Mean Wind Evolution through the Quasi-Biennial Cycle in the Tropical Lower Stratosphere

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(Manuscript received 24 October 1983, in final form 13 April 1984)

ABSTRACT

A study of the zonal wind quasi-biennial oscillation (QBO) between 1972 and 1981 and at the 50 and 30 mb levels was performed using a total of over 5000 monthly mean observations from 79 stations between 20°S and 20°N. At each level and for each month a continuous representation of the zonally averaged zonal wind as a function of latitude, $\bar{u}(\theta)$, was constructed using a simple interpolation procedure. The evolution of $\bar{u}$ through the QBO cycle was then examined. A noteworthy feature seen in each cycle was a strong concentration of westerly acceleration within a few degrees of the equator at the initial onset of the transition away from the extreme easterly phase. Arguments are presented which show that these westerly accelerations are much narrower than those that would be produced by the direct absorption of a vertically propagating Kelvin wave (at least if the wave satisfies the usual WKB scaling). It is suggested that the initial westerly mean wind acceleration in the QBO may be produced in part by the downward transport of mean flow momentum from higher levels. Such transport might result from mean flow diabatic effects in the manner discussed by Plumb and Bell. Within a month or two the strong equatorial westerly acceleration produces a highly inflected mean wind profile with regions on either side of the equator in which $\beta - u_{yy}$ is large and negative.

1. Introduction

The initial discovery of the quasi-biennial oscillation (QBO) of the prevailing zonal wind in the tropical stratosphere (Reed *et al.*, 1961) was naturally followed by a number of studies devoted to the elucidation of the detailed structure of this very interesting phenomenon. The classic work in this regard is that of Reed (1964) who determined the amplitude and phase of the 26-month harmonic of the observed zonal wind at 18 stations equatorward of 25° latitude. These determinations were then used in the construction of a height–latitude (z, θ) section for the QBO amplitude and phase. Similar studies have been conducted by Angell and Korshover (1970), Groves (1973) and Belmont *et al.* (1974). A somewhat different approach to summarizing tropical stratospheric wind data was adopted by Wallace (1967), who presented time–height sections for the zonal winds averaged over several stations located within fairly narrow latitude belts. Also noteworthy is the monograph of Newell *et al.* (1974), who worked with tropical wind analyses rather than single station data. They presented a series of monthly mean height–latitude sections of the zonally-averaged zonal wind $\bar{u}$ for the period July 1957–December 1964. In addition, Newell *et al.* produced time series of their determinations of $\bar{u}$ at a number of latitudes and pressure levels (see their Fig. 10.15).

Important advances in the theory of the QBO have also been made in the last 15 years. In their seminal papers Lindzen (1971) and Holton and Lindzen (1972) showed that a QBO in the zonal wind could be produced by the nonlinear interaction between vertically propagating equatorial waves and the zonally-averaged flow. While the basic Lindzen–Holton (LH) theory now appears to be well established (e.g., Lindzen and Tsay, 1975; Plumb and McEwan, 1978), there have recently been a number of interesting theoretical studies which extend the LH model in various ways. In particular, the papers of Andrews and McIntyre (1976), Holton (1979), Plumb and Bell (1982) and Dunkerton (1982a, 1983b) all discuss the meridional structure of the mean flow accelerations induced by equatorial waves. The predicted asymmetry between the evolution from easterly to westerly wind regimes and vice versa has been considered by Dunkerton (1982b) and Plumb and Bell (1982). There have also been suggestions that barotropic instability (Andrews and McIntyre, 1976) and the effects of stationary Rossby waves (Andrews and McIntyre, 1976; Dunkerton, 1983a) may play some role in the dynamics of the QBO.

These recent theoretical developments motivated the present reexamination of the observed zonal winds in the tropical lower stratosphere. In particular, it was hoped that answers could be provided to the following questions: Can "typical" features in the time evolution of the $\bar{u}(\theta)$ profile within each QBO cycle be identified and do these features accord with the theoretical expectations? Is it possible to characterize the observed asymmetry between easterly to westerly and westerly to easterly transitions? How frequently are the necessary conditions for barotropic instability of the mean flow satisfied? Is there any indication of meridional phase propagation of the QBO [which might be expected if stationary planetary waves play a significant role in the dynamics (Dunkerton, 1983a)]?

To answer these questions a large number of monthly mean wind observations at two lower stratospheric levels over a 10-year period were studied. These data are described in Section 2 and the analysis of the data is discussed in Section 3. Section 4 contains a description of the more interesting results. The conclusions are summarized in Section 5.

2. Data

The data used in the present study were taken from the publication *Monthly Climatic Data for the World* compiled by the U.S. National Climatic Data Center. Monthly mean wind observations for the period 1972–81 at the 50 and 30 mb levels for 79 stations equatorward of 20° were transcribed by hand. This laborious process allowed a subjective examination of the raw values, and data judged to be probably erroneous were eliminated. On the average the monthly means at three stations each month were likely erroneous and had to be discarded. [Frequently encountered problems included the probable omission of the final digit in the "wind direction" entry and probable factor of 2 errors in the "wind speed" entry (this may reflect some confusion about units). It was common to find these problems occurring during several consecutive months at some stations.] The number of observations available at each station is shown in Table 1 and the total number in each year is displayed in Table 2. The data coverage south of about 5°N clearly leaves much to be desired. However, it should be noted that most earlier studies employed even fewer observations in this region. [For example, Reed (1964) and Wallace (1967) had no stations between 2°S and 7°N.]

