Climatology of the Equatorial Lower Stratosphere

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ABSTRACT

Twenty years of radiosonde data have been analyzed in an attempt to develop a latitudinal structure climatology of winds, temperature and geopotential at 30 and 50 mb in the equatorial stratosphere. The fine latitudinal resolution provided by the WMO station network reveals several interesting features in the latitudinal structure of the annual and quasi-biennial cycles which dominate this region. For example, the westerly and easterly acceleration phases of the quasi-biennial oscillation are markedly different. Westerly accelerations appear first at the equator, spreading outward with time to higher latitudes, and are more intense, on average, than the easterly accelerations. The easterly accelerations are more uniform in latitude, but less uniform in time, sometimes occurring in two stages.

The quasi-biennial wind and temperature oscillations are symmetric about the equator, while the annual harmonic in zonal wind is antisymmetric about the equator, but is not proportional to the Coriolis parameter. Monthly mean zonal wind and temperature appear to be in thermal wind balance at the equator.

Some brief remarks are also made concerning variability of the quasi-biennial oscillation and the effects of El Chichón.

1. Introduction

Approximately twenty-five years ago Reed et al. (1961) and Veryard and Ebdon (1961) independently discovered the downward-propagating equatorial zonal wind regimes which came to be known as the stratospheric quasi-biennial oscillation (QBO). Subsequent observational studies revealed quasi-biennial oscillations in mean temperature (U.S. Navy Weather Research Facility, 1964; Nastrom and Belmont, 1975), mean meridional wind (Groves, 1975), and column ozone (Funk and Garnham, 1962; Angell and Korshover, 1973; Wilcox et al., 1977; Hilsenrath et al., 1979; Oltmans and London, 1980; Tolson, 1980; Hasebe, 1980, 1982; Hilsenrath and Schlesinger, 1981). The quasi-biennial zonal wind oscillation has received more recent attention from Wallace (1967, 1973), who reviews the subject in his 1973 paper; from Coy (1979), in which the Balboa–Kwajalein record of mean zonal winds is updated; and Belmont et al. (1975) who, among other things, provide a unique latitude–time cross section of middle atmosphere winds. In this context the observational study by Newell et al. (1974) using meteorological analyses is also of interest.

The ground-based observational studies, including to a lesser extent the important climatology by Reed (U.S. Navy Weather Research Facility, 1964) were all severely limited in their scope either on account of the short temporal records considered or the number of stations investigated, or both. An exception is the very recent work by Hamilton (1984), which examines zonal winds for the period 1972–81 using the monthly mean data compiled in the NOAA publication Monthly Climatic Data for the World (MCDW). Hamilton (1984) has attempted to describe the latitudinal evolution of zonal winds in this decade, primarily at 30 mb, using 79 stations from the MCDW data set within 20° of the equator. Although Hamilton's results are consistent with earlier findings, some interesting details in the latitudinal structure also appear, unknown to previous investigators.

Hamilton (1984) transcribed ten years of MCDW wind data by hand, indeed a remarkable accomplishment. However, the large volume of MCDW data prevented him from examining winds in the previous decade, and the interrelationships throughout the record among wind, temperature, and geopotential. Such interrelationships are essential to the climatology of the region (U.S. Navy Weather Research Facility, 1964). Moreover, it is of interest to determine whether the latitudinal structures observed by Hamilton are characteristic of the 1960s, with its two anomalously long QBO cycles, and of more recent data following the eruption of El Chichón in April 1982.

The purpose of this paper is to use 20 years of MCDW data to update Reed's climatology of winds and temperature (U.S. Navy Weather Research Facility, 1964), taking advantage of the observed zonal symmetry of the quasi-biennial oscillation and the relatively fine latitudinal resolution provided by the WMO station network at 30 and 50 mb. Our outline is as follows: Sections 2 and 3 describe the MCDW data set and our analysis methods, respectively. Results
using the various methods are presented in subsequent sections. These include time series overlays (Section 4), harmonic analysis (Section 5), parabolic curve-fitting in the equatorial zone (Section 6), latitude-time plots of binned data (Section 7), and a composite view of seven QBO cycles (Section 8). Section 9 discusses the observed variability of the quasi-biennial oscillation, focusing attention on the anomalous cycles, evidence of seasonal synchronization, and effects of El Chichón, while Section 10 concludes with a brief theoretical discussion.

