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Atlantic Seasonal Hurricane Frequency. Part I: El Niño and 30 mb Quasi-Biennial Oscillation Influences

WILLIAM M. GRAY

Department of Atmospheric Science, Colorado State University, Fort Collins, CO 80523

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ABSTRACT

This is the first of two papers on Atlantic seasonal hurricane frequency. In this paper, seasonal hurricane frequency as related to El Niño events during 1900–82 and to the equatorial Quasi-Biennial Oscillation (QBO) of stratospheric zonal wind from 1950 to 1982 is discussed. 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 Niños off the South American west coast. A similar negative anomaly in hurricane activity occurs when equatorial winds at 30 mb are from an easterly direction and/or are becoming more easterly with time during the hurricane season. This association of Atlantic hurricane activity with El Niño can also be made with the Southern Oscillation Index. By constrast, seasonal hurricane frequency is slightly above normal in non-El Niño 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.

El Niño events are shown to be related to an anomalous increase in upper tropospheric westerly winds over the Caribbean basin and the equatorial Atlantic. Such anomalous westerly winds inhibit tropical cyclone activity by increasing tropospheric vertical wind shear and giving rise to a regional upper-level environment which is less anticyclonic and consequently less conducive to cyclone development and maintenance. The seasonal frequency of hurricane activity in storm basins elsewhere is much less affected by El Niño events and the QBO.

Seasonal hurricane frequency in the Atlantic and the stratospheric QBO is hypothesized to be associated with the trade-wind nature of Atlantic cyclone formation. Tropical cyclone formation in the other storm basins is primarily associated with monsoon trough conditions which are absent in the Atlantic. Quasi-Biennial Oscillation-induced influences do not positively enhance monsoon trough region vorticity fields as they apparently do with cyclone formations within the trade winds.

Part II discusses the utilization of the information in this paper for the development of a forecast scheme for seasonal hurricane activity variations.

1. Introduction

This is the first of two companion papers on Atlantic seasonal hurricane activity. This paper discusses seasonal hurricane frequency as related to El Niño/Southern Oscillation phenomena and the 30 mb equatorial Quasi-Biennial Oscillation (QBO) of zonal wind direction. El Niño years are those in which anomalous warm water develops off the South American tropical west coast and in the equatorial central Pacific. The QBO of zonal wind in the tropical stratosphere between 15 and 20° latitude has been measured since 1950. This zonal wind oscillation also has a surprising association with Atlantic seasonal hurricane activity.

a. El Niño

This paper will show that tropical eastern and central Pacific sea-surface temperature (SST) warming events associated with El Niño reduce hurricane activity in the western Atlantic during the season following the onset of the El Niño event. Sea-surface temperatures and hurricane activity usually return to normal in the second summer following such an event. Figure 1 shows the 1982 warm anomaly in SST which developed in the eastern half of the tropical Pacific during the most recent El Niño event.

The occurrence of such an El Niño–Atlantic hurricane activity relationship appears to be related to the associated extra-deep cumulus convection found in the eastern Pacific during such warm water episodes. This enhanced convection is associated with anomalously strong westerly upper tropospheric wind patterns 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 Niño events (as determined by Quinn *et al.*, 1978) for the years 1900 to 1976, together with the recent 1982–83 El Niño

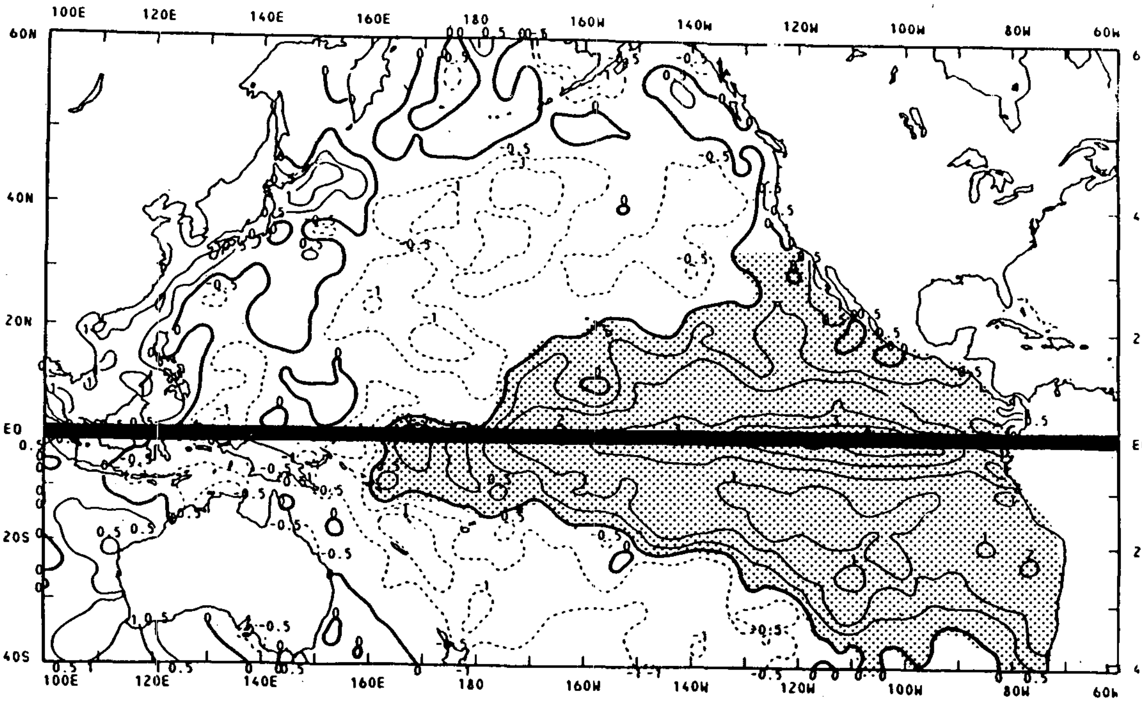

FIG. 1. Sea-surface temperature anomaly (°C) for October 1982 (from Oceanographic Monthly Summary Report of NOAA Earth Satellite Service, 1982). Shading denotes regions of El Niño-induced warming.

event, have been studied. Comparisons are made with the non-El Niño years. See Rasmusson and Carpenter (1982) for a physical description of the usual meteorological events occurring before, during and after the onset of El Niño events. The 1982–83 El Niño was one of the strongest of this century. The onset and the sequence of warming with this El Niño were different from the average El Niño as described by Rasmusson and Carpenter in that the initial warming of SST occurred in the central rather than the eastern Pacific, and the warming came a number of months later in the year than typically occurs. The 1982 El Niño event was also unusual in that it persisted 8–10 months into the following year.

b. The equatorial 30 mb QBO of zonal wind direction

Seasonal hurricane activity occurring in the years 1950–82 with easterly equatorial 30 mb QBO wind during non-El Niño years is studied and compared with seasonal hurricane activity in non-El Niño years when 30 mb equatorial QBO winds are westerly.

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% 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 Niño events.

The following sections present statistical evidence for such a surprisingly strong association of El Niño/QBO events with Atlantic seasonal hurricane activity. A physical hypothesis for such relationships is also advanced. Such phenomenal 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 an association between El Niño and seasonal hurricane activity

Information on El Niño was obtained from Quinn *et al.* (1978), who list strong, moderate, weak and very weak El Niño years for the last two centuries. The intensities of recent El Niño 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, SST data along the Peru and southern Ecuador coasts, and other related parameters.

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

Figure 2 is a plot of the seasonal number of hurricane days for the years 1900–82. In most El

TABLE 1. El Niño years since 1900 by intensity as determined by Quinn *et al.* (1978).

Strong	Moderate	Weak	Very weak
1983*	1976	1969	1975
1982**	1965	1951	1963
1972	1953	1943	1948
1957	1939	1932	1946
1941	1929	1923	
1925	1914	1917	
1918	1905		
1911	1902		

* 1983 was also a strong El Niño year but this was not known at the time of the development of the forecast scheme appearing in Part II.

** 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).

Niño years, hurricane activity as measured by the number of hurricane days is typically much less than for non-El Niño years. Hurricane-day information has been tabulated from Neumann *et al.* (1981) and from the recent information of Lawrence and Pelissier (1982) and Clark (1983) on the 1981 and 1982 hurricane seasons. These reports give track information on all west Atlantic tropical cyclones from 1871 to 1982, and list the hurricane stage of each storm since 1886. A hurricane day is defined as 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 occurred on a single day, two hurricane days were recorded.

This general tendency for a reduction in hurricane activity in El Niño years is also indicated in Table 2, which lists in decreasing order the number of hurricane days occurring in each year since 1900. Note that most of the strong and moderate El Niño 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, nine are strong or moderate El Niño years. Of the 22 years with the largest number of hurricane days, none are El Niño years. The highest five values of El Niño-year hurricane days range from 15 to 27, while values for the five highest non-El Niño-year hurricane days are between 46 and 57. The mean number of hurricane days in moderate and strong El Niño years (as defined by Quinn *et al.,* 1978) was 10.9, versus 23.2 during non-El Niño years. The medians are 9 and 20.5.

A ranking of the number of hurricanes per year gives similar results. Of the 28 years with three hurricanes or less, 12 years (or 43%) were moderate or strong El Niño years. Of the 56 seasons with four or more hurricanes, only four (or 7%) were El Niño years. The mean numbers of hurricanes per season during El Niño and non-El Niño years are 3.0 and 5.4, respectively.

Similar results also are found for the seasonal number of hurricanes and tropical storms (maximum sustained winds > 22 m s^{-1}). Of the 22 years with five or fewer tropical storms and hurricanes, 11 (or 50%) were El Niño years. By contrast, only three of 51 years (or 6%) with seven or more tropical storms and hurricanes were El Niño years. The average numbers of hurricanes and tropical storms per season for El Niño and non-El Niño years are 5.3 and 9.0, respectively.

