Interaction of the quasi-biennial oscillation and stratopause semiannual oscillation

Timothy J. Dunkerton and Donald P. Delisi
Northwest Research Associates, Bellevue, Washington

Abstract. Analysis of rawinsonde and rocketsonde data at Ascension Island (7.6°S, 14.4°W) and Kwajalein (8.7°N, 167°E) in 1962–1991 suggests that the quasi-biennial oscillation (QBO) in the middle stratosphere is synchronized with the seasonal cycle and that descending westerly phases of the stratopause semiannual oscillation (SAO) are strongly influenced by the underlying QBO. The effect of the seasonal cycle on the QBO in the middle stratosphere is revealed in two, perhaps unrelated, observations: first, a tendency for deseasonalized QBO westerly maxima to occur in local winter (or to avoid local summer); second, a smooth, uninterrupted connection between descending SAO westerly shear zones and the formation of a new QBO westerly shear zone aloft. The timing of deseasonalized QBO westerly maxima in the middle stratosphere allows a simple composite of 2- and 3-year cycles to be constructed from the data, illustrating the effect of the QBO on descending westerly phases of the stratopause SAO.

1. Introduction

The quasi-biennial oscillation (QBO) of the equatorial stratosphere is so named because the average period of the oscillation is slightly longer than 2 years. Almost 20 cycles have been observed since rawinsonde data first became available in the early 1950s; the average period is now 28.4 months. Individual cycles range from ~22 to 36 months, i.e., from about 2 to 3 years.

The prefix “quasi” would apply equally well to an oscillation with continuously variable period, or an oscillation consisting of discrete periods (e.g., 24 months, with a few 30- or 36-month cycles) strung together in some regular or irregular fashion. The period of the QBO is customarily measured at mandatory rawinsonde pressure levels, e.g., 50, 30, or 10 mbar [Dunkerton and Delisi, 1985; Angell, 1986; Naujokat, 1986; Dunkerton, 1990]. This approach, based on one-dimensional time series, leads to the conclusion that the QBO period is variable, tending to form a continuous distribution as time progresses. Exact synchronization with the seasonal cycle is not observed, although as noted by Dunkerton [1990], the deseasonalized mean flow acceleration, distribution of phase onsets, and period of the QBO evidently depend on the time of year. This dependence on the seasonal cycle is due, in part, to a pronounced tendency for descending QBO easterlies to “stall” near 30 mbar between July and February [Naujokat, 1986]. Modulation of the QBO by the seasonal cycle can be distinguished from exact synchronization, which would produce one or more delta functions in the distribution of onset times. Both types of behavior were simulated in a QBO model [Dunkerton, 1990].

It was suggested by Lindzen and Holton [1968, p. 1101], however, that the QBO in the middle stratosphere is “synchronized” with the semiannual oscillation (SAO). Onset of QBO westerlies, in particular, is tied to the westerly phase of the SAO, and therefore “the appearance of successive westerly regimes at 30 km tends to be a multiple of 6 months” [Lindzen and Holton, 1968, p. 1106]. Using nearly four decades of rawinsonde data, Dunkerton [1990] found that QBO onsets at 10 mbar are modulated by the semiannual cycle, while onsets at 50 mbar display an annual variation. The comments of Lindzen and Holton, based on a combination of rawinsonde and rocketsonde data extending to higher altitudes, seem to imply a stronger synchronization than found at constant pressure levels by Dunkerton. It is noteworthy that the QBO attains maximum amplitude at or above the 10 mbar level [Hamilton, 1981] so rawinsondes alone cannot describe the entire phenomenon. Moreover, there is no reason to insist that the initiation of a new QBO phase, or maximum anomaly amplitude, should necessarily occur at the same pressure level in every cycle. Lindzen and Holton’s observations may therefore be compatible with Dunkerton’s conclusion, but it is unclear whether the data displayed in their Figure 6 (1962–1966) are representative of a longer time series. Another complication is that rocketsonde data used in the top part of their figure were obtained several degrees from the equator, and the seasonal cycle was not removed.