2. Data source

Data originally published in the MCDW tables were obtained on computer tape for the period 1964–81. Subsequent data through 1983 were transcribed by hand directly from the tables. Wind speed, direction, temperature, and geopotential were obtained at the two standard stratospheric levels 30 and 50 mb in the latitude range within 25° of the equator. Out of the approximately 240 upper air stations in this band, 181 had usable wind data at the stratospheric levels. Most stations obtained data at these levels for only a fraction of the entire period considered. A total of 12,636 data points were utilized in our analysis at 50 mb and 10,630 data points were used at 30 mb. The most noticeable errors in the data were obviously human errors, such as confusion about wind speed units, directions 180° out of phase, and missing digits from wind direction values (Hamilton, 1984). We visually inspected each latitudinal profile and each station time series to assess which data points were obviously incorrect. On the whole the MCDW data was remarkably clean, in the sense that latitudinal profiles of the wind were quite smooth when the erroneous points were removed (as we will demonstrate). The erroneous data amounted to about 5% of the total number of data points.

Data coverage is summarized in Fig. 1, which shows the number of station wind data months per 2° latitude bin at 30 and 50 mb. Bins centered at 0, 4, 6, 8, 10 and 16°S were poorly covered relative to the entire length of record. There are, however, useful shorter station records in some of these bins, particularly towards the end of the 1970s. Temperature and geopotential data were obtained more often than the wind data of Fig. 1, although temperature suffered from a lower signal-to-noise ratio.

3. Analysis methods

a. Harmonic analysis

Individual time series and latitudinally-binned data for winds, temperature, and geopotential were analyzed in frequency space using the method of cyclic descent (Bloomfield, 1976). The harmonic analysis routine searched for the best fit to the annual and semiannual frequencies in each time series. The amplitude and phase of each harmonic was obtained, together with the remaining, residual or deseasonalized component (less time mean). No attempt was made to search for a “quasi-biennial harmonic” for reasons to become clear in subsequent sections.

![Fig. 1. Histogram of the total number of wind data points per two-degree latitudinal bin at 30 mb (solid) and 50 mb (dashed).](image-url)
b. Parabolic fit in the equatorial zone ($|\theta| \leq 10^\circ$)

Latitudinal profiles of zonal wind, temperature, and geopotential within $10^\circ$ of the equator could usually be represented by a parabolic curve fit, or second order Taylor series expansion about the equator:

$$\bar{u}(y, z, t) = a_0(z, t) + a_1(z, t)y + a_2(z, t)y^2, \quad (3.1a)$$
$$\bar{T}(y, z, t) = b_0(z, t) + b_1(z, t)y + b_2(z, t)y^2, \quad (3.1b)$$
$$\bar{q}(y, z, t) = c_0(z, t) + c_1(z, t)y + c_2(z, t)y^2, \quad (3.1c)$$

the coefficients being defined so as to minimize the variance of any quantity, e.g.,

$$\sigma_u^2 = \frac{1}{N} \sum_{i=1}^{N} [\bar{u}_i - \bar{u}(y_i)]^2. \quad (3.2)$$

This procedure yielded latitudinal derivatives far superior to those obtained from raw data points, although there were obviously certain times, such as during the initial westerly acceleration, when the wind profile assumed a more complex shape. Even at these times, however, the parabolic fit was able to retrieve an appropriate "average" equatorial wind in the lowest coefficient $a_0$, when compared to individual time series.

c. Latitudinally-binned data

It was found useful to average together those data points lying in the same latitudinal band. Our analysis utilized $2^\circ$ bins allowing the binned data to be plotted at the average latitude of all stations lying in that particular bin at a given time. Empty bins were then filled by linear interpolation between the nearest filled bins.