A Wilcoxon (Brownlee, 1960) two-sample statistical rank test of the null hypothesis that there is no relationship between El Niño and non-El Niño years and hurricane activity is significant at the 0.1% level for seasonal number of hurricanes, seasonal number of hurricanes and tropical storms, and for the seasonal number of hurricane days.

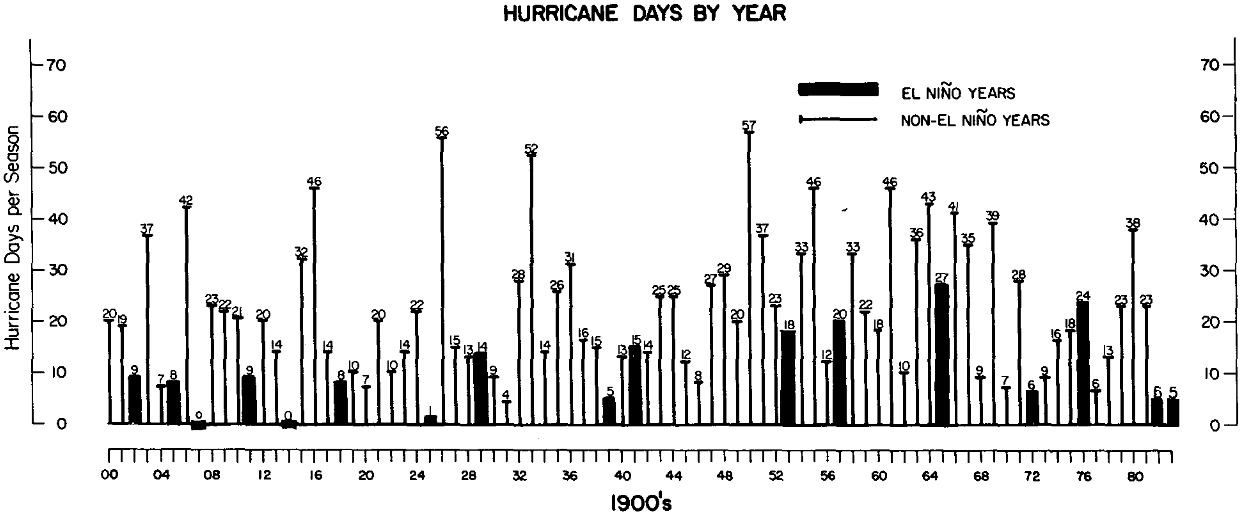

FIG. 2. Number of hurricane days (given at top of lines) in El Niño and non-El Niño years from 1900 to 1982.

TABLE 2. Ranking of Atlantic tropical cyclone seasons from 1900 to 1983 by number of hurricane days in decreasing order. An indication of moderate or strong El Niño for each year is given on the right of each column.

Year	Hurricane days	El Niño strength	Year	Hurricane days	El Niño strength
1950	57		1975	18	
1926	56		1960	18	
1933	52		1953	18	Moderate
1961	46		1974	16	
1955	46		1937	16	
1916	46		1941	15	Strong
1964	43		1938	15	
1906	42		1927	15	
1966	41		1942	14	
1969	39		1934	14	
1980	38		1929	14	Moderate
1951	37		1923	14	
1903	37		1917	14	
1963	36		1913	14	
1967	35		1978	13	
1958	33		1940	13	
1954	33		1928	13	
1915	32		1956	12	
1936	31		1945	12	
1948	29		1962	10	
1971	28		1922	10	
1932	28		1919	10	
1965	27	Moderate	1973	9	
1947	27		1968	9	
1935	26		1930	9	
1944	25		1911	9	Strong
1943	25		1902	9	Moderate
1976	24	Moderate	1946	8	
1981	23		1918	8	Strong
1979	23		1905	8	Moderate
1952	23		1970	7	
1908	23		1920	7	
1959	22		1904	7	
1924	22		1977	6	
1909	22		1972	6	Strong
1910	21		1939	5	Moderate
1957	20	Strong	1982	5	Strong
1949	20		1983	5	Strong
1921	20		1931	4	
1912	20		1925	1	Strong
1900	20		1914	0	Moderate
1901	19		1907	0	

It is also interesting to note that of the 54 major hurricanes[1] striking the United States coast during 1900–76 (as determined by Hebert and Taylor, 1978) plus 1977–83 (determined by the author), only four occurred during the 16 strong and moderate El Niño years. During the other 68 non-El Niño years from 1900 to 1983, there were 50 major hurricane strikes on the coast. The rate of major hurricane strike per El Niño year is 0.25, while that per non-El Niño year is 0.74, a three to one ratio.

a. Track alterations during El Niño years

The tracks of hurricane-intensity tropical cyclones in each of the 15 moderate and strong El Niño years of this century show that hurricane activity is strikingly suppressed for most El Niño years, and also that only a few hurricanes cross the Caribbean–West Indies region from an east to west direction during these years. By contrast, in non-El Niño years, hurricanes are more frequent, and tracks crossing the Caribbean are much more frequent. These differences are better illustrated by comparing Figs. 3, 4 and 5. Figure 4 shows the hurricane intensity storm tracks for a composite of 14 El Niño seasons (1982 and 1983 are not included). Figures 3 and 5 show, respectively, 14 seasons of hurricane intensity storm tracks one year before and one year after each El Niño event. Notice the decreased number of hurricane-intensity storm tracks during El Niño years and the even greater increased number of westerly-tracking systems in the southern part of the hurricane basin during non-El Niño years. The El Niño-year suppression of westerly-tracked cyclones in the Atlantic equatorward of 20°N is substantially larger than the overall difference in hurricane activity between El Niño and non-El Niño years.

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

b. Statistics before 1900

This strong negative association of hurricane activity with El Niño events for the 1900–82 period is not verified for the shorter 1871–99 period, however. Recognition of El Niño events before this century is based primarily on Peruvian rainfall data and other related historical records. The eight strong and mod-

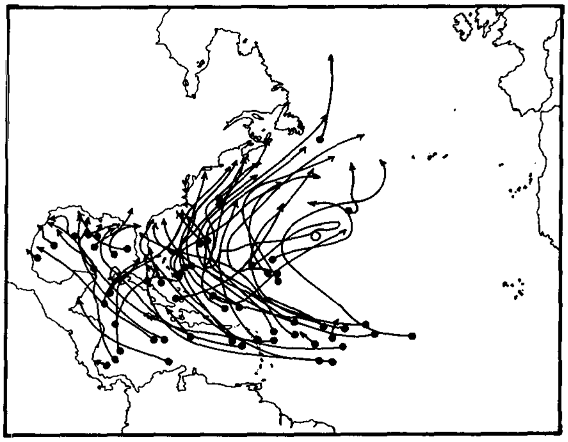

FIG. 3. Fourteen years of hurricane-intensity storm tracks occurring one year before each of 14 El Niño years between 1900 and 1976.

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

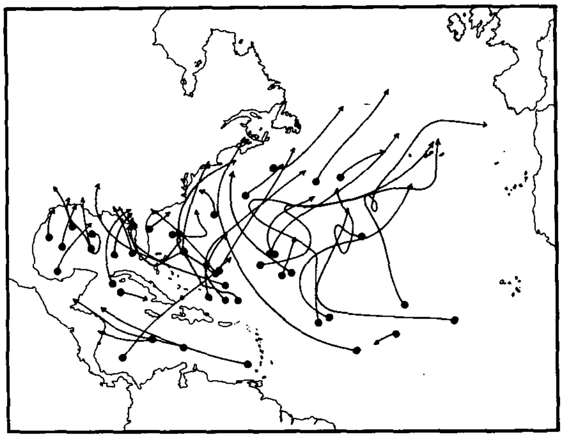

FIG. 4. As in Fig. 3 but during each of the 14 El Niño years.

erate El Niño events of this earlier period as listed by Quinn *et al.* (1978) occurred during 1871, 1877, 1880, 1884, 1887, 1891, 1896 and 1899. These nineteenth-century El Niño years actually show more hurricane activity than the non-El Niño years, an opposite correlation to that observed in this century. The year 1887 was reported to be particularly active, 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 Niño year. The author cannot explain why the El Niño–hurricane activity association during the period 1871–99 is opposite to the much longer twentieth century association. A possible explanation is that the El Niño and hurricane data for this earlier period are less reliable than more recent data. Or, it may be that the physical association of El Niño and hurricane activity (to be discussed in the next section) was just not present during this earlier period. This latter explanation seems less likely, however.

3. Physical processes responsible for suppression of hurricane activity by El Niño

Satellite imagery shows that the warm water that develops in the eastern tropical Pacific during a typical El Niño year is associated with extra amounts of deep cumulus convection throughout this region. It is suggested that this enhanced deep convection develops anomalous upper tropospheric (~200 mb) outflow patterns. Other factors being equal, these outflow patterns act to produce an enhancement of westerly winds (or weaker easterly winds) over the Caribbean and western equatorial Atlantic regions and thus create conditions different from non-El Niño years. An idealization of this process is shown in Fig. 6.

These atypical upper tropospheric westerly winds that occur during El Niño 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 Niño 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 0–15°N be from an easterly direction and that 200 mb westerly winds be present in the subtropical latitude belt 20–30°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, the greater the probability that individual cloud cluster systems will develop into cyclones rather than remaining as traveling depressions and disturbances.

Figure 7 is taken from data composited around the early stages of tropical disturbances as they began 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). Figure 7 shows the type of 200 mb north–south zonal wind shears that are usually associated with individual cases of hurricane development and maintenance. Figure 8 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 at point A, or westerly winds at point B, the greater the likelihood of an above average number of seasonal hurricanes. Hurricane activity is made greater or less by any process which enhances or suppresses such seasonally averaged upper tropospheric wind patterns.

