The Relationship of the Quasi-biennial Oscillation to Atlantic Tropical Storm Activity

LLOYD J. SHAPIRO

Hurricane Research Division/AOML, Miami, Florida

(Manuscript received 14 October 1988, in final form 2 February 1989)

ABSTRACT

Monthly averaged 30 and 50 mb zonal winds at Balboa are used to determine objectively the relationship of the quasi-biennial oscillation (QBO) to seasonal (August through October) Atlantic tropical storm activity during the years 1952–86. The largest correlations between storm activity and the 30 mb wind are found in June, which is 3 months before the center of the season. Extrapolation and direct calculation confirm a near in-phase relationship between tropical storm activity and the zonal wind at about 50 mb.

Zonal winds filtered to remove periods $\lesssim$ 1 yr are used to establish correlations between the QBO and tropical storm activity for 1955–83 that are essentially independent of the month considered. A correlation at 30 mb is established with a conservative estimate of true skill, from both in-phase and out-of-phase information, that explains 30% of the variance in storm activity. The skill is much greater than that estimated from seasonal classifications of the QBO. The statistics are resilient to removal of the effects of the El Niño cycle. When El Niño years are explicitly excluded, the true skill explains an estimated 32% of the variance. Low-latitude storms are even more strongly related to the QBO.

Physical mechanisms possibly responsible for the observed associations are discussed in light of these results. A mechanism for the observed correlations is suggested that emphasizes the difference between lower-tropospheric steering and the lower-stratospheric zonal wind. The relationships of the results, and suggested physical mechanism, to those of Gray are considered.

1. Introduction

The equatorial stratospheric quasi-biennial oscillation (QBO) is most clearly evident as a global-scale, zonally symmetric oscillation of the zonal wind. The observed characteristics of the QBO are reviewed by Wallace (1973) and Holton (1975, 1983). Coy (1979) and Naujokat (1986) display time–height sections of the zonal wind. The QBO has a period of about 26 months, and largest amplitude near 30 mb. The phase of the zonal wind propagates downward at about 1 km/month. The physical mechanism responsible for the general structure and behavior of the QBO has been established (see reviews by Holton 1975, 1983). The QBO has been found to be related to the interannual variability of the extratropical Northern Hemisphere winter stratosphere (Holton and Tan 1982). The large interannual variability associated with the Southern Oscillation, however, complicates the interpretation of the relationships (Van Loon et al. 1982; Van Loon and Labitzke 1987).

The QBO used in the present analysis is specified from monthly averaged 30 and 50 mb (~24 and 21 km) zonal winds at Balboa (9°N, 80°W) for the years 1952 through 1986. The spectrum of the 30 mb wind, u_{30}, is shown in Fig. 1. A clear spectral peak is evident in the QBO frequency band, with a dominant period slightly greater than 2 years. The annual cycle also appears as a weaker, but still significant, signal. The spectrum of the zonal wind at 50 mb (not shown) is very similar to that in Fig. 1, but the power in the QBO frequency band is about half that at 30 mb.

QBOs are also present in the troposphere, but are weaker than that in the stratosphere. Studies have evaluated apparent QBOs in features including sea level zonal wind (Angell and Korshover 1968), and the strength and position of the subtropical highs (Angell and Korshover 1974; Angell et al. 1969). Trenberth (1980) contains references to many such studies. The QBO signal in the Northern Hemisphere troposphere appears to be very weak during the summer (Angell and Korshover 1968). The relationship between tropospheric QBOs and that in the equatorial stratosphere is a topic of recent research (e.g., Trenberth 1980).

Gray (1984a,b) has described a striking relationship between the QBO and Atlantic tropical storm activity. When the stratospheric QBO, as defined by the zonal wind at Balboa near 30 mb, is in the westerly phase of its oscillation during the Atlantic hurricane season, the seasonal number of tropical storms and hurricanes tends to be substantially greater than in the easterly

---

Corresponding author address: Dr. Lloyd J. Shapiro, NOAA/ERL, Hurricane Research Division/AOML, 4301 Rickenbacker Causeway, Miami, FL 33149.

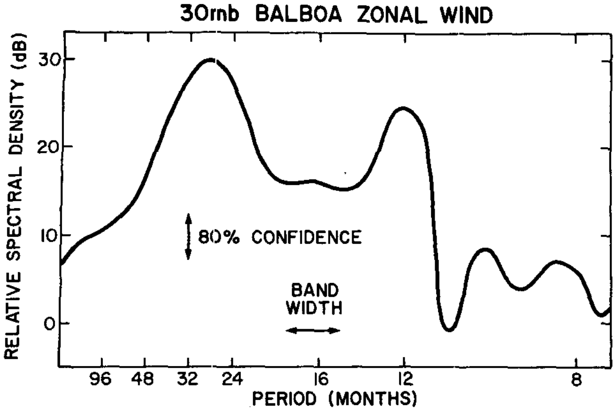

FIG. 1. Spectrum of 30 mb zonal wind at Balboa for 1952–86.

phase. The physical mechanism responsible for the observed relationships was not established. Angell et al. (1969) had previously found an apparent QBO in the monthly frequencies of hurricanes. Shapiro (1982) found a coherence in regional hurricane occurrence that could be related to the QBOs found by Angell et al. (1969).