Figure 1 indicates that certain latitude bands will have empty $2^\circ$ bins quite often. Suffice it to say that there is no entirely satisfactory way to compensate for missing data by any kind of interpolation. Consequently, whatever results are obtained in these regions, particularly the southern tropics, must be viewed as uncertain.

d. Composite profiles

After removing the seasonal cycles and time mean by harmonic analysis, wind profiles were composited in the following manner. First, we searched for zero crossings in the deseasonalized wind in the equatorial bin. Each month containing a zero crossing was assigned the month number 0. Each month before and after this month was assigned a month number $-1, -2$, etc., and $+1, +2$, etc., respectively. Subsequently at each latitude, data points having the same month number were averaged together, keeping westerly acceleration transitions separate from easterly transitions. This averaging was performed for six months on either side of the equatorial zero crossing, resulting in a 13-month composited latitude-time plot of zonal wind for each acceleration phase. (By definition, the "acceleration phase" is the QBO transition period.)

4. Individual station time series

The analysis methods previously outlined are useful on account of the observed zonal symmetry of the quasi-biennial oscillation. The purpose of this section is to briefly show, in agreement with earlier authors, that the assumption of zonal symmetry is accurate, based upon comparison of individual time series for stations at similar latitudes.

Figure 2 compares some of the longer time series of wind speed at the 30 mb level. To make the comparison as meaningful as possible, stations were chosen with similar latitudes but as widely different longitudes as possible (see Table 1). In general, a high degree of zonal symmetry is evident at all latitudes. Quasi-biennial and annual cycles appear at tropical and subtropical latitudes, respectively, as discussed later. (We note in passing that the monthly mean wind speed is nearly equivalent to the monthly mean zonal wind magnitude $|u|$ for latitudes within $20^\circ$ of the equator. Also, the zonally averaged meridional velocity is unobservable in this data.)

Temperature at 30 mb is more difficult to analyze than zonal wind due to its lower signal-to-noise ratio (Fig. 3). A similar amount of apparent zonal symmetry was observed at all latitudes. The anomalous temper-

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<th>Longitude (°E)</th>
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Fig. 2. Time series of 30 mb zonal wind at various latitudes, comparing stations of similar latitude but different longitude. Positive values denote westerlies. (Refer to Table 1 for exact station locations.)
Fig. 2. (Continued)
ature rise in 1982 is apparently attributable to the eruption of El Chichón, at least in part, as discussed further in Section 9c.

5. Results of harmonic analysis

The time series shown in Figs. 2 and 3 give clear evidence of quasi-biennial wind and temperature oscillations in the tropics, an annual wind oscillation in the subtropics, and an annual temperature cycle at all latitudes. There is also a semiannual wind oscillation in the southern subtropics. It is important to note that the seasonal cycles are periodic, whereas the quasi-biennial cycle has a variable period. Consequently, harmonic analysis (Section 3a) was used to remove the annual and semiannual cycles only, and no attempt was made to find a “quasi-biennial harmonic.” Such attempts are unnecessary at best, and misleading at worst—unnecessary because the deseasonalized wind is itself almost entirely quasi-biennial, and misleading because the quasi-biennial oscillation is an almost square-wave phenomenon of variable period. Moreover, as our results will make clear, it is necessary to analyze the two acceleration phases separately on account of their differing space-time structure.

a. Zonal wind

Figure 4 shows the amplitude of the 30 mb wind oscillations as a function of latitude. Amplitudes of
Fig. 3 (Continued)
Fig. 3. (Continued)
quite coarse, there was evidence of similar behavior in Fig. 5 of Belmont et al. (1974). Apparently, the annual cycle at 30 mb is not merely due to residual mean meridional advection of planetary vorticity $\Omega^*$ with $\Omega^*$ independent of latitude. The concept of "residual mean meridional circulation" is discussed, e.g., in Andrews and McIntyre, 1976.)

The amplitude of the annual cycle from harmonic analysis is not zero at the equator, but this result is uncertain. Although we found what appeared to be a distinct spectral peak at 12 months near the equator, there were other peaks in spectral response near 12 months (e.g., 14 months), suggesting that spectral broadening due to the sharp QBO phase transitions may be important at the equator.