Since El Niño 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 will also be below normal

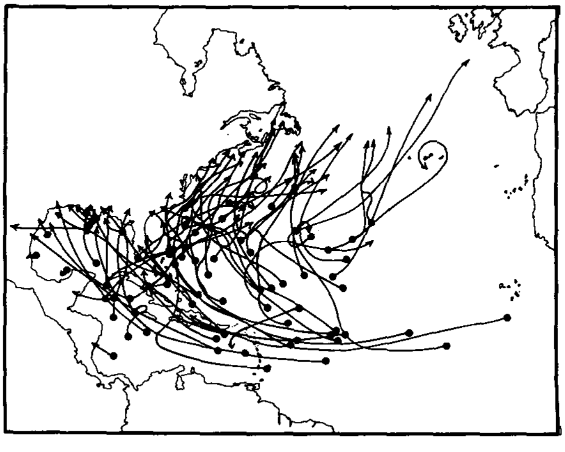

FIG. 5. As in Fig. 3 but for one year after each of the 14 El Niño years.

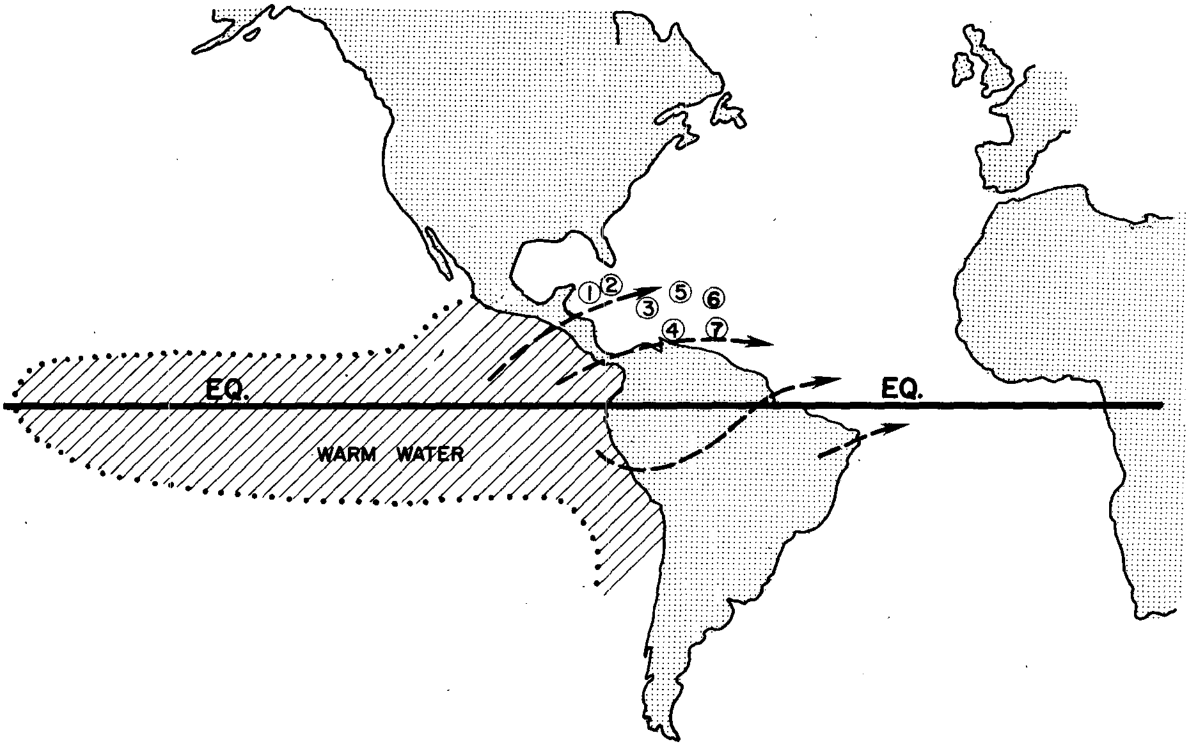

FIG. 6. Deviational upper tropospheric (~200 mb) outflow wind patterns due to enhanced deep-cumulus convection in the eastern tropical Pacific in moderate and strong El Niño years. These wind patterns are hypothesized to result from anomalously warm eastern Pacific water. [Numbers indicate upper-air stations at Swan Island (1), Grand Cayman (2), Kingston, Jamaica (3), Curaçao (4), San Juan (5), St. Maarten (6) and Barbados (7)].

in years when the Southern Oscillation Index (SOI) is low; this is observed to be 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 Niño events from 1900 to 1976 had distinctly lower than normal values of this time-averaged surface pressure difference. The lowest values of this pressure difference were usually associated with the strongest El Niño events. The SOI was also very low during the 1982 El Niño year. Thus, a positive correlation between Atlantic hurricane activity and the Southern Oscillation is definitely present.

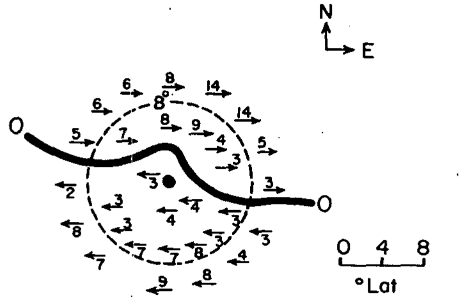

FIG. 7. Composite of 200 mb zonal winds (m s^{-1}) about the center point (large dot) of Caribbean basin tropical weather systems in an early stage of cyclone development (adapted from Gray, 1968).

Figure 9 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). The greater seasonal 200 mb anticyclonic flow which is associated with high SOI (shown by the cross-hatched region of this figure) should be associated with higher values of seasonal hurricane activity. The opposite wind patterns related to low SOI will

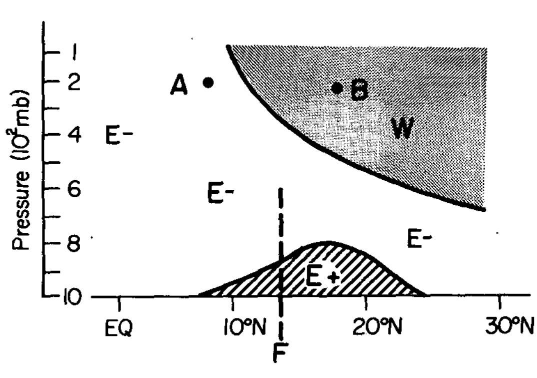

FIG. 8. Schematic north–south vertical cross section of zonal winds in the western Atlantic and Caribbean basin during August–September relative to the typical latitudinal position of tropical cyclone formation indicated by the dashed line F. Westerly and easterly winds are denoted by W and E, respectively, and strong and weak wind speeds by plus and minus signs, respectively.

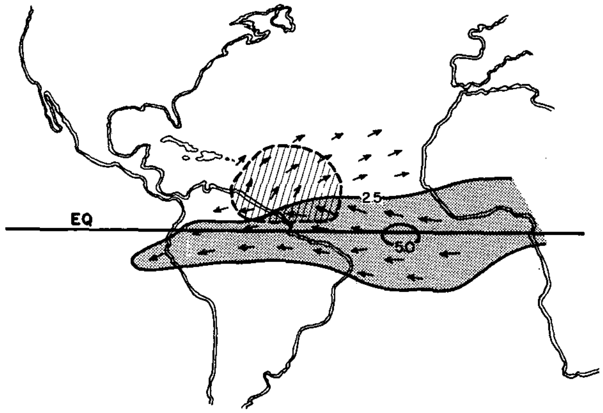

FIG. 9. Vector differences (length proportional to magnitude, with isotachs in m s^{-1}) of 200 mb wind between 17 (summer, fall, winter and spring) seasons with the SOI > 0.65 and 14 seasons with the SOI < −0.65. Adapted from Arkin (1982). Stippled area shows speeds greater than 2.5 m s^{-1}. For explanation of cross-hatched region see text.

lead (as observed) to a suppression of seasonal hurricane activity.

Figure 10 (also adapted from Arkin, 1982) shows 200 mb wind anomalies for the three summers following the onset of El Niño SST warming events in the eastern Pacific in the years 1969 (weak El Niño), 1972 (strong) and 1976 (moderate). These seasonal 200 mb wind anomaly patterns decrease upper-level anticyclonic flow (other factors being equal) and should lead to a suppression of hurricane activity.

Figures 11–14 indicate the type of average August and September upper-level zonal wind changes which El Niño events produced at the four Caribbean Basin stations of Swan Island (1), Curaçao (4), Kingston, Jamaica (3) and Barbados (7) (see Fig. 6 for locations). Upper-level winds have been averaged for the five El Niño years 1957, 1965, 1972, 1976 and 1982, and 18 non-El Niño years since 1957. Notice that the largest wind differences occur in the upper troposphere. Similar 200 mb average zonal wind differences for various hurricane season months for these and other Caribbean basin stations are shown in Table 3. In general, upper tropospheric winds average 2–7 m s^{-1} more from a westerly direction during El Niño years than in non-El Niño years.

Mean El Niño-year changes of 200 mb zonal winds over the southeast United States and Bahaman Island stations (not shown) are considerably less than those over Caribbean basin stations. Thus, in El Niño years, 200 mb north–south wind shear ($\partial u/\partial y$) tends to make 200 mb relative vorticity less negative.