The seasonal Atlantic tropical storm frequency, TS, is shown in Fig. 2 for 1952 through 1986. Only storms that formed during August through October, the central part of the hurricane season when 80% of the storms occurred, are included. All storms classified as subtropical (Neumann et al. 1987) have been omitted. A plus sign (+) is indicated at the top of the figure if the average 30 to 50 mb, August through October zonal wind anomaly of the given year was greater than +3.0 m s^{-1}; a minus sign (−) is indicated if the anomaly was less than −2.7 m s^{-1}. Wind anomalies are evaluated by subtracting the 35-year mean for each calendar month. These classifications of phase, corresponding to west (+), east (−), and transition (no sign), agree almost identically with those given by Gray (1984a) through 1982. The only exception is 1963, classified here as a QBO west season, but as a transition year by Gray. Note that the year 1982 was specified incorrectly in Gray (1984a,b), but has been corrected in later analyses (Dr. William Gray, personal communication 1987).

There is a factor of 1.4 greater tropical storm activity in seasons during the west phase than during the east phase of the QBO. Following Gray (1984b), a predictor of seasonal tropical storm frequency can be developed by assigning the value +1 for seasons in the west phase of the QBO (+), −1 for east (−), and 0 for transition seasons. This measure of the QBO, with correlation coefficient $r = 0.47$, explains 22% of the variance in tropical storm activity. The reduction of variance $R^2 = 0.22$, with $m = 1$ predictor, is based on the developmental data. Random errors inflate R^2 over the true skill, S, and the expected forecast skill on an independent sample, $\langle S_F \rangle$. The methods used to estimate S and $\langle S_F \rangle$ are described in the Appendix. In the present example, $S \approx 0.20$ and $\langle S_F \rangle \approx 0.12$. Thus, the estimated true skill for Atlantic tropical storm activity is substantial. A second predictor can be developed to represent the *change* of the 30 mb zonal wind during the season, as in Gray (1984b), by assigning the value +1 for zonal wind increasing, −1 for decreasing, and 0 for no change. The values in Table 5 of Gray (1984b) are supplemented by −1 in 1983, +1 in 1984, 0 in 1985, and −1 in 1986. The correlation of this second predictor with tropical storm activity is $r = 0.23$. Its inclusion in the regression with the first predictor ($m = 2$) gives $R^2 = 0.22$, $S \approx 0.17$, and $\langle S_F \rangle \approx 0.07$. Since both the estimates of S and $\langle S_F \rangle$ are decreased below that for the phase of the QBO alone, the additional predictor representing the seasonal change of the QBO has no forecast utility.

Gray (1984a,b) also found a strong relationship between seasonal Atlantic tropical cyclone activity and the occurrence of El Niño events. Seasons when a moderate or strong El Niño episode occurred (see Table 1 of Gray 1984a) are designated "EN" on the top of Fig. 2. Tropical storm activity during these seasons tended to be low. Whereas Gray used seasonal data, Shapiro (1987) related monthly Atlantic tropical storm activity to monthly mean winds in the Atlantic basin. Relationships with the El Niño/Southern Oscillation (ENSO) were determined from an objective El Niño index (ENI), based on sea surface temperature (SST) anomalies over the equatorial eastern Pacific through 1983 (Weare 1986). The results supported Gray's hypothesis that changes in the upper-level tropospheric winds in the Atlantic basin modulate storm activity during El Niño episodes. Increased SSTs over the equatorial eastern Pacific are associated with increases in 200 mb westerlies over the North Atlantic basin. The resulting increase in the low-level to 200 mb vertical shear is unfavorable for tropical cyclone development, probably due to the "ventilation" of the de-

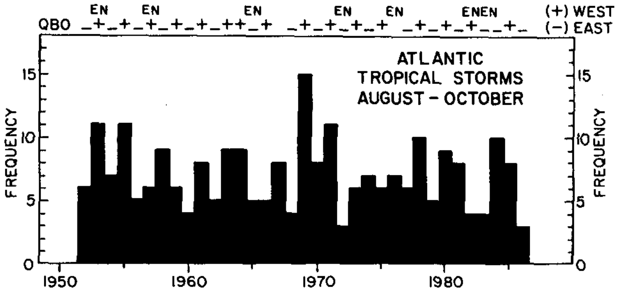

FIG. 2. Atlantic tropical storm activity for August through October, TS. Plus sign (+) indicates a QBO west year, minus sign (−) a QBO east year, and no sign a transition year. El Niño years are designated "EN."

veloping convective system (Gray 1968, 1979). Horizontal advection relative to the moving system tends to prevent the accumulation of heat and moisture that is required for strengthening.

Analyses in section 2 use monthly averaged stratospheric winds at Balboa to determine objectively the relationship of the QBO to Atlantic tropical storm activity. The use of monthly averaged winds allows a more refined and complete analysis of the relationships than is possible with seasonal statistics. The correlations provide information on the vertical level of in-phase association between the QBO and tropical storm development. The use of monthly data also allows the evaluation of conservative estimates of predictive skill that do not depend on the month considered. The effect of the ENSO on the correlations is also evaluated. Implications of the results for the physical mechanisms possibly responsible for the observed relationships are discussed in section 3.