Another view of the deseasonalized wind, based on latitudinally-binned data, is shown in Fig. 5. Among other things, this figure demonstrates that the residual, deseasonalized wind in this region is essentially due to the QBO, and exhibits rapid phase progression away from the equator in the westerly acceleration phase.

Regarding the semiannual signal in Fig. 4, the only significant amplitude at 30 mb is observed in the southern subtropics, with phase independent of latitude, peak semiannual winds occurring in December and June.

b. Temperature

Figure 6 displays the 30 mb temperature decomposition obtained in the same manner as Fig. 4. The annual temperature cycle is small near the equator, and does not depend much on latitude in this region, in agreement with Nastrom and Belmont (1975). The profile of residual amplitude differs from that of zonal winds, decreasing rapidly away from the equator but remaining nonzero in the subtropics. Closer inspection of the deseasonalized temperature and its phase revealed a fairly constant phase in the tropics and subtropics and a gradual 180° phase reversal between 10–14° latitude (cf. Quiraz, 1983, Fig. 7) in both hemispheres, as shown in Fig. 7. Although there is much noise in these time series as discussed earlier, it would be consistent to infer from this data that the QBO temperature oscillation is basically symmetric about the equator.

c. Geopotential

The results of harmonic analysis for geopotential (not shown) indicate that unlike wind and temperature, the annual and residual deseasonalized components are comparable at the equator. Harmonic analysis of the vertical difference in geopotential between 30 and 50 mb, however, would closely resemble that of temperature in the intervening layers, as required for hydrostatic balance.
Fig. 5. deseasonalized time series of zonal wind at 30 mb, from 22°N to 22°S, based on binned data. Positive (negative) values of wind are shown with a heavy (light) line. The vertical scale for wind is 5° latitude = 50 m s⁻¹.

6. Latitudinal profiles near the equator

a. Zonal wind

Figure 8 shows the zonal wind, latitudinal shear, and latitudinal curvature coefficients \(a_0\), \(a_1\), and \(a_2\) at 30 mb. The lowest coefficient \(a_0\) is substantially the same as \(\bar{u}\) at Singapore (Fig. 2e). The quasi-biennial oscillation is of variable period, due to variable \(\bar{u}\) in the transition periods, particularly the easterly acceleration phase. The westerly accelerations are generally larger—what Hamilton (1984) calls the “classical” shear zone asymmetry—although we note that a) the easterly accelerations are, at times, of the same magnitude as the westerly accelerations, and b) the westerly accelerations also vary from cycle to cycle.

The cross-equatorial shear \(a_1\) \(=\bar{u}_x(0)\) is annual, in marked contrast to \(a_0\). The sign of \(a_1\) (not shown) is positive in the northern winter and vice versa. This coefficient is noticeably larger in the westerly phase of the QBO in four out of six cycles. (It should be kept in mind that \(a_1\) is a “best fit” cross-equatorial shear, and is not necessarily equal to the actual value of \(\bar{u}_x(0)\), although this coefficient usually represents the cross-equatorial at all times outside of the acceleration phases.)

The latitudinal curvature \(a_2\) \(=\frac{1}{r}\bar{u}_r(0)\) exhibits excellent anticorrelation with \(a_0\), but is not symmetric.
the parabolic fit is responding to the narrow equatorial westerly acceleration which occurs at his time (Hamilton, 1984; and Sections 7 and 8 herein).

Together, the time series of $a_1$ and $a_2$ imply that the location of the jet maximum

$$y_m = \frac{a_1}{2a_2}$$

(6.1)

is comparable in both phases, because both coefficients are larger in the westerly phase. In an attempt to further explore this interesting behavior we composited the solstice wind profiles into four representative profiles:

a) July–August: QBO easterly phase
b) January–February: QBO easterly phase
c) July–August: QBO westerly phase
d) January–February: QBO westerly phase.