3. Analysis

a. Individual station records

There were a total of 20 (21) stations at the 30 (50) mb levels that had data for at least 90% of the total 120-month record and had no more than two consecutive months with missing data. Complete 120-month time series at these stations were constructed by filling in any missing data using linear interpolation from adjacent months.

b. Continuous representation of $\bar{u}(\theta)$

Table 1 shows that most of the data available for this study come from stations for which continuous time series for the entire 10-year period could not be patched together. To accommodate this difficulty a very simple analysis scheme was developed in order to produce a representation of $\bar{u}(\theta)$ in individual months. A grid in latitude–time space was constructed with spacings of 2° (18°S, 16°S, . . . , 18°N) and 1 month. The interpolated $\bar{u}$ field at a particular point on this grid was obtained simply as a weighted average of all the individual station observations within ±4° latitude and ±1 month of the grid point in question. The weighting factor applied to station data at time t and latitude θ in the computation of the interpolated value at the grid point (θ_0, t_0) was

$$W = \begin{cases} \exp(-(\theta - \theta_0)^2/5), & t = t_0, \\ 0.4 \exp[-(\theta - \theta_0)^2/5], & t = t_0 \pm 1, \end{cases}$$

where θ and θ_0 are in degrees. This factor was designed to most strongly emphasize station data within ~2° of the grid point. Since single station time series show that there can be rather abrupt changes in the prevailing zonal wind, it was thought advisable to limit the radius of influence in the interpolation scheme to one month and to apply a fairly low weight to observations at $t_0 \pm 1$ month. Despite this limitation, time series of the interpolated $\bar{u}$ values at individual latitudes display a high degree of continuity (see Section 4c below).

Most earlier studies of the QBO have considered the time evolution of wind fields from which the long term mean and annual cycle were removed. In the present work this deseasonalization was performed by subtracting the 10-year means for each month of the year. With the exception of the discussion on the possible barotropic instability of the mean flow (Section 4b), all remarks in the text (and all figures) refer to deseasonalized wind profiles.

All of the present results must be regarded with some caution, given the limitations of the available data (particularly south of 5°N). In the following discussion emphasis will be placed on those features that 1) can be seen in each QBO cycle in the period considered, and/or 2) can be found in both single station data and interpolated fields, and/or 3) are also apparent in earlier studies (particularly in the more sophisticated wind analyses presented by Newell *et al.*, 1974).

4. Results

a. Evolution of $\bar{u}(\theta)$ profile

1) OBSERVATIONS

The evolution of the interpolated $\bar{u}$ at 30 mb over most of the first QBO cycle found in the record is shown in Fig. 1. Here the mean winds can be traced

TABLE 1. The number of observations available at each of the 79 stations employed in this study.

Station	Latitude	Longitude	Number at 50 mb	Number at 30 mb	Station	Latitude	Longitude	Number at 50 mb	Number at 30 mb
Guantanamo	19°59′N	75°10′W	46	40	Truk	7°28′N	151°51′E	119	119
Hilo	19°43′N	155°04′W	119	120	Koror	7°20′N	134°29′E	120	120
Port Sudan	19°35′N	37°13′E	44	32	Songkhla	7°11′N	100°37′E	74	65
Mexico City	19°26′N	99°04′W	96	89	Majuro	7°05′N	171°23′E	120	120
Wake Island	19°17′N	166°39′E	120	120	Ponape	6°58′N	158°13′E	119	119
Grand Cayman	19°15′N	81°25′W	120	120	Kota Bharu	6°10′N	102°17′E	93	89
Veracruz	19°11′N	96°10′W	109	104	Kota Kinabalu	5°57′N	116°03′E	113	112
Manzanillo	19°00′N	104°20′W	53	53	Penang	5°18′N	100°16′E	115	114
Chiangmai	18°47′N	98°59′E	65	34	Cayenne	4°50′N	52°22′W	67	65
Santa Domingo	18°30′N	69°57′W	92	83	Bogota	4°42′N	74°08′W	75	65
San Juan	18°26′N	66°00′W	120	120	Gaviotas	4°28′N	70°44′W	44	35
Socorro Island	18°14′N	111°03′W	58	56	Bangui	4°24′N	18°31′E	24	12
Juliana	18°03′N	63°07′W	110	110	Tawau	4°16′N	117°54′E	31	31
Kingston	17°58′N	76°48′W	107	107	Kuantan	3°47′N	103°13′E	87	84
Vishakhapatnam	17°43′N	83°14′W	7	0	Kuala Lumpur	3°06′N	101°39′E	99	99
Hyderabad	17°27′N	78°28′E	35	5	Kuching	1°29′N	110°20′E	65	61
Swan Island	17°24′N	83°56′W	11	11	Singapore	1°20′N	103°53′E	115	114
Johnston Island	16°44′N	169°31′W	120	120	Gan	0°41′S	73°09′E	47	43
Raizet	16°16′N	61°31′W	110	109	Nairobi	1°19′S	36°55′E	99	63
Khartoum	15°36′N	32°33′E	107	63	Fernando	3°50′S	32°25′W	24	12
Ubon	15°15′N	104°53′E	68	58	Seychelles	4°40′S	55°31′E	60	57
Dakar	14°44′N	17°30′W	94	86	Natal	5°55′S	35°15′W	42	39
Guatemala City	14°35′N	90°31′W	37	35	Floriano	6°46′S	93°01′W	32	24
Bankok	13°44′N	100°30′E	90	65	Dar es Salaam	6°53′S	39°12′E	40	24
El Fasher	13°37′N	25°20′E	75	45	Diego Garcia	7°14′S	72°26′E	3	3
Guam	13°33′N	144°50′E	119	119	Atouna	9°48′S	139°02′W	83	83
Naimey-Aero	13°29′N	2°10′E	51	19	Lima	12°01′S	77°07′W	54	39
Barbados	13°04′N	59°29′W	118	117	Cocos Island	12°11′S	96°50′E	76	20
San Andres	12°35′N	81°40′W	62	59	Darwin	12°26′S	130°52′E	116	89
Curacao	12°12′N	68°58′W	116	117	Pago Pago	14°20′S	170°43′W	120	120
Fort Lamy	12°08′N	115°02′E	18	11	Nampula	15°06′S	28°29′E	38	34
Saigon	10°49′N	106°40′E	33	28	Broome	15°57′S	122°13′E	28	1
Piarco	10°36′N	61°22′W	110	109	Willis Island	16°18′S	149°59′E	71	7
San Jose	9°59′N	84°13′W	51	51	Tahiti	17°33′S	149°37′W	115	113
Malakel	9°33′N	31°39′E	37	15	Nandi	17°45′S	127°27′E	83	70
Yap	9°29′N	138°05′E	119	119	Salisbury	17°56′S	31°06′E	35	5
Addis Ababa	8°59′N	38°48′E	99	90	Hao	18°04′S	140°57′W	118	118
Kwajalein	8°43′N	167°44′E	57	56	Tananarive	18°48′S	47°29′E	12	1
Trivandrum	8°29′N	76°57′E	29	1	Townsville	19°16′S	146°46′E	111	64
Minicoy	8°18′N	73°00′E	6	0					