2. Tropical storm activity and the monthly averaged QBO

Use of seasonal QBO statistics, as described in section 1, neglects important information present in the monthly averaged data. Figure 3a shows the reduction of variance due to the correlation between seasonal tropical storm activity, TS, and the 30 and 50 mb zonal winds for each calendar month April through November. For example, the 30 mb value in September is $r^2[\mathrm{TS}, u_{30}(\mathrm{September})]$, where the correlation, $r > 0$, is evaluated for the 35-year sample. At 30 mb the maximum $r^2 = 0.21$ in June, which is 3 months before the center of the August–October season. In a separate calculation (not shown), correlations with tropical storm activity during the individual months August, September, October confirm an average ~3 month lead of u_{30} relative to tropical storm activity. Since the phase of u propagates downward at ~1 km/month, extrapolation implies that the maximum correlation with u should be approximately in phase with storm activity ~3 months × 1 km/month = 3 km below 30 mb. That level is ~21 km, or ~50 mb. The correlation at 50 mb has its largest values during the months August–October, consistent with this extrapolation. Correlations with individual months confirm an average in-phase relationship at that level. The maximum at 50 mb of $r^2 = 0.14$ in August and October; this value is smaller than the maximum at 30 mb since, as noted in the discussion of Fig. 1, the QBO explains less of the total variance in u at the lower level. In spite of its smaller maximum, $r^2(\mathrm{TS}, u_{50}) \geqslant r^2(\mathrm{TS}, u_{30})$ during August–October due to the near in-phase association of u_{50} with tropical storm activity. The implication of this in-phase association for the physical mechanism that may be responsible for the observed relationships is discussed in the next section.

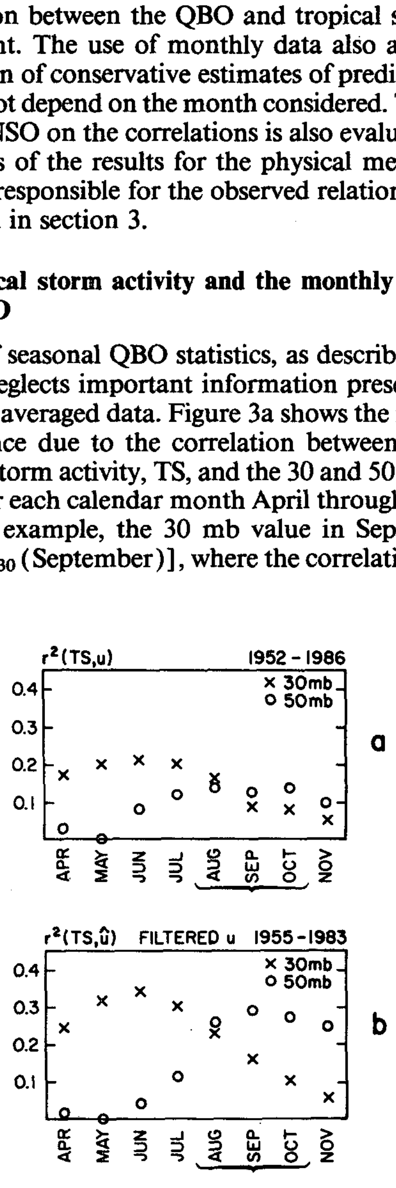

FIG. 3. (a) Reduction of variance, r^2, due to correlation between Atlantic tropical storm activity, TS, and Balboa zonal wind, u, for given calendar months. All correlations $r > 0$, except that in April at 50 mb. The months used to derive TS are bracketed. (b) As in panel (a) but with low-pass filtered zonal winds, $\hat{u}$. Filter is illustrated in Fig. 4.

The amplitude and phase of the QBO depend on the vertical level. Thus, the correlation of tropical storm activity with the QBO at a given level depends on the month considered. Since the physical mechanism for the correlations has not yet been established, there is no a priori reason for choosing any particular month. Selection of the maximum correlation in an a posteriori analysis inflates the artificial skill expected purely by chance (Davis 1977; Shapiro 1984; Shapiro and Chelton 1986). Estimates of S and $\langle S_F \rangle$ that are based on a priori considerations, as described in the Appendix, will tend to be too large. Thus, estimates of true and expected forecast skill are difficult to determine from the correlations presented in Fig. 3a. As is clear in Fig. 1, the raw data contain substantial variability at periods less than on of the order of one year. The difficulties with the estimation of skill can be alleviated by application of a filter designed to remove power at these periods. A low-pass least-squares filter (Bloomfield 1976), with the power response function given in Fig. 4, is applied to the zonal wind series u_{30} and u_{50}. The filter has a span of 6 years and a cutoff period of 14 months, which effectively removes the annual cycle and higher frequencies. Use of the filter necessitates a loss of 3 years at the beginning and end of the record, so only years 1955–83 are considered. Figure 3b shows the reduction of variance in TS from the filtered zonal winds, $\hat{u}_{30}$ and $\hat{u}_{50}$.