All QBO phase transition months, however, were excluded from the composite. Figure 9 shows all the individual data points together with a subjective smooth fit $\tilde{u}(y)$. The composited westerly jet is tightly curved near the equator and, because its maximum is shifted off the equator, exhibits a larger cross-equatorial shear. The jet maximum is easier to locate in the westerly phase, approximately $4^\circ$ off the equator, in the Northern or Southern Hemisphere depending on the season. In the westerly phase we find a subtropical minimum $\tilde{u}$ in the winter hemisphere. On several occasions this minimum is easterly, at

Fig. 7. As in Fig. 5 but for 30 mb temperature with 5-month running mean. The vertical scale for temperature is 5° latitude = 10°C. The temperature increase commencing in April 1982 is most probably due to the eruption of El Chichón.

About zero. Instead, the curvature associated with the westerly QBO phase is noticeably stronger, sometimes particularly so at the onset of this phase. Evidently

Fig. 8. Coefficients of parabolic fit for 30 mb zonal winds. In this and the following figures, points of high variance or otherwise unsatisfactory curve fit are deleted. Wind and curvature at center; cross-equatorial shear (absolute value) at bottom.
which times at least three zeroes of $\tilde{u}(y)$ exist (cf. Fig. 2). In the easterly phase, the jet maximum, if it exists in this region, is perhaps anywhere from 5 to $10^5$ off the equator.

Stevens (1983) has argued that cross-equatorial shear is inertially unstable, and therefore will not occur in the stratosphere, even adducing proof to this effect from Newell et al. (1974). The station data of Fig. 9, however, suggest that $\tilde{u}_y \neq 0$ even at the equator on account of the annual cycle. This shear is larger in the westerly phase, although the latitude of zero vorticity

$$y_b = \frac{a_1}{\beta - 2a_2}$$

(6.2)

(where $\beta = df/du$) is probably comparable in both phases. It might be of some interest to note that a vertical diffusivity $O(0.08 \text{ m}^2 \text{ s}^{-1})$, with Prandtl number of unity, is sufficient to stabilize a constant-equatorial shear of the observed magnitude in the unbounded inertial stability problems addressed by Dunkerton (1981, 1983a).

The cross-equatorial shear observed in Fig. 9 is not visibly enhanced during the westerly or easterly acceleration phases of the QBO. It is difficult to be more specific, because the data coverage is sometimes inadequate south of the equator, and on several occasions shear diminution was observed in the middle of a phase transition entirely on account of the annual cycle. Figure 10 shows profiles of station wind values for 18 months of a QBO cycle. This figure, beginning in October 1978, includes one of the less ambiguous examples of westerly acceleration commencing in October 1979. In the following five months the annual cycle is attempting to create positive cross-equatorial shear, but the westerly QBO acceleration is not visibly enhancing this shear at the equator.

The multiple wind maxima in January 1980 was not commented upon by Hamilton (1984; see his Fig. 4) although it exists in this cycle and the previous westerly acceleration phase (cf. his Fig. 3). Unfortunately, the data coverage cannot establish with absolute certainty that this feature is real or symmetric about the equator.

With regard to the easterly acceleration phase, the cross-equatorial shear is usually weak, as is the latitudinal curvature. The behavior in both acceleration phases is therefore consistent, at least with the equatorial wave “shear diminution” effect found numerically by Holton (1979) and Dunkerton (1983b).

At 50 mb the wind behavior is similar (Fig. 11), although the QBO is slightly weaker in amplitude, and the westerly phase is of longer duration relative to the easterly. Therefore the “classical” shear zone asymmetry consists of two components, the smaller easterly acceleration and a slower easterly shear zone descent rate in this region.

b. Temperature

Figure 12 shows the vertical wind difference between 30 and 50 mb,

$$\Delta a_0 = a_0(30) - a_0(50),$$

(6.3)

together with the temperature curvature coefficient $b_2(30)$. Positive vertical wind shear coincides with negative $\tilde{T}_{yy}$, i.e. a warm local temperature anomaly, as expected from the thermal wind relation at the equator:

$$\beta \tilde{u}_z = -\frac{R}{H} \tilde{T}_{yy},$$

(6.4a)

where $R = 287 \text{ m}^2 \text{ s}^{-2} \text{ K}^{-1}$ and $H$ is the density scale height. In terms of (3.1a, b),

$$\beta \frac{\Delta a_0}{\Delta z} \approx -\frac{2R}{H} b_2$$

(6.4b)
(Δz being the log-pressure vertical distance between 30 and 50 mb in the notation of Holton, 1979). A scatter plot of Δa₀ versus b₂(30) confirmed (6.4b) quantitatively (not shown). Strictly speaking, a better correlation should be obtained with a centered difference, i.e. b₂(40) which, however, was not available—and is not equal to the average of the two levels.