from near the extreme westerly phase (February 1972) to the extreme easterly phase (August 1972) and back to near the extreme westerly phase (April 1973). One feature that is immediately apparent is a difference in the meridional structures of the easterly and westerly mean flow accelerations. The transition from the westerly to the easterly phase proceeds fairly smoothly at all latitudes. On the other hand, the beginning of the transition toward the westerly phase is strongly concentrated in a "tongue" largely confined to within about ±6° of the equator. This quickly results in a profile with sharp easterly maxima on either side of the equator (October 1972). Four months later (February 1973), one easterly peak has disappeared but the westerly jet is still narrower than it ultimately becomes (compare with April 1973). During the period 1972–81 there were another three complete easterly to westerly transitions and the beginning of still another in late 1981. A series of 30 mb $\bar{u}(\theta)$ profiles for each of these events is displayed in Figs. 2–5. In each case the strong equatorial westerly acceleration and the double easterly peaks

TABLE 2. The number of observations available in each of the ten years considered in this study.

Year	Number at 50 mb	Number at 30 mb
1972	548	493
1973	576	515
1974	610	554
1975	590	527
1976	585	513
1977	595	514
1978	599	522
1979	605	508
1980	599	494
1981	618	509
Total	5925	5149

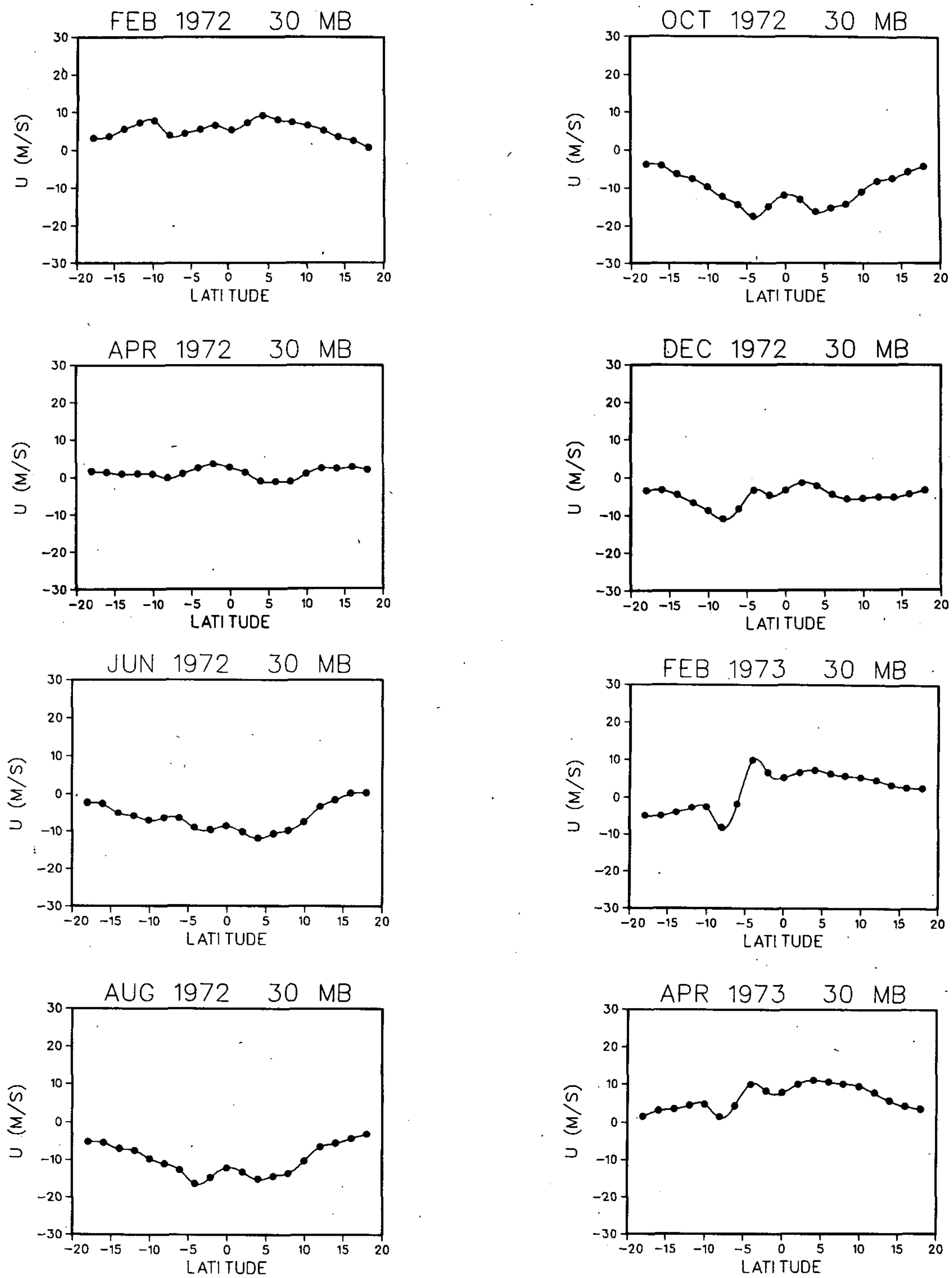

FIG. 1. The interpolated monthly mean zonally averaged zonal wind at 30 mb for a sequence of months beginning with February 1972. The interpolated winds are defined at 2° latitude intervals but have been connected by smooth curves. The long term mean and seasonal cycle have been removed. Negative (positive) latitudes correspond to the Southern (Northern) Hemisphere. Positive winds are westerly.

are evident. This characteristic signal is found in both Northern Hemisphere winter (October 1972, January 1975, November 1979, December 1981) and Northern Hemisphere summer (June 1977). Similar, but less dramatic, behavior is found at the 50 mb level; an example is shown in Fig. 6.

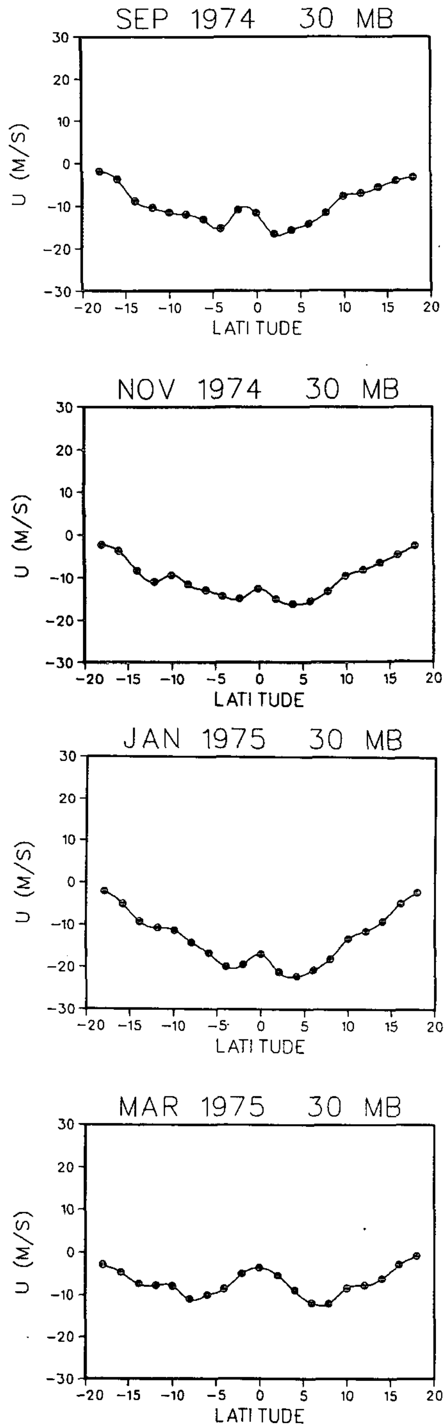

FIG. 2. As in Fig. 1 but for a sequence of months beginning with September 1974.

Evidence for the narrow meridional extent of the initial transition to westerlies can also be found in the monthly mean $u(\theta, z)$ sections given in Fig. 10.24 of Newell *et al.* (1974). During the period they considered there were three easterly to westerly transitions. At the 30 mb level, the characteristic double easterly maxima in each of the three cases can be observed (see their diagrams for May 1959, May 1961 and September 1963).