The correlations in Fig. 3b are larger than those in Fig. 3a, mostly due to the shorter record. The phase relationships are, however, essentially unchanged. The

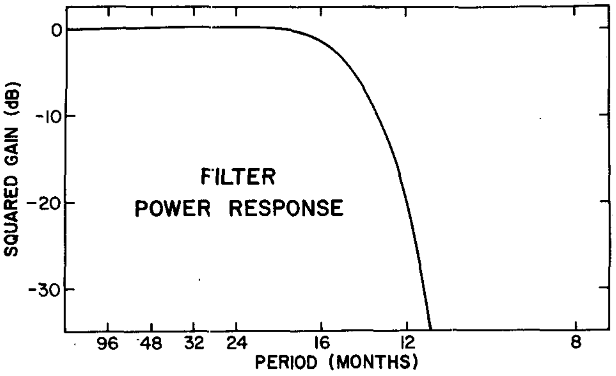

FIG. 4. Power response function of low-pass filter used to derive $\hat{u}$.

maximum correlation of TS with $\hat{u}_{50}$ occurs in September, thus confirming a near in-phase association with tropical storm activity. Due to the dominance of the narrow spectral peak in the QBO frequency band, the time derivative of $\hat{u}_{30}$ is nearly in quadrature with $\hat{u}_{30}$ itself, i.e., $r(\hat{u}_{30}, d(\hat{u}_{30})/dt) \approx 0$ for each month. During August–October $r(\mathrm{TS}, d(\hat{u}_{30})/dt) < 0$ (not shown), consistent with the *lead* of the maximum of $r(\mathrm{TS}, \hat{u}_{30})$ with respect to the hurricane season. This result is contrary to that from the positive correlation between TS and the change of the 30 mb wind during the season, as in section 1 and Gray (1984a,b). In contrast to the present results, Gray (1984a) inferred a *lag* of the 30 mb zonal wind with respect to hurricane and tropical storm development. This association, which implies an in-phase relationship at levels *above* 30 mb (cf. Fig. 24 of Gray 1984a), is modified by the more refined analysis of the present section.

A conservative estimate of the true and expected forecast skill can now be obtained by inclusion of $\hat{u}_{30}$ and $d(\hat{u}_{30})/dt$ in a multiple regression; $R^2[\mathrm{TS}; \hat{u}_{30}, d(\hat{u}_{30})/dt] = 0.35$. This value is nearly independent of the month considered, and is almost the same as the maximum value of $r^2(\mathrm{TS}, \hat{u}_{30})$ seen in Fig. 3b in June. By the standard F-test (e.g., Kleinbaum and Kupper 1978), the multiple correlation is found to be significant at the 99.5% level. Since the two predictors in the regression are chosen before the evaluation of the correlation, values of true and forecast skill can be estimated from a priori considerations ($m = 2$): $S \approx 0.30$ and $\langle S_F \rangle \approx 0.20$. The corresponding estimates at 50 mb are $S \approx 0.24$ and $\langle S_F \rangle \approx 0.14$. An a priori estimate of skill for September from $\hat{u}_{50}$ by itself, based (say) on its in-phase relation to TS, gives $S \approx 0.27$, $\langle S_F \rangle \approx 0.19$. These values are all larger than the estimates of skill based on the seasonal QBO classifications utilized in section 1, for the shorter record 1955–83: for seasonal QBO alone ($m = 1$), $S \approx 0.20$, $\langle S_F \rangle \approx 0.10$; for seasonal QBO and its change during the season ($m = 2$), $S \approx 0.17$, $\langle S_F \rangle \approx 0.06$. Therefore, the use of filtered monthly-averaged QBO statistics increases the estimate of the predictive ability for tropical storm activity from the QBO.

As discussed in section 1, the El Niño plays an important role in determining the character of the Atlantic hurricane season (Gray 1984a; Shapiro 1987). It is necessary to isolate the association of tropical storm activity with the QBO from the possible influence of the ENSO, especially considering the potential difficulties in separating their effects on the circulation (Van Loon et al. 1982; Van Loon and Labitzke 1987). Gray (1984b) found that the seasonal measure of the QBO was essentially independent of the occurrence of moderate or strong El Niño events, so that the two gave essentially independent contributions to the regression. An alternate method of establishing the effect of the ENSO is to use the El Niño index, ENI, as described in section 1.

Shapiro (1987) found a stronger association of the Atlantic tropical circulation with the ENI than with a Southern Oscillation index. The Atlantic circulation is more directly related to the regional SST anomalies over the equatorial central and eastern Pacific, represented by the ENI, than to the more global variations associated with the Southern Oscillation. The correlation between TS and ENI, as measured by Weare's (1986) index averaged for August–October, is $r(\mathrm{TS}, \mathrm{ENI}) = -0.33$, with estimated true skill $S \approx 0.08$. This skill is nearly the same as that obtained by Shapiro (1987) from monthly data. The inclusion of the September $\hat{u}_{30}$ and $d(\hat{u}_{30})/dt$ into the regression then gives a multiple correlation $R^2[\mathrm{TS}; \mathrm{ENI}, \hat{u}_{30}, d(\hat{u}_{30})/dt] = 0.38$, with estimated $S \approx 0.31$. The significance of the additional reduction of variance can be determined from the multiple–partial correlation (e.g., Kleinbaum and Kupper 1978), $R^2[\mathrm{TS}; \hat{u}_{30}, d(\hat{u}_{30})/dt | \mathrm{ENI}] = 0.31$, the reduction of variance due to $\hat{u}_{30}$ and $d(\hat{u}_{30})/dt$ given that ENI is already in the regression. The estimate of the fraction of the remaining true skill explained by the additional predictors is $(0.31 - 0.08)/(1 - 0.08) = 0.25$. This result is to be compared with $S \approx 0.30$, as derived above from $R^2[\mathrm{TS}; \hat{u}_{30}, d(\hat{u}_{30})/dt]$. Application of the F test to the multiple-partial correlation implies that the additional predictors are significant at the 99% level. Thus, accounting for the El Niño cycle retains the strong relationship found between the QBO and tropical storm development. This conclusion agrees with that of Gray (1984a,b).

