheme is that it is easy to apply. Phone calls can be made to the relevant U.S. agencies involved with the monitoring of the QBO and EL Nino events. Springtime SLPA anomalies can be readily calculated from 6-hourly sea-level pressure maps available in most major forecast offices or these meteorological offices could be directly called or procedures established whereby they wire in their station's end-of-month mean sea level pressure. Once this small amount of relevant information is assembled the seasonal forecast can be made in a few minutes and without any cost of computer resources.

Table 15 lists monthly mean sea level pressure information for the 6 key Caribbean Basin stations used for determining SLPA.

TABLE 15

Monthly mean sea level pressure (in mb) for the 6-key Caribbean Basin stations used to determine monthly SLPA. 10 has been dropped from the 1st two digits of each figure.

Station	May	April-May	June	June-July	July	August-September
Brownsville	12.2	12.5	12.8	13.6	14.4	13.6
Merida	11.7	11.9	12.2	13.3	14.3	12.4
Miami	15.9	16.7	16.2	16.9	17.6	15.5
San Juan	15.6	15.7	16.7	16.9	17.1	15.1
Curacao	11.6	11.8	12.3	12.5	12.7	11.3
Barbados	14.2	14.1	14.7	14.9	15.1	13.4

7. Summary and Discussion

The ability to predict with some degree of skill whether a coming Atlantic hurricane season is likely to be above or below normal has, to date, not been possible. The author knows of no objective forecast procedures except those based on pre-season sea-level pressure and/or sea surface temperature. The analysis of these parameters as seasonal forecast tools has been thoroughly explored by Shapiro (1982a, 1982b). Shapiro shows that these parameters either by themselves or in combination correlate with seasonal hurricane activity at about the 0.3 to 0.4 level. Such predictors explain only about 17% or less of the season to season hurricane variance.

What has previously been missing from forecast consideration has been the more reliable memory of the atmosphere as manifested by general circulation features such as the El Nino/Southern Oscillation and the Equatorial stratospheric QBO. These more global circulation features apparently have a longer and better memory than do the more local Atlantic basin predictive signals. It is time that forecasting research on this subject concentrate more on developing global rather than regional predictors. Much higher predictive skill is possible when one combines both global and regional predictors. This is particularly the case if the global and regional predictors are quasi-independent of each other.

Research will continue on improving this forecast scheme for the Atlantic. Another logical step, of course, is to investigate these relationships in the other tropical cyclone ocean basins. A preliminary assessment of the El Nino and QBO influences in these other ocean basins indicate that the seasonal predictive value of the QBO and EN signals are significantly less a factor than in the more marginal and less monsoon trough dominated regions of the west Atlantic-Caribbean Basin. This appears to be especially the case in the highly active western North Pacific tropical cyclone region which always has 15 or more typhoons in all years regardless of El Nino events or what phase the QBO cycle is in.

Although hurricane frequency may not be as greatly influenced in the other ocean basins as it is in the Atlantic by El Nino and QBO events, the location of hurricane activity in some of the other basins can be significantly shifted in El Nino years. For instance the number of tropical cyclones developing near the International Dateline is much enhanced in El Nino years as are the number of cyclones which track westward toward the Hawaiian islands. A follow up paper will discuss El Nino and QBO influences on tropical cyclones in the other ocean basins.

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15. Supplementary Notes

16. Abstracts This paper discusses seasonal hurricane frequency as related to El Nino events during 1900-1982 and to the equatorial Quasi-Biennial Oscillation (QBO) of stratospheric zonal wind from 1950-1982. It is shown that a substantial negative correlation is typically present between the seasonal number of hurricanes, hurricane days, and tropical storms and moderate or strong (15 cases) El Ninos off the South American west coast. A similar negative anomaly in hurricane activity occurs when 30 mb equatorial winds are from an easterly direction and/or are becoming more easterly with time during the hurricane season. The addition of springtime regional sea level pressure data from Caribbean Basin meteorological stations can be combined with this El Nino and QBO information to form a rather skillful forecast scheme for Atlantic seasonal hurricane activity. It appears possible to predict between half and two-thirds of the variance of Atlantic seasonal hurricane activity.