As noted above, the transition from westerlies to

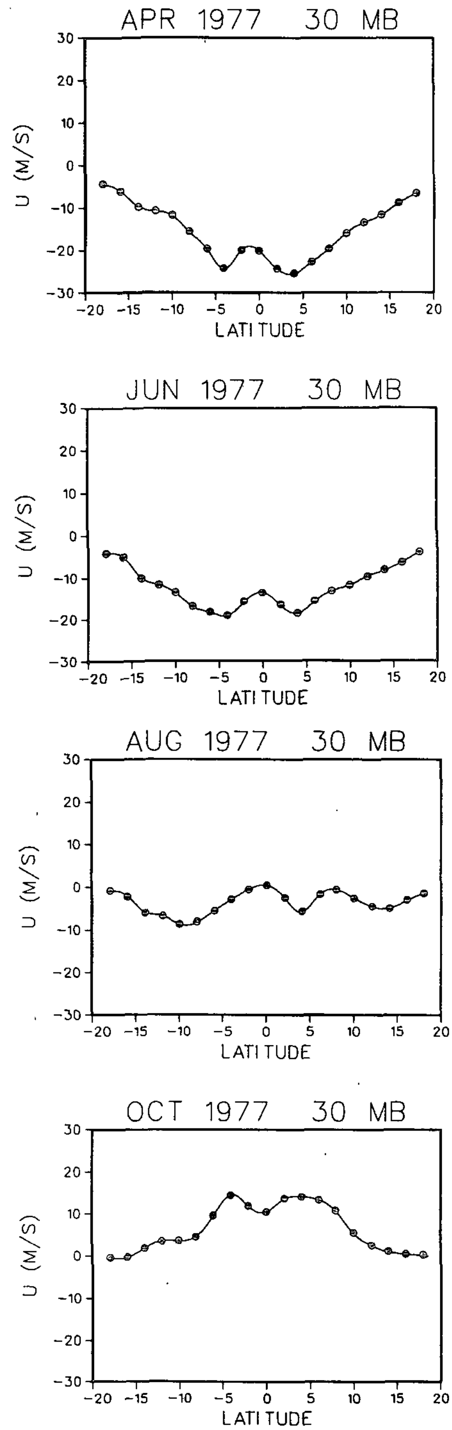

FIG. 3. As in Fig. 1 but for a sequence of months beginning with April 1977.

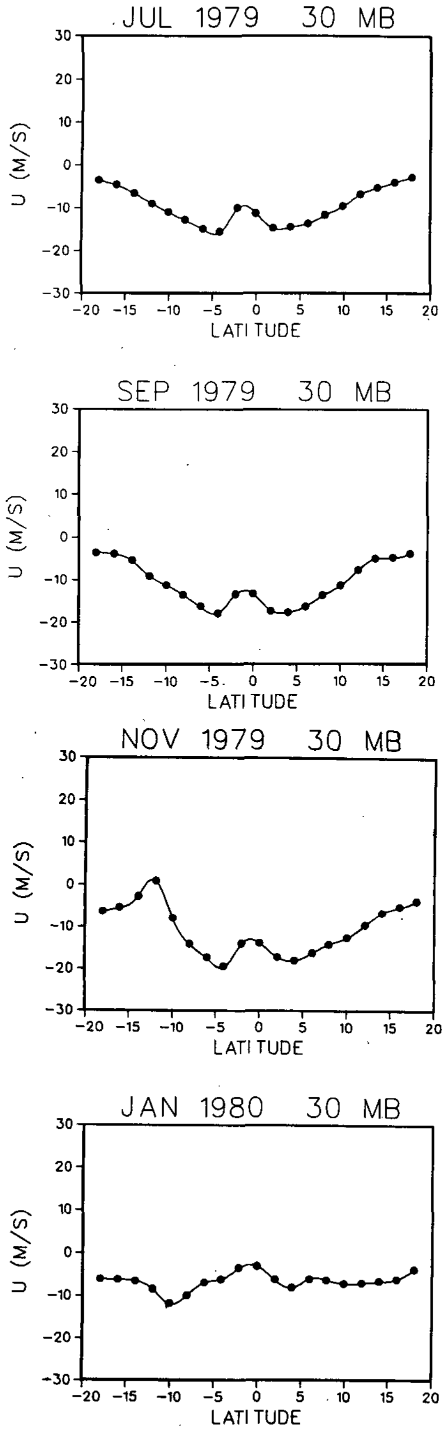

FIG. 4. As in Fig. 1 but for a sequence of months beginning with July 1979.

easterlies displayed in Fig. 1 seems to proceed more smoothly as a function of latitude than the easterly to westerly evolution. Just as the extreme westerly phase is being approached (April 1973), there is an indication of a double westerly peak with an equatorial wind minimum in between. This feature also occurs in other westerly phases, but it generally disappears as the evolution toward mean easterlies begins. The westerly to easterly transitions all proceed more smoothly in the meridional coordinate.