When El Niño years (see Fig. 2) are explicitly excluded from the sample, the estimate of true skill from September $\hat{u}_{30}$ and $d(\hat{u}_{30})/dt$ is $S \approx 0.32$. This value is almost the same as that obtained for all years in the sample, thus confirming the resilience of the statistics to removal of the effects of the El Niño cycle. El Niño events most strongly affect low-latitude systems; the correlation between ENI and tropical storm activity is largest for these systems. When only storms that formed south of 20°N are included in the sample, $S \approx 0.36$

for the non-El Niño years. Thus, low-latitude storms are more strongly related to the QBO than is the seasonal total.

3. Summary and implications for physical mechanisms

The statistical estimates of the predictability of Atlantic tropical storm activity from the QBO are compelling. From both in-phase and out-of-phase information, the present analysis has established a correlation at 30 mb with an estimate of true skill that explains 30% of the variance. The correlation is significant at the 99.5% level. The skill is much greater than that obtained from seasonal classifications of the QBO. When El Niño years are explicitly excluded, the true skill $S \approx 0.32$. The estimated true skill for hurricane activity (not shown), derived separately, explains about 23% of the variance. When El Niño years are excluded, $S \approx 0.24$. The natural question is what physical mechanisms can explain these strong relationships?

The relationships could possibly be explained by a tropospheric QBO that is correlated with both the stratospheric QBO and tropical storm activity. If the stratospheric QBO were correlated with the 200 mb zonal wind over the tropical Atlantic, for example, then modulation of tropical storm activity by the 200 mb winds would lead to a correlation with TS. The tropospheric QBO could be either dynamically coupled to the stratospheric QBO, or due to an alternate mechanism such as air-sea interaction (Nicholls 1978; see discussion in Trenberth 1980). Tropospheric QBOs are weak, however, and appear to be especially so at low latitudes in the Northern Hemisphere summer (Angell and Korshover 1968; Ebdon 1975). My own calculations of the correlation between the 30 mb zonal wind at Balboa and tropospheric winds in the Atlantic south of 40°N (not shown) find no relationships that explain a significant amount of variance. There is no evidence of a tropospheric QBO in the summer tropical Atlantic that is of sufficient strength to account for the substantial correlation between the stratospheric QBO and tropical storm activity.

As noted in section 2, low-latitude storms are even more strongly related to the QBO than is the seasonal total. When only storms that formed south of 20°N are included, $S \approx 0.36$ for the non-El Niño years. Since the stratospheric QBO has its largest amplitude near the equator, a direct physical link is suggested. Gray (1984a) assumed that the correlation between the QBO and hurricane and tropical storm activity was due to a direct interaction in the stratosphere. From the positive correlation between activity and the change of the 30 mb zonal wind during the season, and the inferred lag of the wind relative to storm development, Gray speculated that the correlations could be related to the depth of the westerly anomalies in the stratosphere. No specific mechanism was given for the relationship.

Results of the present study indicate, however, that the 30 mb wind *leads* tropical storm activity. Extrapolation and direct calculation confirm a near in-phase relationship with the zonal wind at about 50 mb. A separate calculation for hurricane activity gives the same result. The present analysis has established a correlation between the filtered zonal wind at 50 mb in September and tropical storm activity with an estimated true skill that explains 27% of the variance. An estimated 17% of the variance in hurricane activity is explained. The in-phase relationship implies that if the correlations are due to a direct interaction between the QBO of the stratospheric zonal wind and the developing tropical systems, then the locus of the interaction should be near 50 mb. More recent evidence reported by Gray (1988) supports this view.