A Wilcoxon two sample rank test of the premise that 200 mb winds are the same between El Niño and non-El Niño years for the period August–September is significant at the 0.1% level for both of these periods. A similar statistical analysis by individual months before the onset of the most active part of the hurricane season shows the following probabilities that no difference exists in 200 mb Caribbean Basin zonal winds between El Niño and non-El Niño years: for April, 0.374; for May, 0.041; for June, 0.015; and for July, 0.001. Wind data for May through July thus contain a degree of potentially predictive signal that might also be used for verification or refinement of the El Niño signal.

a. *Precipitation departures during El Niño years*

An analysis of precipitation anomalies throughout the Caribbean basin region during the last six moderate and strong El Niño years, 1957, 1965, 1972, 1976 and 1982, shows that, in general, precipitation is suppressed by only 0–10%. Table 4 shows the percentage precipitation departure from normal by month for each of these six El Niño 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% below normal in the strong El Niño years of 1972 and 1982, respectively, it was 8% above normal for the strong El Niño year of 1957. For all six El Niño years, average precipitation during the August–October period is only observed to be 5% below that of the non-El Niño years.

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

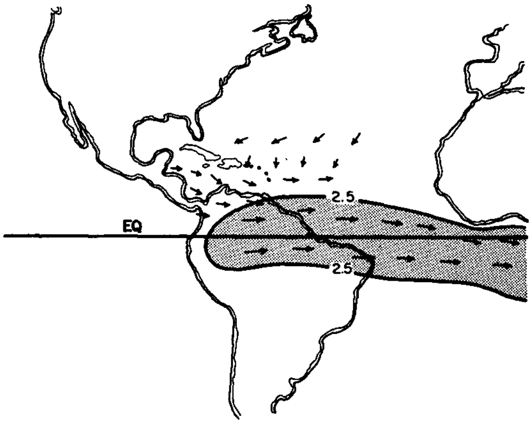

FIG. 10. 200 mb wind vector anomalies with isotachs for the three summer seasons following the onset of El Niño-type SST warming off the South American coast for the years 1969, 1972 and 1976. Adapted from Arkin (1982). Shaded area shows speeds greater than 2.5 m s^{-1}.

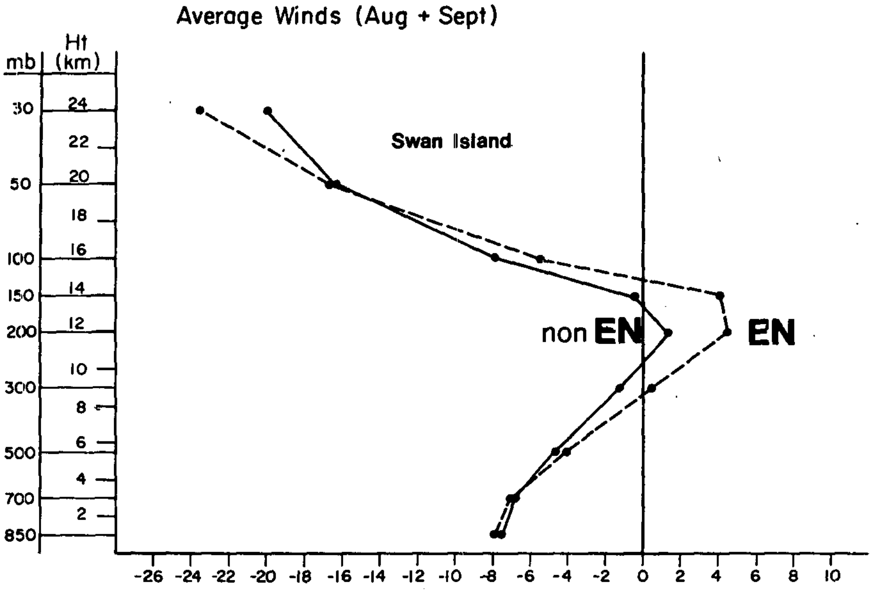

FIG. 11. Vertical profile of zonal wind during August and September at Swan Island (point 1 in Fig. 6) for an average of the last five El Niño years (1957, 1965, 1972, 1976, and 1982), denoted by EN and 18 other non-El Niño years (non EN).

b. Pressure departures during El Niño years

A similar analysis of sea-level pressure differences between El Niño and non-El Niño years (Table 5) shows no meaningful results. In addition, upper-level pressure-height, temperature and moisture differences between El Niño and non-El Niño years also showed no apparent differences. It is thus concluded that the primary meterological processes responsible for the suppression of hurricane activity in El Niño years are increased upper tropospheric westerlies in the 0–18° latitude belt and the associated anomalous dynamical factors.

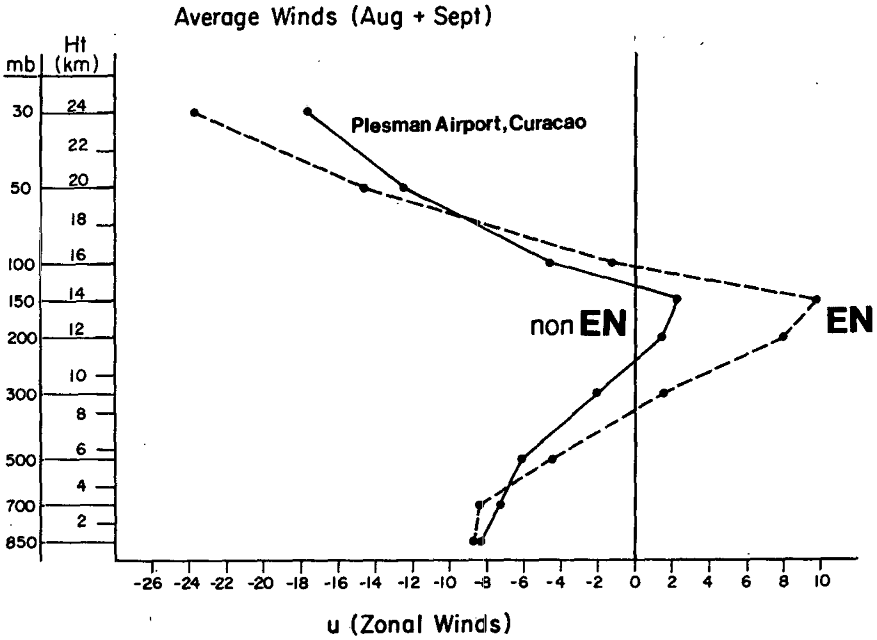

FIG. 12. As in Fig. 11 but for Curaçao (point 4 in Fig. 6).

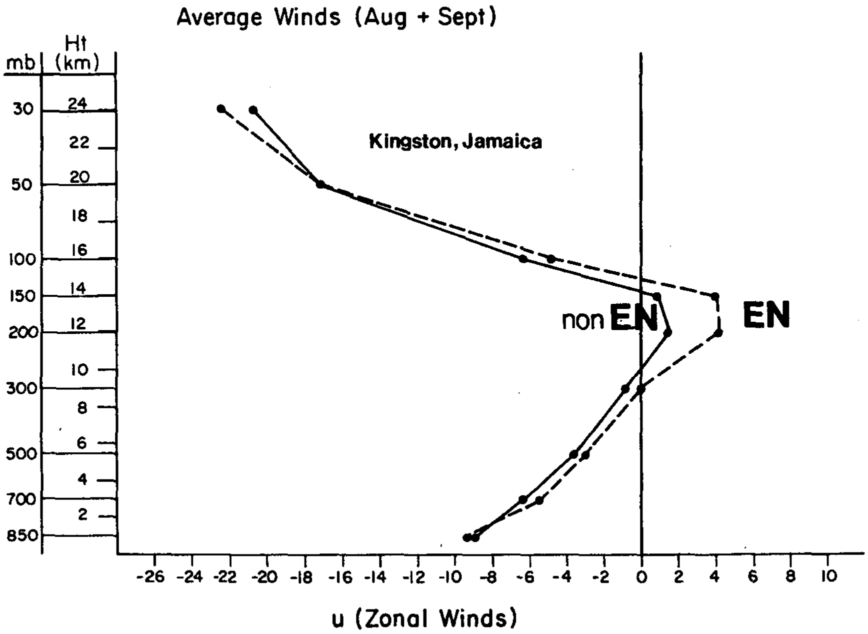

FIG. 13. As in Fig. 11 but for Kingston, Jamaica (point 3 in Fig. 6).

c. Modification of seasonal tropical cyclone activity in other global storm basins by El Niño

The large reduction in west Atlantic seasonal tropical cyclone activity during El Niño years is not experienced in the other tropical cyclone ocean basins. Table 6 shows the number of hurricanes and tropical storms that occurred in the three other Northern Hemisphere tropical cyclone basins one season before moderate or strong El Niño years (−1), during El Niño years (+1), or in other years more than one year away from El Niño events.

Although storm numbers may be somewhat underreported for earlier years (particularly the weaker storms), the relative magnitude of seasonal tropical cyclone activity before, during and after El Niño years should be generally reliable. Note that El Niño years appear to affect hurricane and tropical cyclone

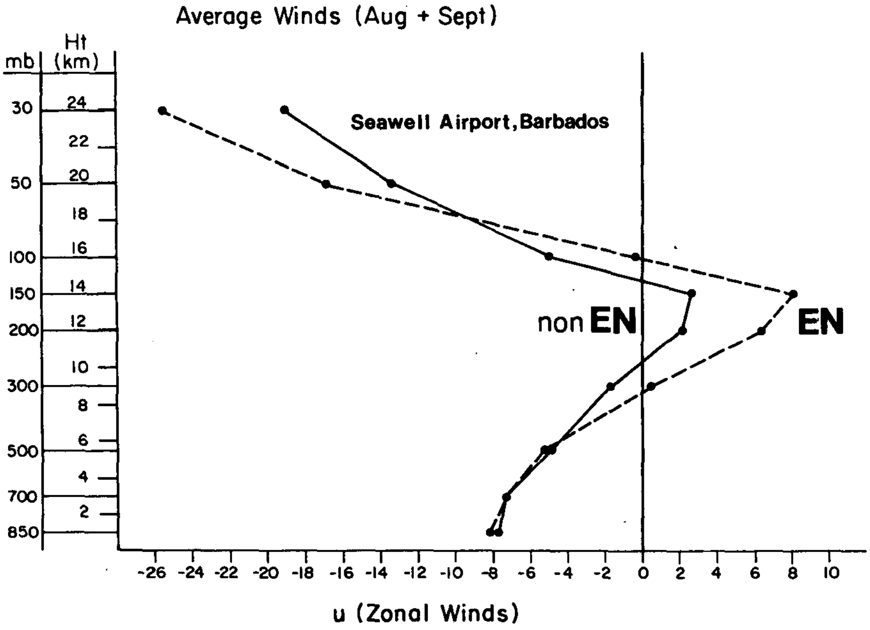

FIG. 14. As in Fig. 11 but for Barbados (point 7 in Fig. 6).