17. Key Words and Document Analysis. 17a. Descriptors

Seasonal hurricane prediction
Hurricane variability
El Nino
QBO of equatorial 30 mb winds

17b. Identifiers/Open-Ended Terms

17c. COSATI Field/Group

18. Availability Statement	19. Security Class (This Report) UNCLASSIFIED	21. No. of Pages 105
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FORECASTS OF WEST ATLANTIC SEASONAL HURRICANE ACTIVITY FOR 1983 AND 1984

(Based on background information contained in CSU Dept. of Atmospheric Science Report No. 370)

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(As of 15 July 1983)

Based on the information contained in the Colorado State University, Dept. of Atmospheric Science Report No. 370 titled "Atlantic Seasonal Hurricane Frequency" Parts I and II, the author offers predictions of seasonal hurricane activity for the coming 1983 and 1984 seasons. Although the confidence in the 1984 seasonal prediction is lower than that of the 1983 season forecast, it is based on objective criteria. Forecasts are believed to contain skill above that of climatology, the only other objective estimate now available.

Equations (1) through (3) - pages 27, 28 and 31 of Paper II of CSU Report No. 370 give the required 30 mb QBO of zonal wind, El Nino, and Sea Level Pressure Anomaly (SLPA) information needed for these predictions.

1. QBO Influence. Table 1 contains information on the observed equatorial 30 mb stratospheric zonal winds at Singapore; Balboa, C.Z., and Ascension Island through June of this year. A general change over of these wind patterns from westerly to easterly occurred between May and June of this year. The best estimates as to the extrapolated wind patterns for the months of July through October 1983 are also given in this table. Note that in the hurricane season months of August through October 1983 30 mb equatorial stratospheric easterly winds are expected to prevail and that these easterly winds should be increasing with time during the hurricane season. If other factors remained constant this should lead to a suppression of 1983 hurricane activity by two hurricanes, two hurricanes and tropical storms and 10 hurricane days (see discussion page 27 of Paper II in report 370).

TABLE 1

RECENT 30 MB ZONAL WINDS AND EXTRAPOLATED VALUES
FOR AUGUST TO OCTOBER 1983
(IN M/S)

MONTH 1983	SINGAPORE 1-1/2°N	BALBOA, C.Z. 9°N	ASCENSION 8°S	
JANUARY	14	12	-2	W
FEBRUARY	12	14	+3	↓
MARCH	13	-1	-1	
APRIL	13	+8	+1	
MAY	12	-3	-1	CHANGE OVER
JUNE	-7	-15	-11	
JULY	-15	-20	-15	E
AUGUST	-20	-25	-20	↓
SEPTEMBER	-25	-30	-25	
OCTOBER	-30	-30	-30	

EXTRAPOLATED

Figure 1 shows a vertical cross-section of stratospheric zonal winds during the last three hurricane seasons and an extrapolation of these zonal winds through the 1983 and 1984 hurricane seasons based on information through June of this year. Although August to October 1983 should be a season of 30 mb easterly winds and increasing easterly winds, August to October 1984 should be a season of 30 mb westerly winds and increasing westerly winds. For reasons discussed in Report 370 these types of 30 mb zonal wind changes should act (other factors remaining constant) to suppress hurricane activity in 1983 but enhance it in 1984.

El Nino Influences. Some residual influences from the very strong and late occurring El Nino of 1982 appears to be persisting into