In the Northern Hemisphere summer, the stratospheric winds near the equator are easterly. For example, Fig. 5 displays the mean zonal wind, $U(p)$, at Curacao (12°N, 69°W) in September for the years 1969–78. The mean zonal wind $U(p)$ for the years during the east or west phase of the QBO is also shown at 30, 50 and 100 mb. The winds have been linearly interpolated between the subset of mandatory levels reported in Monthly Climatic Data for the World (available from the National Climatic Data Center, NESDIS, NOAA, Federal Building, Asheville, NC 28801). As noted by Gray (1988), when the QBO is

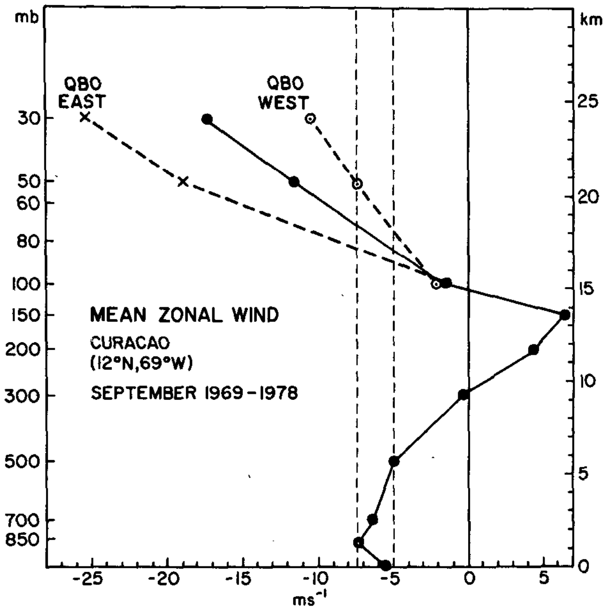

FIG. 5. Mean zonal wind, U, at Curacao for September, 1969–78. Crosses (×) indicate average for QBO east years (1970, 1972, 1974, 1977), open circles (O) for QBO west years (1969, 1971, 1973, 1975, 1978).

in the west phase of its oscillation the easterlies are reduced. The variability at 100 mb and below is small. Thus the easterly vertical shear across the 100 to 50 mb layer is substantially smaller during the west than during the east phase.

Gray (1988) attributes the effect of the QBO to the direct influence of the zonal wind on convective penetration above the tropopause, and hypothesizes that tropical cyclone activity "is inhibited in easterly phase QBO periods because of the extra lower stratospheric wind ventilation and resulting greater upper tropospheric to lower stratospheric vertical wind shear." Gray (1988) reports that this vertical shear may also explain increased tropical cyclone activity in the low-latitude northwest Pacific during the east phase of the QBO, opposite to the relationship in the Atlantic. The effect of the QBO on the vertical shear suggests a possible thermodynamic influence on tropical systems. The stratospheric QBO is in near geostrophic balance even very close to the equator (Reed 1962). An easterly vertical shear is in balance with a poleward temperature gradient, so the near-equatorial temperature is relatively cold. Thus, the smaller easterly vertical shear during the west phase of the QBO is associated with a warmer near-equatorial temperature in the 50 to 100 mb layer than during the east phase. Since this warmer temperature would tend to stabilize the lower stratosphere, it is not likely to explain the observed increase in tropical storm activity during the west phase.

Tropical systems in the trade easterlies propagate westward as a coherent system due to vertical coupling by convection. Convective towers can extend above the level of zero buoyancy, often to levels as high as the tropopause, near 100 mb. Shapiro (1986) found that the synoptic-scale wave disturbances in the tropical Atlantic propagated westward slightly faster than the easterly wind at the 850 mb "steering" level. The phase speed was nearly constant up to ~150 mb, implying convective coupling at least up to that level. There is evidence that the circulation of developing tropical disturbances extends substantially higher. For example, the upper-level vorticity center in a developing Caribbean system analyzed by Yanai (1968) extended above the highest analysis level of 100 mb (see his Fig. 10a). The formative tropical cyclone studied by Fett (1966) displayed a similar structure. Stronger tropical systems, tropical storms and hurricanes, are even more clearly coupled to the lower stratosphere. Results based on rawinsonde data (e.g., Koteswaram 1967) and U-2 aircraft flights (see Figs. 16–20 of Black 1977) confirm that cold anomalies associated with hurricanes often extend above the tropopause into the 60 to 80 mb layer (see also discussion in Gray 1988). The anomalies are probably due to air rising adiabatically above the convection. The role of the anomalies in the evolution of the storms has not, however, been established.

The zonal winds in Fig. 5 thus suggest a possible interpretation of the observed association between the QBO and Atlantic tropical storm activity that is more closely related to the steering winds at lower tropospheric levels than in Gray's (1988) hypothesis. Although tropical cyclone genesis is relatively uncommon in the southeast Caribbean, where Curacao is located, the winds in Fig. 5 do well represent the typical influence of the QBO on the environment in which Atlantic disturbances evolve. The vertical dashed lines in Fig. 5 delineate the approximate range of speeds of disturbances in the Atlantic trade easterlies, as represented by the Curacao winds. Weak disturbances tend to propagate at approximately the speed of the 850 mb zonal wind, as noted above. The phase speed $c = -7.5$ m s^{-1} is the 850 mb wind speed at Curacao. Stronger systems, including tropical storms and hurricanes, move at speeds close to the wind at midtropospheric, 500–700 mb, levels (Chan and Gray 1982). The speed $c = -5$ m s^{-1} is the speed of the 500 mb zonal wind at Curacao. The *relative* wind, $U - c$, which advects air relative to the moving system, depends on the phase of the QBO. For the slower systems with $c \sim -5$ m s^{-1}, for example, the relative wind at 70 mb is close to 0 m s^{-1} during the west phase of the QBO, but ~ -7 m s^{-1} during the east phase. The small relative advection during the west phase could allow greater coupling of the lower stratosphere with the tropospheric system than during the east phase of the QBO. The upper-level cold anomaly, for example, could be more easily maintained. The strong relative winds during the east phase could advect air away from the developing system, thereby disturbing its organization and inhibiting intensification.