TABLE 3. Caribbean basin 200 mb multimonth average zonal winds (m s^{-1}) by station for the last five El Niño years and 21 other non-El Niño years.

	El Niño		Non-El Niño		El Niño minus non-El Niño	
Station	Aug–Sept mean	June–Oct mean	Aug–Sept mean	June–Oct mean	Aug–Sept mean	June–Oct mean
Swan Island	4.0	5.3	1.2	2.5	2.8	2.8
Santo Domingo	4.3	5.8	2.1	3.9	2.2	1.9
San Andres Island	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	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	0.1	2.5	2.3	2.3
Plesman, Curaçao	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

activity in the three other Northern Hemisphere tropical cyclone basins much less than in the western Atlantic basin.

Table 7 portrays similar relationships for hurricane and tropical cyclone activity in the three Southern Hemisphere storm basins. Again, no large and systematic reduction or enhancement of hurricane and tropical cyclone activity is observed one year before the onset of El Niño years (−1), during years of moderate or strong El Niño onsets (0), one (+1) or two years (+2) after El Niño years, or in all the other years. Note that, compared with the west Atlantic, the seasonal frequency of tropical cyclone and hurricane activity is not so much influenced by El Niño events.

Nicholls (1984) has recently reported that low values of the SOI cause a significant reduction in early season Australian region tropical cyclone activity and a modest lowering of the whole Australian seasonal hurricane activity. This SOI and Australian region tropical cyclone relationship is much weaker than that experienced in the Atlantic, however.

The author does not mean to imply that the locations and tracks of tropical systems in the other global storm basis are not often influenced by El Niño. It appears that a larger number of tropical cyclones in the northeastern Pacific basin do track farther westward than normal in El Niño years. El Niño events also cause southeast Pacific storms to form farther eastward than normal. Also, in the year following an El Niño year, seasonal storm activity in the northwest Pacific Ocean sometimes commences at a later date. Tropical cyclone and hurricane activity during the 1982–83 El Niño especially emphasized these features. Many more tropical cyclones (eight systems) formed east of the Dateline in the South Pacific in 1982–83 than in any previous year of record. However, tropical cyclone activity in the South Indian Ocean and Australian region was below normal during the 1982–83 hurricane season. Overall, the Southern Hemisphere had a normal amount of tropical cyclone activity during this season.

Such modulations of tropical cyclone formation points and tracks in non-Atlantic Ocean basins are generally less than in the Atlantic. The Caribbean basin and equatorial Atlantic are directly downwind from the major eastern Pacific El Niño SST warming events. Cyclone formation in the Atlantic is thus, in general, much more sensitive to El Niño influences than in the other tropical cyclone regions. The west Atlantic basin is unique in being so influenced by El Niño events.

TABLE 4. Average percentage precipitation departure of 15–20 West Indies region stations for each summer month of the last six strong and moderate El Niño events.

Year	Jun	Jul	Aug	Sept	Oct	Average
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
Average	−11	−5	−7	−3	−2	−5

d. Summary

It appears that the role of El Niño in suppressing seasonal hurricane activity results primarily from its influence (direct or indirect) in causing abnormally strong upper tropospheric westerly winds in the equatorial west Atlantic and the Caribbean basin. The influence of El Niño on other meteorological parameters is much less detectable.

4. The stratospheric QBO and seasonal west Atlantic tropical cyclone activity

Information on the QBO of the stratospheric equatorial zonal winds is available only since 1950. Con-

TABLE 5. Sea-level pressure (1000 mb) occurring in various months at Caribbean basin stations during El Niño and non-El Niño years between 1950 and 1982 and differences between these pressures.

	El Niño years			Non-El Niño years			El Niño minus non-El Niño years		
Station	May	Aug–Sep mean	Jun–Oct mean	May	Aug–Sep mean	Jun–Oct mean	May	Aug–Sep mean	Jun–Oct mean
Cayenne, French Guiana	12.6	12.9	12.8	12.5	12.8	12.9	0.1	0.1	−0.1
Jacksonville, Florida	16.6	17.1	17.2	16.8	16.8	17.1	−0.2	0.3	0.1
Maracay, Venezuela	12.6	12.2	12.6	12.7	13.7	13.6	−0.1	−1.5	−1.0
Merida, Mexico	11.8	13.0	13.3	11.7	12.5	13.1	−0.1	0.5	0.2
Nassau, Bahamas	16.1	15.3	16.1	16.8	16.0	16.3	−0.7	−0.7	−0.2
Plesman, Curaçao	11.7	11.6	11.8	11.6	11.3	11.4	0.1	0.3	0.4
San Juan, Puerto Rico	15.9	15.3	15.6	15.7	15.1	15.5	0.2	0.2	0.1
Seawell, Barbados	13.9	13.7	14.1	14.2	13.4	13.7	−0.3	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	0.4	0.2	0.3

tinuous and reliable equatorial wind information at levels of 30 mb and higher are not available before that time. Zonal wind oscillations since 1950 are shown in Fig. 15: The top diagram is from Coy (1979) for the period up to 1978. The bottom diagram is for information since 1978 as furnished to the author by R. Quiroz personal communication, 1982) of the NOAA Climate Analysis Center. The shaded areas on these diagrams denote periods when the global equatorial stratospheric winds are westerly. Non-shaded areas denote times when equatorial winds are from the east. The near-biennial nature of this wind oscillation is clearly evident. For a general description of this wind oscillation see the review paper by Wallace (1973).

This paper will not discuss the physical processes responsible for these zonal wind oscillations, since this has been a subject of study by a large number of scientists over the last two decades. This section only explores the apparent association of the QBO and Atlantic seasonal hurricane activity. Despite the extensive literature available on the QBO, the author is aware of no research that relates such biennial stratospheric wind changes to seasonal variations in hurricane activity.

Table 8 presents numerical rankings of the number of hurricanes per season and 30 mb equatorial zonal wind directions since 1950. Note that hurricane activity is, in general, more frequent when the 30 mb stratospheric winds are westerly and less frequent when they are from the east. The average number of hurricanes per year with 30 mb westerly winds is 6.7, while for easterly winds it is 4.6. The number of hurricane days per season for 30 mb winds from the west and east is 31 and 15 days, respectively, a two to one ratio.

TABLE 6. Northern Hemisphere mean seasonal number of hurricanes and tropical storms for one year before (−1), during (0) and one year after (+1) a moderate or strong El Niño (EN).

Ocean basin	EN −1	EN 0	EN +1	Other years
North Indian Ocean (1911–82), 12 events	5.3	5.5	6.9	5.6
Northwest Pacific (1900–82), 15 events	25.8	26.6	26.8	25.7
Northeast Pacific (1949–82), 6 events	12.0	12.3	11.2	11.9
Total	43.1	44.4	44.9	41.2

TABLE 7. As in Table 6 but for the Southern Hemisphere.

Ocean basin	EN −1	EN 0	EN +1	EN +2	Other years
South Indian Ocean (1911–82), 12 events	8.6	7.3	7.4	6.5	7.8
Australia region (1904–82), 13 events	6.5	8.2	6.2	7.2	7.2
Southeast Pacific (1939–82), 7 events	7.1	8.0	7.3	7.3	7.3
Average	7.4	7.8	7.0	7.0	7.5