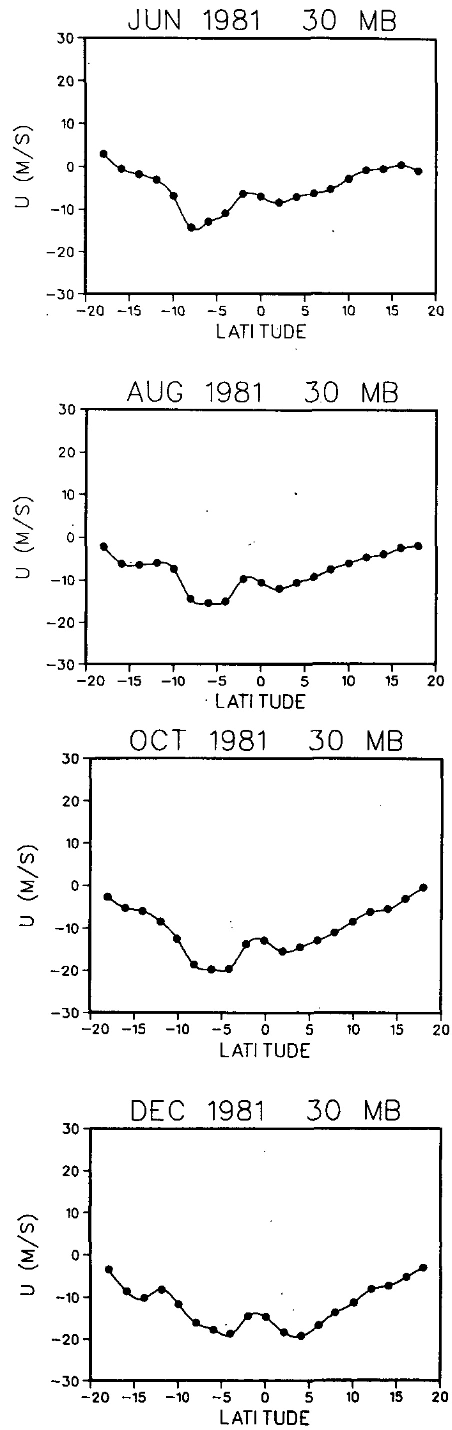

FIG. 5. As in Fig. 1 but for a sequence of months beginning with June 1981.

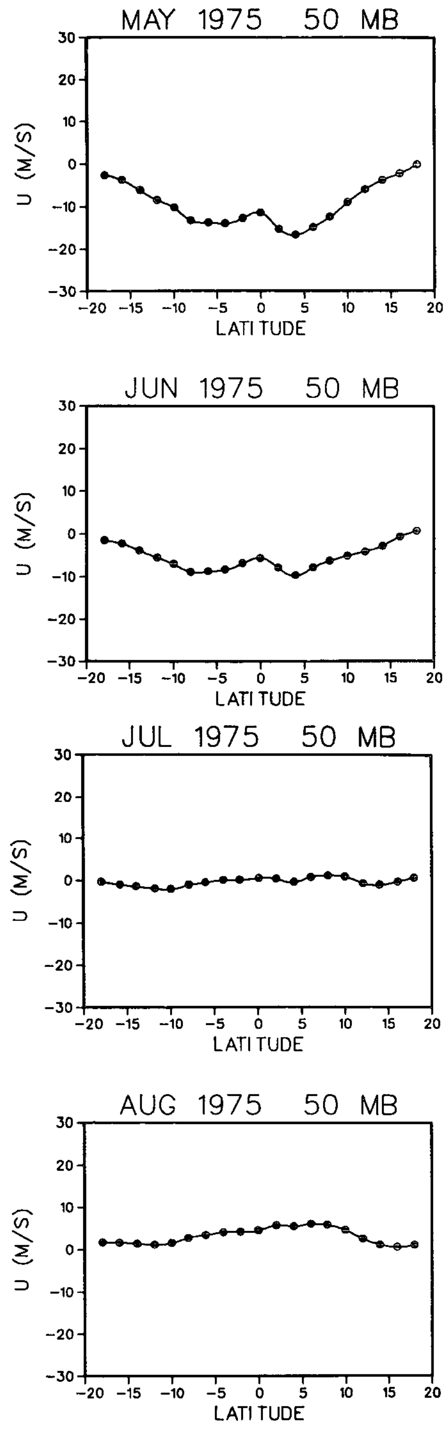

FIG. 6. As in Fig. 1 but for 50 mb winds between May and August 1975.

2) Comparison of observed westerly accelerations with theory

In the LH theory the mean flow acceleration responsible for the easterly to westerly transition is produced by a convergence of eddy momentum flux associated with a vertically propagating equatorial Kelvin wave. In most theoretical studies the dynamics of this Kelvin wave have been treated within WKB approximations that require 1) the local vertical scale for wave phase variations be small compared with the vertical scale of mean flow variations and 2) the time scale for phase variations of the wave be small compared with time scale for variations in the mean flow or in wave amplitude. When these "slowly varying" requirements are fulfilled, the meridional structure of the wave at any particular time t_0 and height z_0 depends only on the instantaneous mean flow at that height, $\bar{u}(\theta, z_0, t_0)$. Furthermore, the results of explicit numerical calculations (Holton, 1970; Simmons, 1978) suggest that the meridional structure of the Kelvin wave is mainly determined by the Doppler-shifted wave frequency at the equator and is rather insensitive to the presence of meridional shear in the mean flow.

The phase speed of the prominent Kelvin wave which is observed in the lower stratosphere is ~25 m s^{-1} relative to the ground (Wallace, 1973). Thus the Doppler-shifted phase speed at the equator appropriate at the extreme easterly phase of the QBO is $c^* \approx 55$ m s^{-1}. Now the constant mean wind solution for a Kelvin wave on an equatorial β-plane (e.g., Holton, 1975) has the perturbation meridional wind v' identically zero. In addition, the perturbation zonal wind u' and temperature T' both vary as

$$\exp[-y^2/(2\Delta^2)],$$

where y is the meridional distance from the equator and

$$\Delta \equiv (c^*/\beta)^{1/2}.$$

An expression for the wave-induced mean flow acceleration appropriate to stratospheric equatorial waves is given by Andrews and McIntyre (1976) as their Eq. (7.4). This expression can be summarized as follows:

$$\left.\frac{\partial \bar{u}}{\partial t}\right|_{\text{wave-induced}} = \text{terms proportional to } \overline{Q'T'} \text{ and } \overline{X'u'}$$

$$+ \text{ terms proportional to } \frac{\partial}{\partial t}(\overline{T'^2}) \text{ and } \frac{\partial}{\partial t}(\overline{u'^2})$$

$$+ \text{ terms involving } v',$$

where Q' and X' are the diabatic heating and zonal force per unit mass which act to dissipate the wave and the overbar denotes a zonal average. It is reasonable to suppose that Q' will have roughly the same meridional structure as T', and that X' will have roughly the same meridional structure as u'. [For the case of wave dissipation by infrared cooling it can be demonstrated that Q' and T' do indeed have the same meridional structure if the wave satisfies the usual "slowly varying" requirements (Fels, 1982)]. Furthermore, it seems likely that the most important contribution to the wave transience terms in the expression for the acceleration should result simply from a sudden increase in Kelvin wave amplitude due to a switch-on of wave activity propagating from below (Dunkerton, 1981a,b). Thus it is reasonable to expect that the Kelvin wave-induced mean flow acceleration should be roughly proportional to

$$\exp(-y^2/\Delta^2).$$

Now when $c^* = 55$ m s^{-1}, $\Delta \approx 2200$ km which is equivalent to about 20° of latitude. This indicates a much broader region of westerly acceleration than is actually observed in the initial transition away from the extreme easterly phase of the QBO.

3) POSSIBLE RESOLUTION OF DISCREPANCIES BETWEEN OBSERVATIONS AND THEORY

There are at least three aspects of the theoretical treatment discussed above that merit some attention. The first of these is the solution for meridional structure of the Kelvin wave. The inclusion of spherical geometry and a realistic $\bar{u}(\theta)$ profile would no doubt have some effect on the calculated wave fields. However, the correspondence between the constant $\bar{u}$, β-plane Kelvin wave solutions and the results of more realistic calculations is quite remarkable (see, for example, Table 4 of Simmons, 1978) and it is most unlikely that this factor alone could account for the large difference between observations and theory.

The second aspect to be reconsidered is the "slowly varying" approximation for the Kelvin wave. The vertical wavelength of the Kelvin wave is proportional to the magnitude of the Doppler-shifted phase speed (e.g., Holton, 1975) and thus becomes larger during the easterly phase of the QBO. When $c^* = 55$ m s^{-1}, the vertical wavelength is ~18 km (assuming a Brunt–Väisälä frequency of 0.02 s^{-1}). The vertical scale for wave phase variation is thus ~3 km. This is still quite short compared with typical vertical scales for $\bar{u}$ variation over most of the stratosphere. However, the vertical profile of $\bar{u}$ at a time when $\bar{u}$ is strongly easterly at 30 mb will generally display a strong shear zone somewhere above 30 mb separating the easterlies in the lower stratosphere from the descending westerly regime aloft. The vertical scale for $\bar{u}$ variations within this shear zone is often ~5 km, and it is possible that the slowly varying approximation may break down at the base of this shear layer. The question of how a violation of the WKB scaling at the base of the shear layer could affect the meridional structure of the Kelvin wave is a problem that may be worth investigating. The possibility of a breakdown of the WKB approximation for equatorial stratospheric Kelvin waves has received some recent observational support in the work of Salby *et al.* (1984). They examined daily satellite temperature analyses for the middle atmosphere and found evidence for both upward- and downward-propagating Kelvin waves, suggesting that vertical reflections may be occurring.

A third issue that should be considered relates to the possibility that some other mechanism is responsible for producing most of the observed westerly accelerations (at least at the onset of the transition away from the easterly phase). In particular, at the time when the westerly accelerations begin at 30 mb (for example) there will be a strong equatorial westerly jet at a level just a few kilometers above 30 mb. If this westerly mean flow momentum can be transported downward then it might contribute to the initial westerly acceleration at the 30 mb level. Once this initial acceleration has acted for a month or two the equatorial easterly $\bar{u}$ will be considerably reduced in magnitude. This in turn will lead to increased Kelvin wave absorption at 30 mb (e.g., Holton and Lindzen, 1972; Plumb, 1977). This will eventually lead to a narrow westerly equatorial jet at 30 mb (since the meridional width of the Kelvin wave will decrease as the equatorial $\bar{u}$ becomes more westerly).

This suggestion concerning the initial westerly accelerations in the QBO is made more plausible by the work of Dickinson (1968) and Plumb and Bell (1982) who found that the mean meridional circulation induced by the zonally averaged diabatic heating term can act to transport mean flow momentum vertically. In particular, westerly shear zones (which are warm near the equator) are associated with diabatic cooling and hence mean sinking (Plumb and Bell, 1982). This sinking advects the mean flow westerlies downward . If one considers westerly shears of 5×10^{-3} s^{-1} (i.e., 25 m s^{-1} over 5 km), then a mean sinking of 4×10^{-4} m s^{-1} would produce an advective contribution to the zonal mean acceleration greater than 5 m s^{-1} month^{-1}. This magnitude of mean sinking would be produced by a diabatic cooling of about 0.4 K day^{-1}. Given that the maximum observed equatorial QBO temperature perturbation at 30 mb is about 2 K, this would require the equivalent of a linear cooling coefficient of 0.2 day^{-1}. This is rather larger than traditional estimates of the Newtonian cooling coefficient at this level. However, the work of Fels (1982) shows that infrared radiative transfer can act very effectively to damp temperature perturbations with small vertical scales (such as that presumably associated with a descending shear zone in the QBO). It is interesting to note that in the numerical simulation of Plumb and Bell (1982), which did not include the scale-dependence of radiative cooling, the mean flow diabatic effects were found to have a significant influence on the zonal mean momentum budget (see their Figs. 5 and 6).