The purpose of this paper is to examine a longer time series of rawinsonde and rocketsonde data at Ascension Island (7.6°S, 14.4°W) and Kwajalein (8.7°N, 167°E), extending from 1962 to 1991. Our results demonstrate that Lindzen and Holton’s [1968] comments are generally valid at these off-equatorial locations during the time period analyzed. We also find that QBO westerly maxima tend to occur in local winter (or to avoid local summer) even when the seasonal cycle is removed from the data. Using deseasonalized westerly maxima to delimit QBO cycles, most of the deseasonalized QBO periods can be approximated by cycles of 24 or 36-month duration, with perhaps one or two 30-month cycles. This observation can be used to construct composite QBO cycles of 2 or 3 years’ duration, illustrating more succinctly the seasonal synchronization of QBO onsets and extrema in the middle stratosphere and the effect of the QBO on descending westerly phases of the SAO.

2. Data Analysis

Data from the historical rocketsonde network were obtained from a variety of sources and processed to form monthly means
of zonal wind at each station. Measurements were binned into 0.2 scale-height intervals (approximately 1.4 km, using a nominal pressure scale height of 7 km). The binned soundings were averaged together in each month, and a minimum of \( M \) soundings were required per month. Satisfactory results were obtained with \( M = 1 \), although “monthly mean” data are noisy, due to insufficient soundings, near the endpoints of the time period. The number of soundings per year at Ascension and Kwajalein is shown in Figure 1.

Rocket soundings usually include a partially overlapping, contemporaneous rawinsonde profile. After binning, rocketsonde and rawinsonde data were blended using a linear ramp in the height interval 3.7–4.7 scale heights. Starting at 3.7 scale heights, rawinsonde data were tapered to zero at 4.7 scale heights, and starting at 4.7 scale heights, rocketsonde data were tapered to zero at 3.7 scale heights, such that their combined weights equaled unity at each level in this height interval. The climatological seasonal cycle was obtained by averaging all months individually. Data were deseasonalized by removing the climatological seasonal cycle at each station from the respective time series. For clarity of presentation, blended data were smoothed once according to

\[
\bar{u}_{jk} = \sum_{p=1}^{+1} \sum_{q=-1}^{+1} u_{j+p,k+q} w_{j+p,k+q} + 7u_{jk} \tag{1}
\]

where

\[
w_{j,k} = \begin{cases} 1 & \text{if } u_{j,k} \text{ exists} \\ 0 & \text{otherwise} \end{cases} \tag{2}
\]

3. Results

Figures 2a–2g show time-height cross sections of monthly mean zonal wind at Ascension and Kwajalein. Several quantities are displayed: (1) deseasonalized westerlies equal to 20 ms\(^{-1}\) (thick solid contours); (2) deseasonalized easterlies equal to \(-20\) ms\(^{-1}\) (thin solid contours); (3) zonal wind with seasonal cycle included: (mostly westerly) winds \(\geq 5\) ms\(^{-1}\) (light shading); thin dotted contours in the shaded region indicate westerlies at 15 and 35 ms\(^{-1}\); (4) zonal wind with seasonal cycle included: (weak easterly) winds \(\leq 15\) ms\(^{-1}\) (unshaded); thin dotted contours in the unshaded region indicate westerlies at 35 and 55 ms\(^{-1}\); (6) regions where the shear-zone parameter \( R > 1 \) (see below), indicative of descending shear zones (diagonal lines). Blank regions indicate missing data. The definition of \( R \) is

\[
R = \text{sgn}(\bar{u}_z \cdot \bar{u}_\theta) \left( \frac{\bar{u}_z}{\sigma_z} \right)^2 + \left( \frac{\bar{u}_\theta}{\sigma_\theta} \right)^2 \tag{3}
\]

where \( \bar{u} \) is the mean zonal wind with seasonal cycle included, \( \bar{u}_z \) and \( \bar{u}_\theta \) are vertical shear and mean flow acceleration, respectively; \( \sigma_z \) and \( \sigma_\theta \) are the standard deviations of these quantities over the entire grid. \( R \) is a measure of shear-zone strength that gives equal emphasis to vertical shear and mean flow acceleration and is independent of the plot aspect ratio. Large positive \( R \) indicates shear-zone descent, since

\[
\frac{dz}{dt} = \frac{\bar{u}_\theta}{\bar{u}_z} \tag{4}
\]

Figure 2 shows that weak easterlies (dark shading) often run through the center of descending SAO/QBO shear zones at Ascension and Kwajalein.