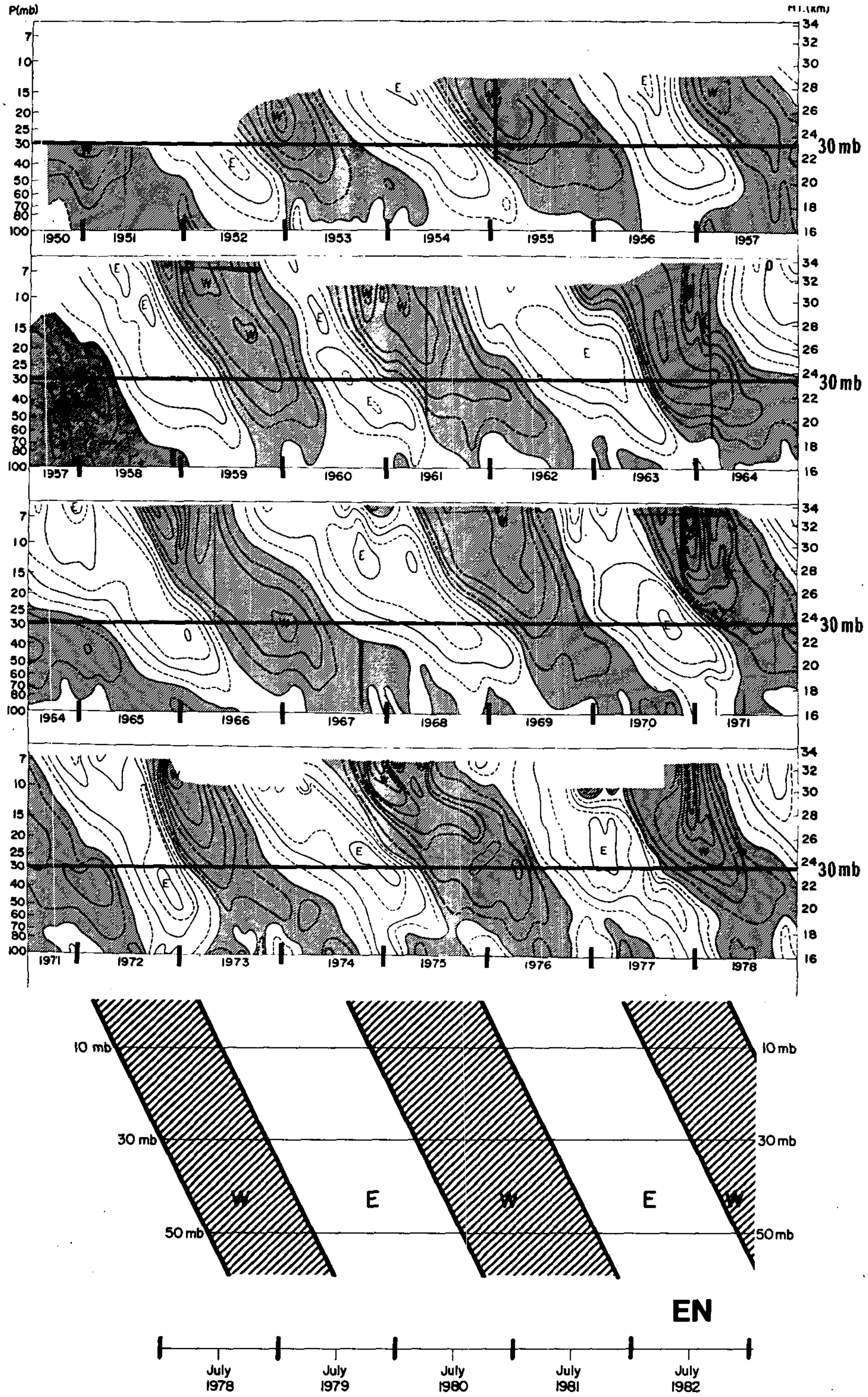

FIG. 15. Vertical plot of stratospheric zonal wind from 1950 to 1982. Westerly winds are shaded. Top plot is from Coy (1979) and bottom plot from information furnished by R. Quiroz (personal communication, 1982). Isolines in top diagram are at intervals of 10 m.

Figure 16 is a plot of the number of hurricane days per year from 1949 through 1983 by easterly and westerly 30 mb wind category. (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

TABLE 8. Ranking of the number of Atlantic hurricanes per season between 1949 and 1983 by the direction of 30 mb equatorial zonal winds from the east (E) or west (W).

Year	Number of hurricanes	Direction of 30 mb winds
1950	11	W
1969	10	W
1980	9	W
1955	9	W
1961	8	W
1954	8	E
1951	8	—
1981	7	—
1966	7	W
1963	7	—
1959	7	W
1958	7	E
1976	6	—
1975	6	W
1971	6	W
1967	6	—
1964	6	W
1953	6	W
1952	6	E
1979	5	E
1978	5	W
1977	5	E
1970	5	E
1974	4	E
1973	4	W
1968	4	E
1965	4	E
1960	4	E
1956	4	E
1972	3	E
1962	3	E
1957	3	W
1983	3	E
1982	2	W

mb wind was from the east.) Disregarding El Niño years, these ratios are 7.4:5.2 for seasonal number of hurricanes, and 34:18 for hurricane days per season. The association of seasonal number of hurricane days with the QBO zonal wind direction is apparent.

Figures 17 and 18 compare the tracks of all cyclones of hurricane intensity for 12 non-El Niño years between 1950 and 1982 when 30 mb seasonal winds were from the west with a similar sample of 12 non-El Niño years when 30 mb seasonal winds were from the east. Note the greater number of hurricane-intensity tracks with 30 mb westerly wind situations.

It is also observed that seasonal hurricane activity is related to 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 19 and 20 portray the tracks of hurricane-intensity storms for 12 non-El Niño years between 1950 and 1982 when 30 mb zonal winds were increasing with time during the hurricane season, versus 12 non-El Niño years when 30 mb zonal winds were decreasing during the hurricane season. There were 42% more hurricanes and 60% more hurricane days in non-El Niño seasons (13 cases) with increasing 30 mb westerly winds (or decreasing easterly winds) than in seasons (12 cases) with 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

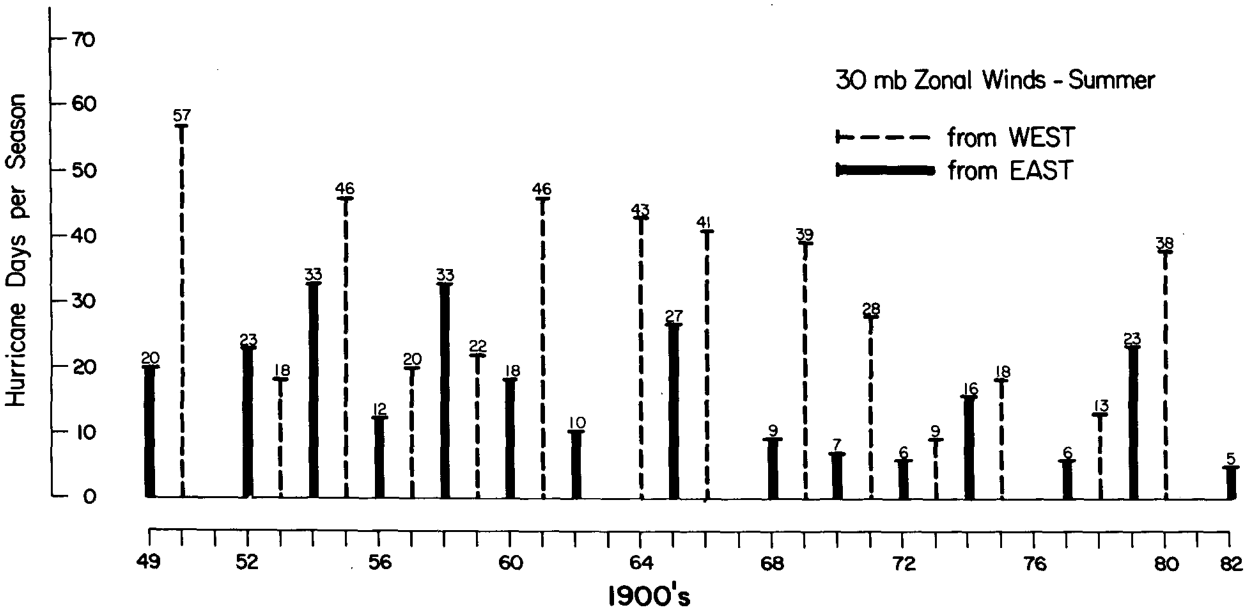

FIG. 16. Relationship between 30 mb stratospheric wind direction and seasonal number of hurricane days from 1949 to 1982. Years with no observation are those in which the 30 mb zonal wind is changing direction or is very weak.

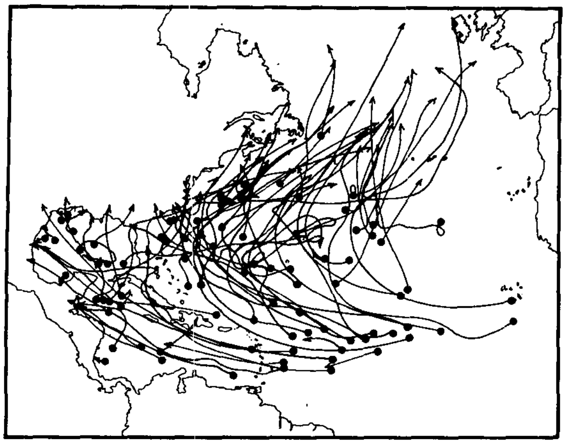

FIG. 17. Tracks of hurricane intensity cyclones during 12 non-El Niño years (1951, 1955, 1959, 1961, 1964, 1966, 1969, 1971, 1973, 1975, 1978 and 1980) when seasonal 30 mb equatorial winds were from the *west*.

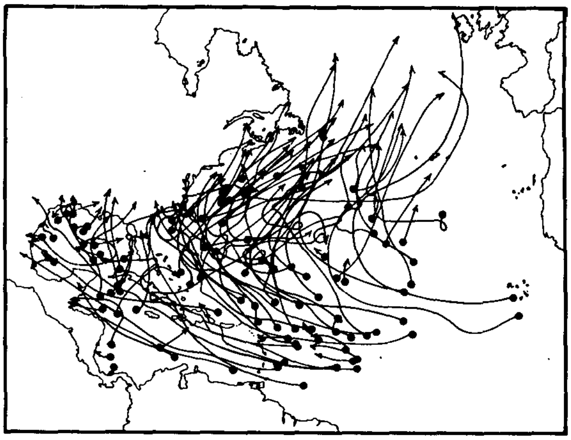

FIG. 19. Tracks of hurricane-intensity storms during 12 non-El Niño years (1950, 1952, 1955, 1959, 1961, 1963, 1966, 1969, 1971, 1975, 1979 and 1980) when 30 mb equatorial zonal winds were *increasing* during the hurricane season.

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 increasing east wind cases. Those non-El Niño seasons in which 30 mb winds were from the west and increasing with time from the west (nine cases in the 1950–82 period) had 62% more hurricanes and 205% more hurricane days than seasons when 30 mb winds were from the east and increasing in speed from the east (seven cases in the 1950–82 period). Figures 21 and 22 show hurricane-intensity storm tracks in these two situations. Westerly wind years are observed to have a much larger number of hurricane track storms. Note that the number of westerly-tracking hurricane-intensity storm tracks south and southeast of Bermuda is greatly reduced in east wind and east wind increasing cases compared to west wind and west wind increasing cases.