Temperature curve fitting at both levels is summarized in Fig. 13. The lowest coefficient b₀ exhibits a more complex behavior than the other variables presented here, due to the superposition of an annual cycle and other trends. The gradient coefficient b₁ is omitted from the figure, being very small as required by thermal wind balance.

c. Geopotential

Geopotential coefficients c₀(30) and c₀(50) (Fig. 14) contain both annual and quasi-biennial harmonics, as does their vertical difference

\[ \Delta c_0 = c_0(30) - c_0(50) \]  \hspace{1cm} (6.5)

which is in excellent agreement with temperature, as required for hydrostatic balance.

7. Latitude-time structure at 30 and 50 mb: 1964–83

A latitude-time plot of monthly mean zonal wind at 30 mb is displayed in Fig. 15. This figure was
constructed using binned data (Section 3c). The shading interval is 10 m s\(^{-1}\) proceeding from negative (light) values to positive (dark). We replotted this figure, incidentally, without plotting \(\bar{u}\) if an empty bin was surrounded on both sides by another empty bin (i.e. if that bin value might not be trustworthy). The similarity in the conclusions obtained, however, makes it desirable for aesthetic reasons to present the entire figure with interpolated values.

Some of the features in Fig. 15 and its counterpart

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**Fig. 11.** As in Fig. 8 but for the 50 mb zonal winds.

**Fig. 12.** As in Fig. 8 but for the vertical wind difference between 30 and 50 mb. For comparison, the 30 mb temperature curvature is also shown.
at 50 mb (Fig. 16) were seen in Belmont *et al.* (1974). However, the data coverage in the present case is significantly greater, and we believe this figure provides the first detailed view of the quasi-biennial oscillation in the latitude–time plane. Some of the information in this plot is more readily apparent than in time series or individual wind profiles. For example, the variability in the westerly acceleration is apparent in Fig. 15. Of more interest is the variability in the distribution of $\bar{u}(y, t)$ and the difference between the two acceleration phases. The westerly "nose" (defined, e.g., by the zero wind line) is present at the equator in all cycles except January 1973. Inspection of the raw station data confirmed that the westerly acceleration was indeed uniform in latitude at this time, and also stronger than in any other cycle. Another noticeable feature is the apparent oscillation of the westerly wind maximum about the equator due to the annual cycle.

With regard to the easterly acceleration phase at 30 mb, the magnitude of $\bar{u}_e$ is occasionally comparable to the westerly acceleration, but the average easterly acceleration is unambiguously weaker. The seasonal cycle is also of interest here. Note, for example, that those easterly transitions seeming to occur in two stages often give the appearance, at least, of having one or both stages coincide with the equinoctial acceleration in the summer subtropics. These include:

- May 1964: 1st stage
- April 1965: 2nd stage
- May 1967: 1st stage
- October 1967: 2nd stage
- October 1973: 1st stage
- April 1974: 2nd stage

Even single stage transitions seem to occur close to an equinoctial transition, including April 1972, May 1976, and March 1979. (Sometimes when the acceleration occurs in two stages, the effect of the 1st stage is to bring $\bar{u}$ to near zero.)

At 50 mb the pattern of zonal wind is slightly different (Fig. 16). There is less evidence of the westerly "nose" and a tendency for the easterly accelerations to propagate into the equator. The latter feature is consistent with the evidence cited in the previous paragraph, since the QBO phase descends in time, but the annual cycle does not. Also evident is the asymmetry in the duration of the westerly and easterly phases mentioned earlier.