3.1. Deseasonalized QBO Westerly Maxima

Westerly shear zones in the QBO descend faster than easterly shear zones, on the average, so that QBO westerly regimes are short-lived in the middle stratosphere, and it is relatively easy to determine the time of maximum deseasonalized westerlies (inside the thick solid contours). At Ascension the
deseasonalized QBO westerly maxima are located around 3.5–5 scale heights (25–35 km) and tend to occur in the middle of a calendar year. Such was the case in 1966, 1969, 1971, 1975, 1980, and 1985. Westerlies were probably a bit early in 1973 (a data gap) and slightly late in 1982 and 1987. (It would be more accurate to say that westerlies in 1982 and 1987 were early, by 6–9 months, due to unusually fast shear-zone descent.) At Ascension it is safe to conclude that in the time period shown, deseasonalized QBO westerly maxima tend to prefer local winter (i.e., northern hemisphere summer) or to avoid local summer (i.e., northern hemisphere winter). The same is evidently true of deseasonalized QBO easterly minima.

Comparing the two stations when simultaneous data are available, the deseasonalized westerly maxima at Ascension often lag those at Kwajalein by several (≤6) months, as in 1971, probably 1973, 1975, and 1980. In 1982 the maximum at Ascension preceded that at Kwajalein, while in 1985 and 1987, the maxima near 28 km were nearly coincident.

All of the deseasonalized QBO westerly maxima occur inside a westerly regime of the QBO defined by the total zonal wind (with seasonal cycle included) indicated by light shading. The annual cycle has a dramatic effect on QBO westerly regimes in the layer ~21–35 km, often splitting them in half about local summer. Such was the case at Ascension in early 1966, 1975, 1980, and 1988, and at Kwajalein in the middle of 1971, 1975, 1977, 1980, 1982, 1985, and 1987.

The tendency for deseasonalized QBO westerly maxima in the middle stratosphere to occur at the same time of year is useful for constructing 2- and 3-year composite QBOs (section 3.3).

3.2. Descending QBO Westerly Shear Zones

The “synchronization” observed by Lindzen and Holton [1968] describes how a new westerly shear zone of the QBO is triggered by a descending westerly shear zone of the stratosphere SAO. According to Figure 2, at Ascension there is indeed a spectacular and generally reliable connection between descending westerly shear zones of the SAO and QBO in the 28–56 km layer. Here, it is always the westerly acceleration phase of the “first” SAO cycle in a calendar year that connects to a new QBO westerly shear zone. This is not surprising, since at Ascension, the first SAO cycle is stronger than the second cycle, on the average, and SAO westerlies descend farther into the stratosphere in the first cycle [Garcia et al., this issue] (see