Table 9 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 in the period 1950–82 that were not El Niño years. Notice the quite systematic frequency differences that occur for these various categories of wind direction, wind speed change, and combination of wind direction and wind speed change. This table also gives *P*-values of the Wilcoxon

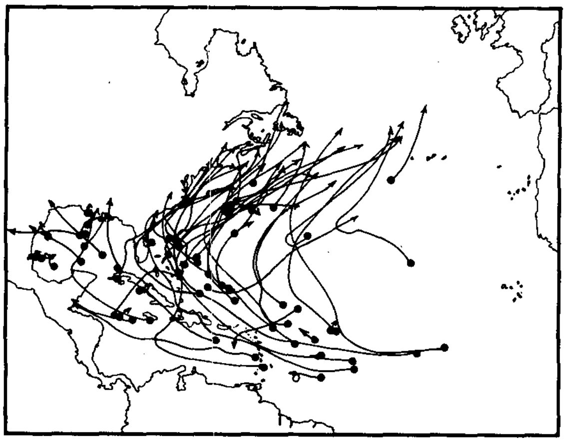

FIG. 18. Tracks hurricane-intensity cyclones in 12 non-El Niño years (1952, 1954, 1956, 1958, 1960, 1962, 1968, 1970, 1974, 1977, 1979 and 1981) when seasonal 30 mb equatorial winds were from the *east*.

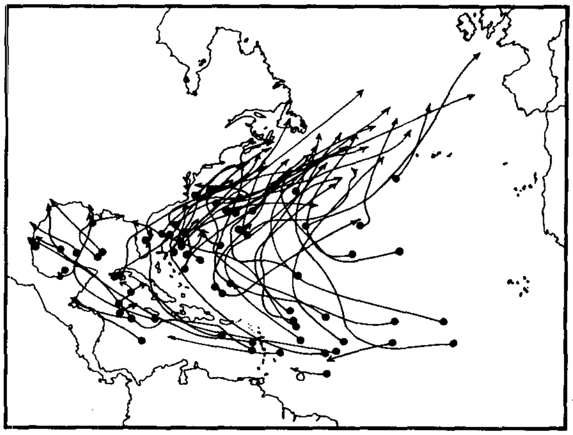

FIG. 20. Tracks of hurricane-intensity storms during 12 non-El Niño years (1951, 1956, 1958, 1962, 1964, 1967, 1968, 1970, 1973, 1974, 1978, 1981) when 30 mb equatorial zonal winds were *decreasing* during the hurricane season.

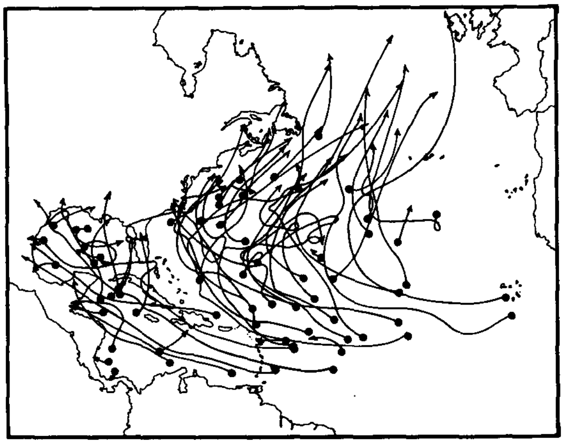

FIG. 21. Tracks of all hurricane-intensity storms for the nine seasons when 30 mb equatorial zonal winds were *westerly* and *increasing* in westerly strength during the hurricane season.

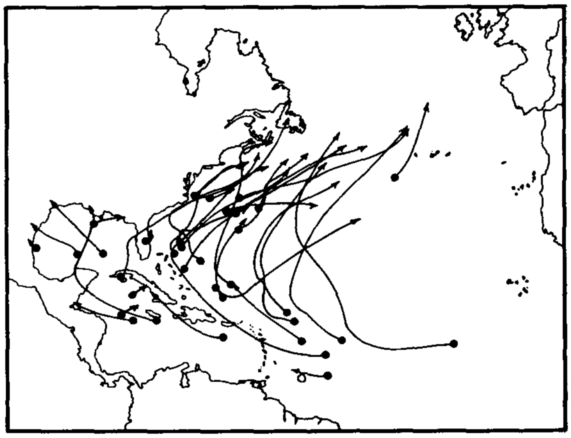

FIG. 22. Tracks of all hurricane-intensity storms for the seven seasons when 30 mb equatorial zonal winds were *easterly* and *increasing* in easterly strength during the hurricane season. To give an equivalent number of seasons with Fig. 21, 1954 and 1967 also have been added: 1954 has east winds and no appreciable change of wind speed, and 1967 has only small zonal wind but increasing easterly winds.

two-rank statistical test of the null hypothesis that no relationship exists between these various wind categories and hurricane activity. In all but two cases, *P*-values are significant at the 1% level.

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

a. 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 westerly and easterly winds. The greater the thickness of the stratospheric layer of westerly winds (or thinness of the layer of easterly 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 Niño seasons of 1950, 1955, 1959, 1961, 1966, 1969, 1971, 1975 and 1980

TABLE 9. 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 Niño years in the period 1950–82. Information pertains to 30 mb zonal winds of Fig. 15. The number of years involved in each average is shown in parentheses.

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 significance level	<1%	<1%	<1%
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 significance level	<1%	<5%	<5%
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 significance level	<1%	<1%	<1%

(Fig. 21 gives tracks), 30 mb westerly winds were increasing with time during the hurricane season, and stratospheric winds from 10 to 50 mb were almost all from the west (see Fig. 23). 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 when 30 mb winds from either east or west are decreasing with time. In these cases, the sloping directional phase lines cause a change in sign of the zonal wind between 10 and 50 mb. This results in a decreasing thickness of unidirectional 10–50 mb zonal winds.

Figure 24 portrays in idealized form the relative

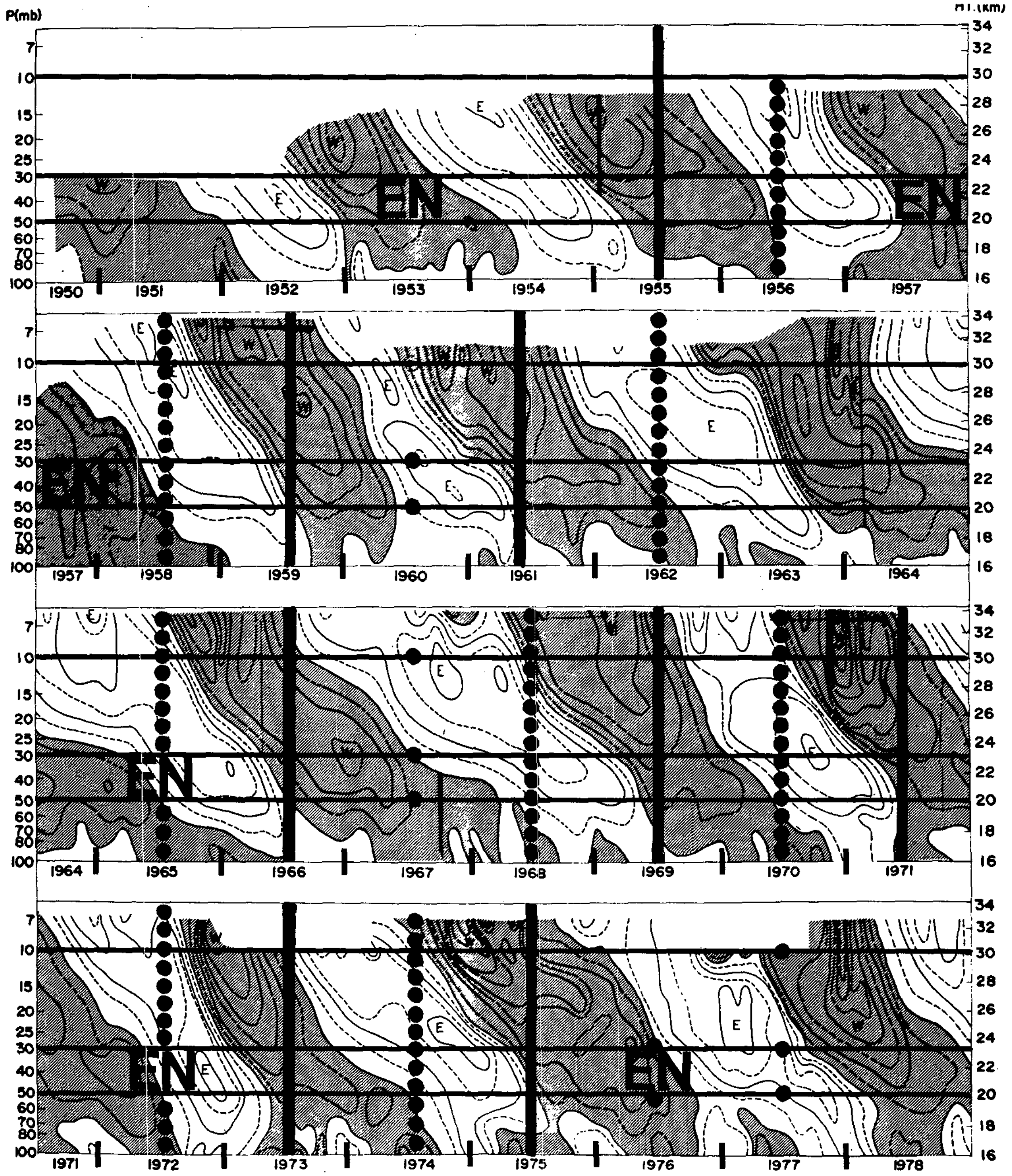

FIG. 23. Designation of non-El Niņo seasons with deep zonal westerly winds (vertical solid lines) increasing with time versus non-El Niņo seasons with deep easterly winds (vertical dotted lines) increasing with time. El Niño years are indicated by EN.