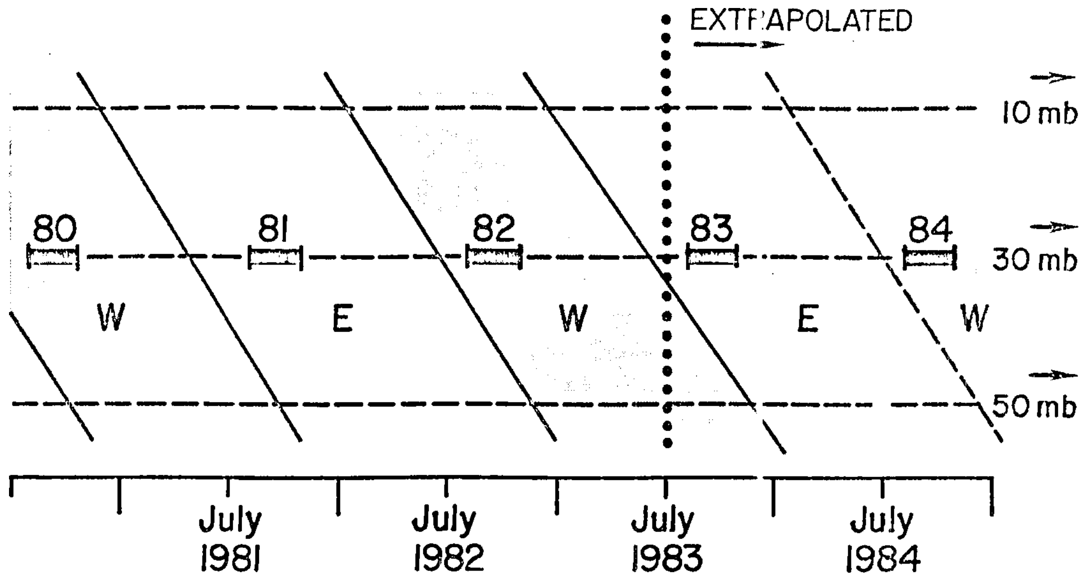

Fig. 1. Vertical cross-section of 30 mb equatorial zonal winds for the period of 1980 through 1984. Information beyond July 1983 has been extrapolated. West wind (W) periods are shaded. Easterly winds are denoted by E. The August through October periods of each hurricane season are denoted by the thick line of the 30 mb level.

mid-1983. As of the end of June warm SST was still present off the South American west coast and stronger than normal 200 mb westerly winds existed over the equatorial west Atlantic. Although these East Pacific SST and Atlantic 200 mb westerly wind patterns are unfavorable for hurricane activity, their influence is waning with time. El Nino influences are not expected to persist for very long into the August-October period. Nevertheless, some residual El Nino inhibition of the normal 1983 Atlantic hurricane season frequency should likely be expected to the extent of one less hurricane, one less hurricane and tropical cyclone, and five less hurricane days.

The effects of the 1982-83 El Nino should be completely gone by the 1984 season and since the typical period between significant El Nino events is 4-6 years or more, another El Nino should not be anticipated until the period of 1986 to 1988 or so. The 1984 hurricane season should thus not be encumbered by the inhibiting influence of an El Nino.

Sea Level Pressure Anomaly (SLPA). Table 2 gives information on April-May, and June 1983 SLPA in mb. Note that the average of all 6 key Caribbean Basin station SLPA values are more than 1 mb below average. Such negative springtime SLPA (other factors remaining constant) indicates a higher than normal level of hurricane activity by two hurricanes, two hurricanes and tropical storms, and 10 hurricane days (see page 14 of Part II of Report 370).

TABLE 2

PRE-1983 HURRICANE SEASON
SEA LEVEL PRESSURE ANOMALY (SLPA) - IN MB
(FROM DATA SUPPLIED BY C. NEUMANN AND A. PIKE OF NHC)

	APRIL-MAY	JUNE
BROWNSVILLE	-1.8	-1.7
MERIDA	-1.7	-2.1
MIAMI	-1.1	-1.3
SAN JUAN	-1.4	-1.3
CURACAO	-1.3	-0.8
BARBADOS	-0.9	-0.3
MEAN	-1.37	-1.25

Table 3 gives numerical values for each term of the 3 seasonal hurricane activity prediction equations (1-3 of Part II, Report No. 370) for the 1983 season. Number of hurricanes, number of hurricanes and tropical storms, and number of hurricane days are forecast to be 5

TABLE 3

1983 PREDICTED SEASONAL HURRICANE ACTIVITY

$$\begin{pmatrix}\text{PREDICTED NO.}\\ \text{OF HURRICANES}\\ \text{PER SEASON}\end{pmatrix} = 6 + (QBO_1 + QBO_2) + EN + SLPA$$
$$= 6 + (-1) + (-1) + (-1) + (+2) = \boxed{5}, \begin{pmatrix}\text{1 Below}\\ \text{Normal}\end{pmatrix}$$

$$\begin{pmatrix}\text{PREDICTED NO. OF}\\ \text{HURRICANES AND}\\ \text{TROPICAL STORMS}\\ \text{PER SEASON}\end{pmatrix} = 9 + QBO + EN + SLPA$$
$$= 9 + (-2) + (-1) + (+2) = \boxed{8}, \left(\text{1 Below Normal}\right)$$

$$\begin{pmatrix}\text{PREDICTED NO. OF}\\ \text{HURRICANE DAYS}\\ \text{PER SEASON}\end{pmatrix} = 25 + (QBO_1 + QBO_2) + EN + SLPA$$
$$= 25 + (-10) + (-5) + (-5) + (+10) = \boxed{15}, \begin{pmatrix}\text{10 Below}\\ \text{Normal}\end{pmatrix}$$

(1 below normal), 8 (1 below normal), and 15 (10 below normal) respectively. The 1983 hurricane season is thus predicted to be a season of slightly below normal hurricane activity.

A similar prediction for 1984 without the springtime surface pressure information is given in Table 4. Prediction equations indicate values of 8 (2 above normal), 11 (2 above normal) and 40 (15 above normal) for the 1984 seasonal number of hurricanes, number of hurricanes and tropical storms, and number of hurricane days.