Figure 2. Time-height cross sections of monthly mean zonal wind at (a, b, d, f) Ascension and (c, e, g) Kwajalein. Deseasonalized winds equal to 20 ms$^{-1}$ are shown by thick solid contours; deseasonalized winds equal to $\pm 20$ ms$^{-1}$ are shown by thin solid contours. Light shading indicates winds (with seasonal cycle included) greater than $\pm 5$ ms$^{-1}$, i.e., westerlies or very weak easterlies. Thin dotted contours in the shaded region indicate westerlies at 15 and 35 ms$^{-1}$. Dark shading indicates winds (with seasonal cycle included) between $\pm 15$ and $\pm 5$ ms$^{-1}$. Easterly winds (with seasonal cycle included) less than $\pm 15$ ms$^{-1}$ are unshaded. Thin dotted contours in the unshaded region indicate easterlies at $\pm 35$ and $\pm 55$ ms$^{-1}$. Diagonal lines indicate regions where the shear-zone parameter $R$ is greater than 1 (see text). Altitude is approximate using a nominal pressure scale height of 7 km.
also section 3.3). On closer inspection the Ascension data suggest two distinct patterns of connection. The more common pattern is for SAO westerlies to descend in what might be called “year 0” (1965, 1968, 1970, 1972, 1974, probably 1977, 1979, and 1984) and to initiate a new QBO westerly regime then, but the decasionalized QBO westerly maximum near 28 km is delayed until the following “year 1” (1966, 1969, 1971, probably 1973, 1975, possibly 1978, 1980, and 1985). A less
common pattern is for the QBO westerly onset and maximum to occur in the same year (1982, 1987, and probably 1963) when the westerly shear zone descends unusually fast (possibly due to the enhanced Kelvin-wave activity found by Maruyama [1991, 1994] and Sato and Dunkerton [this issue]). There is apparently no relation, however, between the type of SAO/QBO connection pattern and the period of the next QBO cycle. Faster descent of QBO westerlies does not guarantee a
short QBO cycle, because the total period is also determined by the rate of QBO easterly shear-zone descent, which varies considerably [Dunkerton and Delisi, 1985; Dunkerton, 1990]. At Kwajalein, the situation is more complicated. Generally speaking, a new westerly phase of the QBO defined in terms of the total zonal wind (with seasonal cycle included) connects to the “second” SAO cycle in a calendar year, rather than to the first cycle as at Ascension. This also is not surprising, since at
Kwajalein, the second cycle is slightly stronger than the first, and SAO westerlies descend farther in the second cycle [Garcia et al., this issue] (see also section 3.3). The seasonal variation is stronger at Ascension, so that interpolated equatorial data display the same variation as at Ascension, consistent with balanced winds derived from satellite data [see Delisi and Dunkerton, 1988]. On the other hand, there are several occasions when the region of large shear-zonal parameter $R > 1$ connects back to the first SAO cycle, despite the fact that QBO westerlies connect to the second cycle. Such was the case in 1970, 1974, 1976, 1979, and 1981. (Note that a contiguous region of large $R$ has the same sign of shear and acceleration throughout; for example, the above mentioned times correspond to westerly shear and acceleration lying atop the QBO easterly phase.) In some years (e.g., 1972, 1976, 1981, 1991) the region of large shear parameter connects to the second cycle, a situation which can occur only if the SAO westerly onset precedes that of the QBO (since positive $R$ indicates a descending shear zone). In 1984 there was apparently no connection to the SAO, and in later years, the data are scarce and quite noisy.

It is interesting to consider what is happening at Kwajalein when the region of large shear-zonal parameter $R$ "bridges the gap" across northern hemisphere summer even though the westerlies themselves do not connect. Development of climatological easterlies in northern hemisphere summer evidently disrupts the connection between SAO and QBO westerlies without erasing the strong westerly shear zone formed during the first SAO cycle. The annual cycle of zonal wind is due primarily to horizontal advection of angular momentum by the mean meridional circulation and is characterized by relatively weak vertical shear and acceleration, compared to that associated with the westerly SAO and QBO. $R$ therefore tends to emphasize the SAO and QBO, so that a similar pattern is found at the two stations.

There is evidently a wave transport process common to both stations (e.g., Kelvin wave, mean-flow interaction) causing QBO westerly shear zones to form at the same time, despite the cross-equatorial asymmetry introduced by the annual cycle. The QBO and climatological SAO are not exactly symmetric about the equator, however [Garcia et al., this issue] (see also section 3.3). Differences of mean flow evolution between the two stations may indicate that some aspects of wave transport are sensitive to local conditions (e.g., gravity wave, mean-flow interaction).

Regions of strong easterly shear and acceleration are also apparent in Figure 2, but the connection between SAO and QBO, if any, is difficult to ascertain. Dunkerton [1990] found that easterly onsets at 10 mbar are modulated by the seasonal cycle, perhaps due to the modulation of onsets at 50 mbar. Periods of stalled easterly descent during northern hemisphere winter are visible at lower levels of the QBO, especially at Kwajalein.