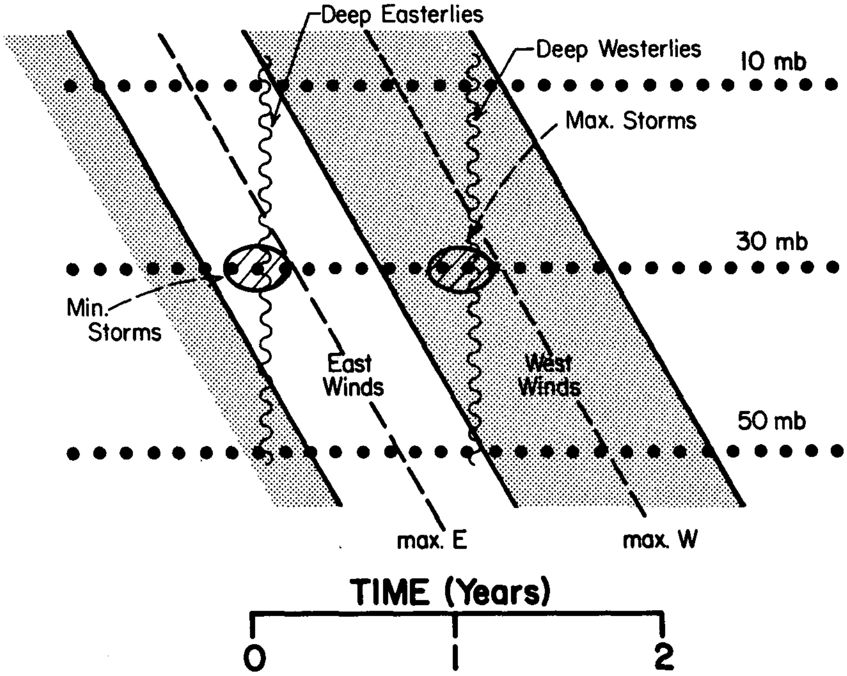

FIG. 24. Typical variation of 10–50 mb stratospheric zonal wind events when the 30 mb westerly winds are increasing in strength (vertical wavy lines in shaded region and in other cases when 30 mb easterly winds are increasing in strength (vertical wavy lines in unshaded region). These are the times when the enhancement and suppression of the QBO influence on seasonal hurricane activity is observed to be greatest.

positions of these different phases of the biennial oscillation in terms of maximum depths of stratospheric easterly and westerly winds and associated positions of 30 mb wind changes relative to typical maximum and minimum seasonal hurricane activity.

b. *Relationship of the QBO with other parameters*

A careful analysis of tropospheric temperature and precipitation information from Caribbean basin stations for all the non-El Niño years since 1950 (for precipitation) and 1957 (for temperature) shows almost no differences between the various classes of 30 mb QBO zonal wind categories. For instance, Table 10 gives information on the percentage precipitation differences between nine of the 27 non-El Niño hurricane seasons with 30 mb stratospheric winds were from the west and increasing in westerly direction with time, and the nine other non-El Niño seasons when 30 mb winds were from the east and increasing in easterly speed with time (seven cases) or no change in speed (two cases) occurred. The nine other non-El Niño years of this 1950–82 period are also shown. Note that mean precipitation differences between these three categories of 30 mb QBO zonal wind differ by less than ±5%. Individual monthly mean precipitation differences are less than ±10%. As with the El Niño information given in the previous section, it appears that it is not the number or rainfall intensities of the individual weather systems that are altered between the different phases of the QBO zonal wind signal. Instead, it is likely that these differences are due to the existence of the rain-producing weather systems in a more favorable large-scale environment when 30 mb winds are from a westerly rather than easterly direction.

c. *Surface pressure anomaly–QBO association*

The 30 mb zonal wind oscillation is best detected in surface pressure. A comparison of the August–September mean sea-level pressure anomaly (SLPA)

TABLE 10. Monthly mean percentage precipitation departures from the average at 15–20 Caribbean basin stations for 27 non-El Niño years divided into three classes of 30 mb QBO zonal wind.

	Month					
30 mb QBO wind category	Jun	Jul	Aug	Sep	Oct	Five-month average
Nine non-El Niño seasons of west winds and west winds increasing	−8	−4	−1	−4	+8	−2
Nine Non-El Niño seasons of east winds and east winds increasing	+10	+9	+1	+2	0	+4
Other nine non-El Niño seasons	−2	−5	+1	+2	−8	−2

TABLE 11. Mean August–September sea-level pressure anomaly (SLPA) for the six-station Caribbean basin average for the various phases of the 30 mb QBO zonal wind oscillation in non-El Niño years. The number of years involved in each average is shown in parentheses.

30 mb zonal wind (u)	SLPA (mb)
West wind	−0.14 (12)
East wind	+0.07 (12)
Difference (W − E)	−0.21
Cases of $\partial u/\partial t$ positive	−0.29 (12)
Cases of $\partial u/\partial t$ negative	+0.10 (12)
Difference (positive − negative)	−0.39
West and $\partial u/\partial t$ positive	−0.26 (9)
East and $\partial u/\partial t$ negative	+0.23 (7)
Difference (W − E)	−0.49

with the different phases of the QBO for the six-station Caribbean basin average is given in Table 11. 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. Through harmonic analysis, Angell *et al.* (1969) have demonstrated a 24–28 month period in surface pressure at many global stations and also a detectable quasi-biennial period in hurricane frequency.

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 an association between the QBO and seasonal hurricane activity. It is well known that seasonal hurricane activity is negatively correlated with seasonal SLPA. This has been documented by Shapiro (1982) and in Part II (Gray, 1984, this issue) of this study.

d. QBO–tropical cyclone relationships in other regions

A prominent QBO and seasonal hurricane frequency relationship such as that observed in the Atlantic is not detectable or is very weak in the other storm basins. Tables 12 and 13 show the 30 mb QBO phases related to the seasonal average number of tropical cyclones and hurricanes that occurred in the other global tropical cyclone basins between 1950 and 1982. Notice the general lack of QBO modulation of storm activities in these other cyclone basins. The Atlantic is the only cyclone basin with a prominent QBO and seasonal cyclone relationship.

This regional difference in the association of QBO and seasonal tropical cyclone frequency is believed to be due to the climatological wind differences which exist between the equatorial Atlantic and the other tropical cyclone basins. Tropical cyclones of the equatorial Atlantic do not form in association with a monsoon trough as do 80–90% of the tropical cyclones elsewhere (Gray, 1968, 1979). Most Atlantic tropical cyclones form within the broad trade wind belt of the west Atlantic where monsoon troughs do not occur.

e. Physical linkage for the QBO–hurricane activity association

Since the QBO–hurricane relationship is a distinctive phenomenon of the equatorial western Atlantic where monsoon trough circulations typically do not play a role in hurricane formation, this would seem to be major direction of investigation: How can the QBO signal be related to seasonal hurricane activity in an equatorial trade wind region but not a monsoon trough region?

We are presently engaged in research to try to establish a physical understanding of this large and quite surprising association of Atlantic hurricane activity and the QBO. Present knowledge and space considerations do not justify a full discussion at this time.

5. Discussion

It is hoped that this paper has demonstrated the importance of the global circulation component to the regional problem of seasonal hurricane variability.

TABLE 12. Mean seasonal number of hurricanes and tropical storms by various 30 mb QBO zonal (U) wind categories for other Northern Hemisphere storm basins for the period 1950–82.

Storm basin	West wind	East wind	West wind minus east wind	U increases during season	U decreases during season	U increase minus U decrease
North Indian Ocean	5.9	4.9	1.0	5.6	5.7	−0.1
Northwest Pacific	25.8	26.9	−1.1	25.2	28.3	−3.1
Northeast Pacific	11.9	12.0	−0.1	11.0	13.6	−2.6
Total	43.6	43.8	−0.2	41.8	47.6	−5.8

TABLE 13. As in Table 12 but for Southern Hemisphere storm basins.

Storm basin	West wind	East wind	West wind minus east wind	*U* increases during season	*U* decreases during season	*U* increase minus *U* decrease
South Pacific	7.6	5.8	1.8	6.7	6.7	0.0
Australia Region	8.9	9.4	−0.5	9.6	9.1	0.5
South Indian Ocean	8.8	10.2	−1.4	9.4	9.8	−0.4
Total	25.3	25.4	−0.1	25.7	25.6	0.1

These linkages of El Niño and the 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 the effects of the QBO and El Niño signals are combined. It is interesting to note the very low degree of seasonal hurricane activity that occurred in the strong El Niño (very low SOI) years of 1972 (only six hurricane days) and 1983 (five hurricane days), when 30 mb easterly stratospheric QBO regimes were simultaneously present with strong El Niño events.

There is a growing awareness of the biennial variability of a number of tropospheric phenomena (Angell *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 atmosphere–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 for the Atlantic region only.

Influences of the QBO and El Niño on Atlantic storm frequency are likely more pronounced than in the other ocean basins because the Atlantic is a more marginal region for hurricane activity. The usual type of tropical storm development within a monsoon trough does not typically occur in the Atlantic. Atlantic yearly hurricane activity can vary from zero (as in 1907 and 1914) or one (as in 1906, 1919 and 1925) to 10 (as in 1933 and 1969) or 11 (as in 1916 and 1950). 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 changes. In El Niño years (and low SOI situations) hurricane activity in the Australian region (Nicholls, 1979, 1984) 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., often may not be the most important influences on 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 discussed by Madden and Julian (1971, 1972), and circulation changes brought about by fluctuations in the strength of the Asian summer monsoon. Future papers will deal with these topics.

Part II will discuss how information on El Niño and the 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.

For more information on this subject the reader can consult a more detailed Colorado State University project report (see Gray, 1983).

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