For the faster disturbances with $c \sim -7.5$ m s^{-1}, the contrast between the magnitude of the relative wind at 70 mb during the west phase ($\sim$2.5 m s^{-1}) and the east phase (~ -4.5 m s^{-1}) is not as extreme. For these faster, propagating, systems another mechanism may also influence disturbance development. During the east phase of the QBO the critical level, where $U = c$, is at ~80 mb; during the west phase it is at ~50 mb. Absorption of upward wave energy fluxes, due to convective heating, near the critical level (Shapiro et al. 1988) could contribute to decoupling of the lower stratosphere from the developing system. Secondary circulations generated by energy flux convergence near the level of absorption may possibly modulate system development, by interaction with the convection. These effects would be greater during the east phase of the QBO, when the critical level is lower.

Although this analysis refers to a typical situation in the Atlantic trades, it is only illustrative; the difference between the relative winds, and the critical levels, in the east and west phases of the QBO will depend on the actual speed of the disturbance as well as the zonal wind profile during each phase. The present conjecture emphasizes the difference between lower-tropospheric steering and the lower-stratospheric wind, while the hypothesis of Gray (1988) emphasizes differences between upper-tropospheric and lower-stratospheric winds. Favorable upper-tropospheric winds, which affect the low-level to 200 mb vertical shear, are a crucial prerequisite for tropical cyclone formation. Changes in these upper-tropospheric winds are not, however, associated with the QBO.

More observations of developing tropical systems in different wind regimes are clearly required before the present conjecture can be confirmed. Observations and modeling of disturbance development require a realistic representation of the interactions and feedbacks that contribute to the evolution of the convective system, including vertical coupling by momentum transports and energy fluxes across the tropopause. These interactions and feedbacks are difficult to model and are not well understood. The statistical results presented here, particularly the near in-phase relationship between tropical storm activity and the 50 mb zonal wind, provide a quantitative context in which to place any proposed physical mechanism. It is still possible, of course, that a tropospheric QBO—in phase with the 50 mb stratospheric zonal wind—will be identified that can explain the relationships.

Acknowledgments. I am greatly appreciative to Mr. Robert Black and Drs. Peter Black, Kirby Hanson, Stephen Lord, Duane Stevens and Hugh Willoughby for discussions that have helped to clarify my thoughts on this topic. The stratospheric wind values were provided by Dr. J. K. Angell of the Air Resources Laboratory, NOAA.

APPENDIX

Estimates of True Skill and Expected Forecast Skill

The regression equations for the prediction of tropical storm activity are developed from a finite data sample. Thus, random errors will artificially inflate the skill (e.g., Davis 1977). An estimate of the artificial skill expected purely by chance, $\langle S_A \rangle$, and true skill, S, are easily obtained (Chelton 1983):

$$\langle S_A \rangle \approx (m/N^*)(1-R^2)/(1-m/N^*),$$

where R^2 is the reduction of variance (the "hindcast" skill), m is the number of predictors, and N^* is the effective number of degrees of freedom. Since the predictand series, the seasonal number of tropical storms, is nearly random (serially uncorrelated) $N^* \approx N$, the number of samples in the series. In general, a conservative estimate of N^* can be determined from hindcasts at long lag (Davis 1977; Chelton 1983). The true skill is estimated by

$$S \approx R^2 - \langle S_A \rangle \approx (R^2 - m/N^*)/(1-m/N^*).$$

The expected forecast skill on an independent sample, $\langle S_F \rangle$, is estimated using a jackknife technique (Mosteller and Tukey 1977). The technique utilizes N regressions, each developed from the series with one sample (or several samples) withheld. Each regression equation is used to forecast the withheld, independent, predictand. The skill is then established from the N forecasts.

REFERENCES

Angell, J., and J. Korshover, 1968: Additional evidence for quasi-biennial variations in tropospheric parameters. *Mon. Wea. Rev.*, **96**, 778–784.

——, and ——, 1974: Quasi-biennial and long-term fluctuations in the centers of action. *Mon. Wea. Rev.*, **102**, 669–678.

——, —— and G. Cotten, 1969: Quasi-biennial variations in the "centers of action". *Mon. Wea. Rev.*, **97**, 867–872.

Black, P., 1977: Some aspects of tropical storm structure revealed by handheld camera photographs from space. *Skylab Explores the Earth*, NASA SP-380, 417–462. [Available from the Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20402. Stock No. 003-000-00674-8.]

Bloomfield, P., 1976: *Fourier Analysis of Time Series: An Introduction*, Wiley, 258 pp.

Chan, J., and W. Gray, 1982: Tropical cyclone movement and surrounding flow relationships. *Mon. Wea. Rev.*, **110**, 1354–1374.

Chelton, D., 1983: Effects of sampling errors in statistical estimation. *Deep-Sea Res.*, **30**, 1083–1103.

Coy, L., 1979: An unusually large westerly amplitude of the quasi-biennial oscillation. *J. Atmos. Sci.*, **36**, 174–176. Corrigendum: 1980, **37**, 912–913.