### 3.3. Composite 2- and 3-year QBOs

The preceding discussion emphasizes the role of the seasonal cycle in determining the onset of QBO westerly phases and the timing of deseasonalized QBO westerly maxima in the middle stratosphere. The data also reveal an effect of the QBO on descending westerly phases of the SAO, vividly displayed in Figure 6 of Linden and Holton [1968]: SAO westerlies descend farther into the middle stratosphere as the westerly phase of the QBO wanes in the lowermost stratosphere. This behavior is apparent in Figure 2 (some good examples are 1973–1974 at Kwajalein and 1980–1981 at both stations [see Garcia et al., this issue] and was partially explained by Dunkerton [1979] as being due to the effect of the westerly QBO on Kelvin-wave transport. The QBO also modulates gravity-wave transport [Dunkerton, this issue], which is important in the SAO [Hitchman and Levy, 1988].

Another view of this phenomenon is obtained by constructing composites of two- and three-year QBOs, taking advantage of the observation in Figure 2 that deseasonalized QBO westerly maxima in the middle stratosphere are approximately synchronized with the seasonal cycle. Using deseasonalized westerly maxima at Kwajalein, together with Ascension Island data in time periods not covered at Kwajalein, we partitioned all of the observed QBO cycles into 2- or 3-year categories as follows: "2-year" cycles: 1969–1970, 1971–1972, 1973–1974, 1978–1979, 1983–1984, 1988–1989; "3-year" cycles: 1963–1965, 1966–1968, 1975–1977, 1980–1982, 1985–1987. In most cases this selection put deseasonalized QBO westerly maxima in the first year of the composite. In a few cases it may have been better to allow for 30-month cycles, for example, to account for the early arrival of QBO westerlies at Ascension at the end of 1962 and 1987. Nevertheless, we rounded each cycle to the nearest integral number of years (guided by Kwajalein data) in order to maximize the number of cycles in each composite. This compromise is not meant to suggest that 30-month cycles are unimportant but rather that the data record is too short to account for them.

Figure 3 shows 2- and 3-year composite QBOs at each station together with the climatological seasonal cycle derived from all years. Composite QBOs were derived using the total zonal wind (with seasonal cycle included) and display the effect of the QBO on descending westerly phases of the SAO. This effect is clearly seen in the 3-year composite, especially in the first (second) SAO cycle at Ascension (Kwajalein), i.e., the SAO westerly phase that normally descends farther at each station. The other SAO westerly phase is also influenced by the QBO but descends only about as far as the westerly phase immediately preceding it.

The fundamental difference between two- and three-year composite QBOs is the descending easterly phase, which is slower in the 3-year composite and contains an additional "ledge," or stall, just above 21 km (especially at Kwajalein). The different rate of easterly shear-zone descent can be detected at both stations in the first year of the composite, as well as in later years, suggesting a variation of QBO forcing on a longer timescale than the QBO itself. The QBO period is known to vary on a decadal timescale [Dunkerton and Delisi, 1985].

Another difference involves the onset of the new QBO westerly phase in the middle stratosphere. In the 2-year composite at Ascension the first SAO westerly phase in year 2 triggers a new QBO westerly phase. Similarly, in the 2-year composite at Kwajalein the second SAO westerly phase in year 2 is connected to a new QBO westerly phase, and there is evidence of a weak "bridge" to the first SAO cycle where $R > 1$ (diagonal lines) in the middle of year 2. We can unambiguously identify the start of the new QBO westerly phase, because its descent to the lower stratosphere is uninterrupted. On the other hand, the 3-year composites indicate that a new westerly shear zone forms in the middle stratosphere during year 2 but stalls. At Ascension this stall occurs at the base of the first and second SAO cycles in year 2, while at Kwajalein, it occurs at the base.
of the second cycle in year 2 and of the first cycle in year 3. At Ascension the stalled westerly shear zone seems disconnected from the onset of the true QBO westerly phase, which is triggered by the first SAO cycle in year 3. At Kwajalein the shear zone forms a little later, and there is a weak connection to the QBO onset.