8. Composite view of 30 mb winds

Using the method of Section 3d, a composite view of the deseasonalized zonal wind was constructed for each acceleration phase, the results of which are shown in Fig. 17. The deseasonalized acceleration phases exhibit a high degree of hemispheric symmetry. Indeed, a perfect symmetry would be consistent with the accuracy of our data coverage, although by the same token one cannot establish exact hemispheric symmetry with the present data. As already discussed, the acceleration phases are markedly different, westerly accelerations appearing first at the equator and propagating outward while maintaining much of their initial intensity. Easterly accelerations are more uniform in latitude, but less uniform in time. Their magnitude on average is about 75% of the westerly accelerations.

![Fig. 14. As in Fig. 8, but for 30 and 50 mb geopotential, and their vertical difference. Units = dam.](image-url)
Fig. 15. Latitude-time plot of monthly mean zonal wind at 30 mb. Shading interval is 10 m s⁻¹, proceeding from negative (light) values to positive (dark). White shading is for winds just below 30 m s⁻¹, and black indicates winds greater than 10 m s⁻¹. Computer plotting utilized a ¾₉₀₀ smoothing in both latitude and time. (The zero wind line is the outer boundary of the diagonally striped region.)
9. Variability of the quasi-biennial oscillation

a. Anomalous QBO cycles

The quasi-biennial oscillation is more regular than the Southern Oscillation, but it is not a purely biennial oscillation. Figure 18 shows the period of the oscillation at 50 mb, defined as the length of time between zero crossings in the deseasonalized monthly mean zonal wind at Kwajalein and Balboa (9°N), published in Coy (1979). Singapore data are also used. The period is plotted as a function of the time of year in which the easterly QBO phase begins. The average period is 27 months with standard deviation of 4 months. It will be noted, however, that the distribution of periods is also skewed on account of the anomalous long cycles which are farther from the average than the anomalous short periods. Two long cycles occurred in the 1960s. The MCDW observations, however, do not indicate any outstanding differences in the latitude–time structure of these cycles, other than their duration. The easterly acceleration phases occurred in two stages, although a two-stage easterly onset does not necessarily imply a long QBO cycle.

Figure 19 shows the period of individual QBO phases (i.e., half-cycles) at three levels, together with an estimate of the shear zone descent rate. Anomalous long cycles in the 1960s are primarily due to an unusually slow easterly shear zone descent. Note lengthened westerly (easterly) phases at 50 (20) mb.

None of these time series is correlated with the Southern Oscillation Index (e.g., Easter Island pressure minus Darwin). The contraction of QBO period seems to appear at 10–12 year intervals (also in 1983). However, this feature is more prominent on account of the anomalous long QBO cycles in the 1960s, and attempts to correlate the QBO period with the solar cycle are inconclusive without a longer record.

b. Synchronization with the seasonal cycle

The quasi-biennial oscillation was originally believed to be biennial. Although this is not the case, there are indications that the seasonal cycle might have some effect on the timing of the QBO. Consistent with Fig. 16, Fig. 18 indicates a clustering of 50 mb easterly onset in the Northern Hemisphere summer. Exploring this possibility in a little more depth, we examined Coy's record at other levels, as shown in Table 2. The maximum number of occurrences of phase onset (for each phase) is shown in italic. There appears to be a preference for the QBO phases to descend at the same time of the year, except at the upper levels where there seems to be a semiannual preference in the easterly phase onset.

The shortness of the data record raises the possibility that such clusters are random, and might lead to spurious conclusions. It will be worthwhile to present an updated version of Table 2 in the coming years. At present, the evidence of seasonal synchronization is suggestive. The fact that most month pairs have at least one QBO phase onset, however, indicates that the QBO is not simply a biennial oscillation that "skips."

c. El Chichón

Quiroz (1983, 1984) has attempted to isolate a temperature perturbation in the lower stratosphere attributable to the eruption of El Chichón. There is little doubt that an anomalous temperature rise occurred after April 1982. Figure 20 shows the latitude–time plot of temperature at 30 mb, using binned data and a five-point smoother (1-1-1 in latitude and time). This figure emphasizes the positive temperature anomalies only.
The latitudinal spread of the anomaly militates against any related effect in the zonal wind field, as Quiroz (1984) correctly pointed out. Apparently the volcanic aerosol distribution is not sufficiently narrow in latitude for the diabatic heating mechanism discussed by Dunkerton (1983c) to have any effect in this case. Indeed, at the time of this writing, the new westerly QBO wind regime has just begun at 10 mb. (R. Quiroz, personal communication, 1984).