Davis, R., 1977: Techniques for statistical analysis and prediction of geophysical fluid systems. *Geophys. Astrophys. Fluid Dyn.*, **8**, 245–277.

Ebdon, R., 1975: The quasi-biennial oscillation and its association with tropospheric circulation patterns. *Meteor. Mag.*, **104**, 282–297.

Fett, R., 1966: Upper-level structure of the formative tropical cyclone. *Mon. Wea. Rev.*, **94**, 9–18.

Gray, W., 1968: A global view of the origin of tropical disturbances and storms. *Mon. Wea. Rev.*, **96**, 669–700.

——, 1979: Hurricanes: Their formation, structure and likely role in the tropical circulation. *Meteorology over the Tropical Oceans*, D. B. Shaw, Ed., Roy. Meteor. Soc., 155–218.

——, 1984a: Atlantic seasonal hurricane frequency. Part I: El Niño and 30 mb quasi-biennial oscillation influences. *Mon. Wea. Rev.*, **112**, 1649–1668.

——, 1984b: Atlantic seasonal hurricane frequency. Part II: Forecasting its variability. *Mon. Wea. Rev.*, **112**, 1669–1683.

——, 1988: Environmental influences on tropical cyclones. *Aust. Meteor. Mag.*, **36** 127–140.

Holton, J., 1975: *The Dynamic Meteorology of the Stratosphere and Mesosphere. Meteor. Monogr.* No. 37, Amer. Meteor. Soc., 216 pp.

——, 1983: The stratosphere and its links to the troposphere. *Large-scale Dynamical Processes in the Atmosphere*, B. Hoskins and R. Pearce, Eds., Academic Press, 277–304.

——, and H.-C. Tan, 1982: The quasi-biennial oscillation in the Northern Hemisphere lower stratosphere. *J. Meteor. Soc. Japan*, **60**, 140–147.

Kleinbaum, B., and L. Kupper, 1978: *Applied Regression Analysis and Other Multivariate Methods.* Wadsworth, 556 pp.

Koteswaram, P., 1967: On the structure of hurricanes in the upper troposphere and lower stratosphere. *Mon. Wea. Rev.*, **95**, 541–564.

Mosteller, F., and J. Tukey, 1977: *Data Analysis and Regression.* Addison-Wesley, 586 pp.

Naujokat, B., 1986: An update of the observed quasi-biennial oscillation of the stratospheric winds over the tropics. *J. Atmos. Sci.*, **43,** 1873–1877.

Neumann, C., B. Jarvinen and A. Pike, 1987: *Tropical Cyclones of the North Atlantic Ocean, 1871–1986.* National Climatic Data Center, 186 pp. [Available from the National Environmental Satellite Data and Information Service, National Climatic Data Center, Asheville, NC 28801.]

Nicholls, N., 1978: Air–sea interaction and the quasi-biennial oscillation. *Mon. Wea. Rev.*, **106,** 1505–1508.

Reed, R., 1962: Evidence of geostrophic motion in the equatorial stratosphere. *Quart. J. Roy. Meteor. Soc.*, **88,** 324–327.

Shapiro, L., 1982: Hurricane climatic fluctuations. Part I: Patterns and cycles. *Mon. Wea. Rev.*, **110,** 1007–1013.

——, 1984: Sampling errors in statistical models of tropical cyclone motion: A comparison of predictor screening and EOF techniques. *Mon. Wea. Rev.*, **112,** 1378–1388.

——, 1986: The three-dimensional structure of synoptic-scale disturbances over the tropical Atlantic. *Mon. Wea. Rev.*, **114,** 1876–1891.

——, 1987: Month-to-month variability of the Atlantic tropical circulation and its relationship to tropical storm formation. *Mon. Wea. Rev.*, **115,** 2598–2614.

——, and D. Chelton, 1986: Comments on "Strategies for Assessing Skill and Significance of Screening Regression Models with Emphasis on Monte Carlo Techniques". *J. Climate Appl. Meteor.*, **25,** 1295–1298.

——, D. Stevens and P. Ciesielski, 1988: A comparison of observed and model-derived structures of Caribbean easterly waves. *Mon. Wea. Rev.*, **116,** 921–938.

Trenberth, K., 1980: Atmospheric quasi-biennial oscillations. *Mon. Wea. Rev.*, **108,** 1370–1377.

Van Loon, H., and K. Labitzke, 1987: The Southern Oscillation. Part V: The anomalies in the lower stratosphere of the Northern Hemisphere in winter and a comparison with the quasi-biennial oscillation. *Mon. Wea. Rev.*, **115,** 357–369.

——, C. Zerefos and C. Repapis, 1982: The Southern Oscillation in the stratosphere. *Mon. Wea. Rev.*, **110,** 225–229.

Wallace, J., 1973: General circulation of the tropical lower stratosphere. *Rev. Geophys. Space Phys.*, **11,** 191–222.

Weare, B., 1986: An extension of an El Niño index. *Mon. Wea. Rev.*, **114,** 644–647.

Yanai, M., 1968: Evolution of a tropical disturbance in the Caribbean Sea region. *J. Meteor. Soc. Japan,* **46,** 86–109.