The impression gained in the middle stratosphere is that a new westerly phase of the QBO tries to form in the middle of
year 2 in the 3-year composite but does not immediately initiate westerly shear-zone descent. This event may be likened to a "false start" of the QBO that either has no connection to the true onset of the next QBO westerly phase or represents an onset that will be delayed, partially interrupted by the annual cycle in year 3.

Descent of the new westerly phase in the 3-year composite is also delayed by the slower descent of QBO easterlies at lower levels and (as a result) a slower decay of westerlies in the lowermost stratosphere. Continuous descent of the new QBO westerly shear zone from the middle stratosphere begins in the last year of all composites, as westerlies in the lowermost stratosphere come to an end. It is clear that a new westerly shear zone can form in the middle stratosphere prior to the complete decay of QBO westerlies in the lowermost stratosphere but cannot descend into the lower stratosphere until the old westerlies decay. This observation suggests that (1) the phase speeds of westerly waves responsible for formation of a new shear zone in the middle stratosphere exceed the maximum speed of westerly winds in the lower stratosphere and (2) additional waves, with slower phase speed and/or slower vertical group velocity, are necessary for final descent of QBO westerlies.

Examples of stalled westerly onsets in the middle stratosphere are found in several "3-year" cycles in Figure 2 (e.g., 1967, 1976, 1981), demonstrating that this behavior is not an artifact of the composite procedure. A characteristic feature of the premature onset is for two adjacent westerly phases of the SAO to be linked together at their base. It should be noted in this context that our distinction between SAO and QBO westerlies is somewhat artificial: near-equatorial westerlies are produced by vertical transport of momentum due to a continuous spectrum of waves. Formation of SAO and QBO westerlies therefore may be viewed as part of a single process. The only fundamental difference between the stratosphere SAO and QBO is that the former is controlled by a "pacemaker" due to horizontal advection of angular momentum by the seasonally varying diabatic circulation [Dunkerton, 1991]. The downward extent of the SAO's synchronizing influence on the QBO, on the other hand, is confined to the middle stratosphere and is ineffective at lower levels.

Regions of strong shear and acceleration (\( R > 1 \)) associated with the easterly phase of the SAO are also modulated by the QBO, although the effect is not so dramatic nor as convincing as in the SAO westerly phase. This is to be expected since the SAO easterly phase is due primarily to horizontal advection rather than vertical wave propagation.

4. Conclusion

Analysis of rawinsonde and rocketsonde data at Ascension Island (7.6°S, 14.4°W) and Kwajalein (8.7°N, 167°E) in 1962-1991 suggests that the quasi-biennial oscillation (QBO) in the middle stratosphere is synchronized with the seasonal cycle and that descending westerly phases of the stratosphere semiannual oscillation (SAO) are strongly influenced by the underlying QBO. The effect of the seasonal cycle on the QBO in the middle stratosphere is revealed in two, perhaps unrelated, observations: first, a tendency for deseasonalized QBO westerly maxima to occur in local winter (or to avoid local summer); second, a smooth, uninterrupted connection between descending SAO westerly shear zones and the formation of a new QBO westerly shear zone aloft. The timing of deseasonalized QBO westerly maxima in the middle stratosphere allows a simple composite of 2- and 3-year cycles to be constructed from the data, illustrating the effect of the QBO on descending westerly phases of the stratosphere SAO.

Given the fact that QBO westerly maxima do not always occur at the same time with respect to the westerly onset initiated by the SAO (section 2.2), these two aspects of seasonal synchronization may be distinct. Formation of a new westerly shear zone clearly involves vertical transport of momentum by wave motions [Lindzen and Holton, 1968], but the timing of QBO westerly maxima is also influenced by other factors, such as horizontal advection of angular momentum by the mean meridional circulation. In the westerly phase, horizontal advection translates the equatorial angular momentum maximum into the winter hemisphere in a manner consistent with observations. The easterly phase has a small angular momentum gradient and is affected by horizontal advection to a much lesser degree [Dunkerton, 1991]. We cannot rule out the possibility that differences of wave transport at the two stations may also affect the timing of QBO extrema.