Figure 2 shows that 1983 is one of 5 of the last 33 years when April-May SLPA was below 1.0 mb. In all of the four previous years when SLPA was less than -1.0 mb, the following year's April-May SLPA was positive or near zero. It appears that when April-May SLPA is much

TABLE 4

1984 PREDICTED SEASONAL HURRICANE ACTIVITY

$$\begin{pmatrix}\text{PREDICTED NO.}\\ \text{OF HURRICANES}\\ \text{PER SEASON}\end{pmatrix} = 6 + (QBO_1 + QBO_2) + EN + SLPA$$

$$= \quad +1 \quad +1 \quad +0 \quad +\ ? \qquad = \boxed{8} \pm (0\text{-}2)$$

Depending on April-May '84 SLPA

$$\begin{pmatrix}\text{PREDICTED NO. OF}\\ \text{HURRICANES AND}\\ \text{TROPICAL STORMS}\\ \text{PER SEASON}\end{pmatrix} = 9 + QBO + EN + SLPA$$

$$= \quad +1.5 \quad +0.7 \quad +\ ? \qquad = \boxed{11} \pm (0\text{-}2)$$

Depending on April-May '84 SLPA

$$\begin{pmatrix}\text{PREDICTED NO. OF}\\ \text{HURRICANE DAYS}\\ \text{PER SEASON}\end{pmatrix} = 25 + (QBO_1 + QBO_2) + EN + SLPA$$

$$+10 \quad +5 \quad +0 \quad +\ ? \qquad = \boxed{40} \pm (0\text{-}10)$$

Depending on April-May '84 SLPA

below normal in one year it returns to a more normal pressure value the next year. If this general observation is to repeat itself in the period from 1983 to 1984, then we might expect 1984's April-May SLPA to be in the normal range of ± 0.4 mb when no correction for SLPA is made. If this assumption is made then the 1984 hurricane activity is forecast to be as in Table 4 with no pressure correction. 1984 will thus be an above normal hurricane activity year.

Table 5 gives a summary of these 1983 and 1984 forecasts.

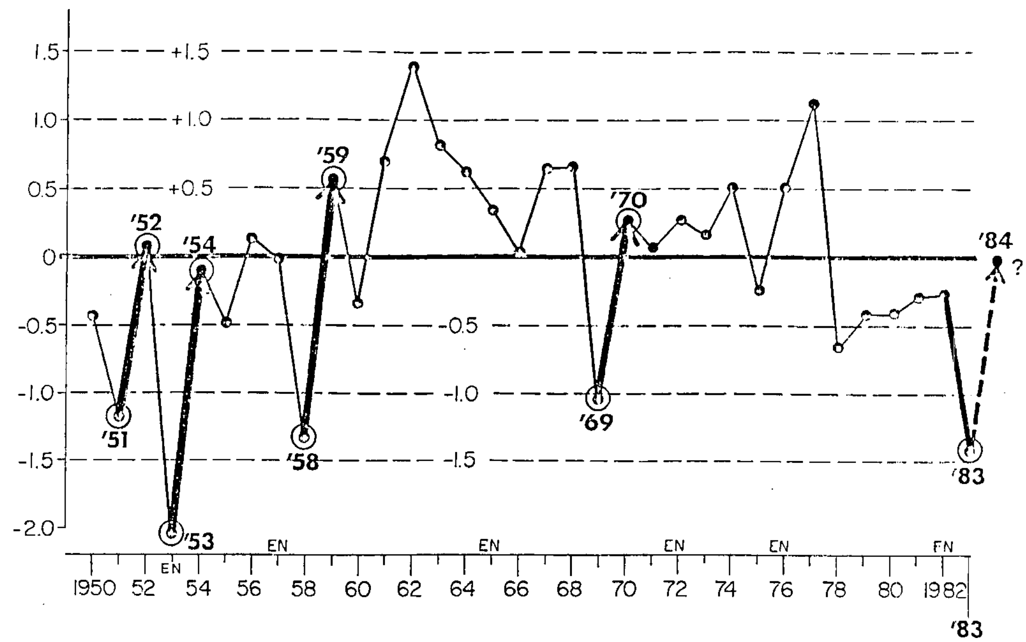

Fig. 2. Yearly variation of April-May mean Caribbean Basin SLPA for 6 standard stations.

TABLE 5

SUMMARY

SEASONAL FORECASTS FOR 1983 AND 1984

	1983	1984
NUMBER OF HURRICANES	5	8
NUMBER OF HURRICANES AND TROPICAL STORMS	8	11
NUMBER OF HURRICANE DAYS	15	40

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