Incidentally, a similar anomaly occurred in geopotential after April 1982 leading to elevated heights at all tropical latitudes.

10. Theoretical discussion

Hamilton (1984) has conjectured that the westerly nose might be caused by downward advection of momentum at the equator associated with the diabatic circulation (Plumb and Bell, 1982). Hamilton pointed out that the observed Kelvin wave (Wallace and Kousky, 1968) probably cannot explain the initial westerly acceleration at places like Singapore because the Kelvin wave-induced body force per unit mass should be of much larger latitudinal extent than that of the observed acceleration (assuming latitudinally-

| Table 2. Number of occurrences of QBO phase onset at Kwajalein and Balboa (9°N) from Coy (1979), as a function of time of year and height. |

<table>
<thead>
<tr>
<th>Time of year</th>
<th>Height (km)</th>
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<tbody>
<tr>
<td>Westerly onset</td>
<td></td>
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<tr>
<td>0</td>
<td>2</td>
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<tr>
<td>2</td>
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constant damping). However, further numerical work must be done to verify the role of the diabatic circulation. First, it will be necessary to know the radiative equilibrium temperature at each point in the QBO so that the advective contribution to $\tilde{u}$ can be evaluated. At present, this is an unsolved problem, although accurate radiative algorithms now exist (T. Ackerman, personal communication, 1984). We expect that radiative equilibrium will depend in part on the ozone concentration, and hence, on the vertical advection, so that the problem is (at least to some extent) circular. Second, the narrow latitudinal distribution of $\tilde{u}$ is suggestive of other equatorial modes, such as low phase speed Kelvin waves and higher order inertia-gravity waves. The latter might, in fact, create more complicated zonal wind profiles (e.g., Andrews and McIntyre, 1976). Both kinds of modes would have smaller latitudinal and vertical scales. Third, if instability of the Kelvin wave-induced shear zones contributes to the mean flow acceleration, this would give rise to a latitudinally-dependent mechanical damping coefficient, causing the westerly mean flow acceleration to be more strongly peaked at the equator (where the Kelvin–Helmholtz instability should first appear). Finally, it will be of interest to establish the vertical structure of the westerly acceleration. Hamilton (1984) has suggested that at some higher level the westerly nose might be absent. This would not necessarily be the case in every cycle, however, because the semianual oscillation, with its very strong vertical wind shear, is sometimes seen to link up with the QBO westerly onset (Wallace, 1973).

With regard to the easterly acceleration phase, theory must explain the broad and fairly constant latitudinal scale of the acceleration. In fact, this feature is consistent with the effects of latitudinal shear on the Rossby-gravity wave (Dunkerton, 1983b) and also assuming that some small wave transience or mechanical damping is present (Andrews and
McIntyre, 1976). More problematic is the variability of \( v \) in time. It is unclear whether this is due to variable Rossby-gravity wave excitation in the troposphere (and if so, why for example is the Southern Oscillation Index irrelevant?), or if some other easterly force is present, possibly associated with the seasonal cycle. Synchronization of QBO simulations was discussed by Dunkerton (1983d).

We conclude this paper by calling attention to a feature in the westerly QBO phase which has not received sufficient emphasis in the literature. It was mentioned in connection with Fig. 9 that the solstice profiles of wind at 30 mb frequently have an easterly minimum in the subtropics, located between the QBO (absolute) westerlies and the extratropical winter westerlies. This is confirmed by Fig. 15 (e.g., northern winter 1969).

The theoretical implications of this observation are not yet clear. But superficially it appears that the usual notion of stationary planetary waves propagating freely across the equator from winter to summer in the westerly QBO phase may not always apply. Studies attempting to discern high-latitude effects of the QBO on extratropical planetary wave propagation might therefore wish to distinguish between wind profiles having altogether one or three zeroes in the westerly QBO phase.

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