The relation of SAO and QBO westerly onsets prompts two questions: first, whether a downward influence of the SAO on the QBO is consistent with the theory of the QBO; second, whether synchronization in the middle stratosphere has any effect on the QBO as a whole. In the Lindzen and Holton [1968] theory, downward influence is mathematically possible because the absorption of a continuous spectrum of gravity waves at critical levels is equivalent to downward advection [Dunkerton, this issue]. In the Holton and Lindzen [1972] theory, on the other hand, downward influence cannot occur apart from a small diffusion term [Plumb, 1977] due to the assumed discrete spectrum of absorbed waves. The real world is closer to the Lindzen and Holton (1968) model except that waves are absorbed prior to their critical levels [Dunkerton, this issue]. Therefore downward influence is possible due to wave driving alone. The QBO-induced mean meridional circulation also causes downward advection of westerly shear [Dunkerton, 1991].

Concerning the impact of synchronization on the QBO as a whole, it is clear that the total QBO period is controlled by a number of factors in addition to the initial impulse provided by the SAO. Descending easterlies, in particular, are quite erratic and strongly modulated by the seasonal cycle throughout their descent. The seasonal cycle affects the QBO in the lower stratosphere [Dunkerton, 1990; Kinnemeyer and Pawson, 1996] in a manner distinct from its effect in the middle stratosphere. Long-term variations of QBO forcing are also possible, e.g., due to El Niño-Southern Oscillation [Maruyama and Tsuchida, 1988]. Synchronization in the middle stratosphere constrains the timing of QBO phases and onsets in this region but does little to determine whether the next onset will occur two, two and a half, or three years later. Thus, although we have shown that the onset of a new QBO cycle is synchronized with the seasonal cycle, such information is insufficient to predict how long this QBO cycle will last, or in which year the next cycle will begin. To understand an entire QBO cycle requires knowledge of dynamical mechanisms relevant to the mean flow evolution throughout the cycle.

Variations of shear-zone descent occurring from one cycle to the next reconcile the observation of synchronization in the middle stratosphere with the analysis of QBO period on constant pressure levels [Dunkerton, 1990], suggesting that the QBO is modulated but not exactly synchronized by the sea-
sonal cycle. It should be noted that the SAO itself is not exactly synchronized, due to interannual variability in the winter hemisphere [Delisi and Dunkerton, 1988]. Therefore exact synchronization of the QBO is not expected in the middle stratosphere.

Unfortunately, no rocketsonde data are available on the equator, and rocketsondes are no longer used for routine measurements of the middle atmosphere. It is possible that due to their limited time span, our data may not be representative of a longer time series. Also, because these data were obtained at two stations off the equator, it is uncertain to what extent our conclusions apply at the equator, or which of the stations more closely represents the equatorial flow. While QBOs at each station share much in common, the synchronization and modulation effects emphasized in this paper differ somewhat between the two stations, because annual and semiannual cycles are not symmetric about the equator [Garcia et al., this issue].

The historical record describing this multifaceted relationship between the QBO and the seasonal cycle underscores the need for reliable, long-term measurements of wind in the equatorial middle atmosphere. By all appearances the rocketsonde data will never be extended in time. Satellite observations with global coverage [e.g., Orland et al., 1996] are well suited to describe these oscillations (and any longitudinal asymmetry) and will eventually lead to a better understanding of dynamical mechanisms involved in seasonal modulation or synchronization of the QBO. Fine vertical resolution, will, of course, be required to adequately represent descending shear zones in the SAO and QDO.

Acknowledgments. The authors thank Donal O’Sullivan for helpful discussion and Lloyd Lowe for programming assistance. This research was supported by the National Aeronautics and Space Administration, contract NASW-4844, the National Science Foundation, grant ATM-950613, and NWRA IR&D.

References


D. P. Delisi and T. J. Dunkerton, Northwest Research Associates, P. O. Box 3027, Bellevue, WA 98009. (e-mail: tjd@nwra.com)

(Received June 3, 1996, revised November 20, 1996, accepted November 23, 1996.)