b. The possibility of barotropic instability

Andrews and McIntyre (1976) noted that the meridional profile of the easterly mean flow acceleration associated with a vertically propagating Rossby–gravity wave can become highly inflected under some conditions. This led them to suggest that the easterly wave forcing in the QBO might produce barotropically unstable mean flow profiles. They further suggested that these profiles would then be quickly smoothed out by eddy transports from rapidly growing barotropically unstable waves. More recent work (Dunkerton, 1982a,b) shows that the effect of the Rossby–gravity wave by itself is not likely to result in barotropically unstable mean wind distributions.

In light of this interest in the possible development of barotropic instabilities in the tropical lower stratosphere, a computation of the total mean flow vorticity gradient

$$\eta = \beta - \frac{1\partial^2\bar{u}}{a^2\partial\theta^2}$$

was performed for each month using the present $\bar{u}(\theta)$ profiles. The second derivative was calculated using simple centered differencing on a 2° latitude grid. The results followed a fairly consistent pattern, particularly at 30 mb. When the maximum easterly phase is reached, η generally becomes negative at one or two grid points near the maximum wind. A typical example is represented in Fig. 7 which shows the ratio η/β at 30 mb in August 1972 [the corresponding $\bar{u}$ profile (but with the annual cycle removed) is given in Fig. 1 (August 1972, 30 mb panel)]. Once the westerly transition begins, two easterly maxima appear on either side of the equator; associated with each maximum is a region where η is very large and negative. An example is displayed in Fig. 8 which is a plot of η/β for December 1981 [the $\bar{u}$ profile for this month is given in Fig. 5 (December 1981, 30 mb panel)].

The regions of negative mean flow vorticity gradients usually persist for at least a couple of months,

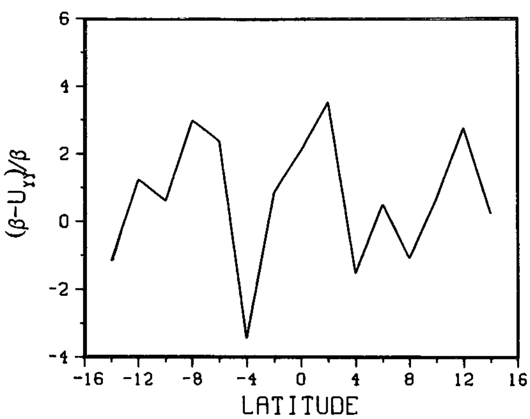

FIG. 7. The ratio of the total mean flow vorticity gradient to the planetary vorticity gradient calculated from finite differences on a 2° latitude grid for August 1972.

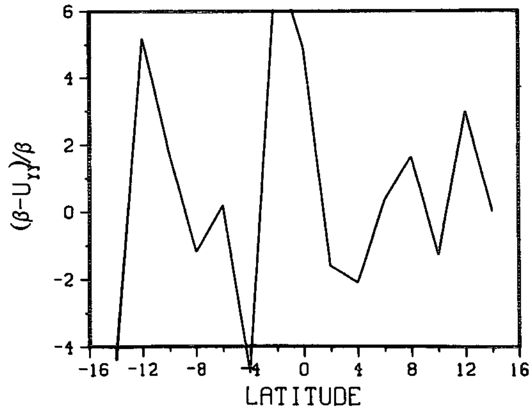

FIG. 8. As in Fig. 7 but for December 1981.

but they are generally limited to only one or two adjacent points on the 2° latitude grid. Thus, the validity of any conclusions regarding the barotropic stability of the mean zonal wind will depend on the ability of the present data to resolve quite small-scale features. It is comforting in this regard to note that mean flow profiles with negative vorticity gradients are also evident during the transition to westerlies in the results of Newell *et al.* (1974). One very good example is shown in their $\bar{u}$ section for May 1959 (their Fig. 10.24). Simple estimates of the mean flow curvature from this diagram indicate that in this month $\eta/\beta \approx -2$ at about 11°N and 20 mb.

In summary, it appears likely that in every cycle of the QBO, Rayleigh's condition for barotropic stability is strongly violated just after the extreme easterly phase in the middle stratosphere. Regions of negative vorticity gradient persist for time periods on the order of two months. This would indicate that *in situ* barotropic instability may not act as a very efficient mechanism in smoothing the mean flow profile in the tropical stratosphere.

c. *Time series of the mean flow at individual latitudes*

One aspect of the observed wind evolution in the tropical stratosphere that has received much attention in the past is the so-called "shear zone asymmetry" issue. Most published $\bar{u}(z, t)$ sections for individual stations show a clear tendency for the easterly-to-westerly transitions to occur more rapidly than the westerly-to-easterly transitions; see, for example, Coy's (1980) diagram for a station near 9°N. This point is of particular interest since the model of Holton and Lindzen (1972) predicted the opposite evolutional asymmetry.

Figure 9 shows the unsmoothed time series (with the mean and annual cycle removed) of the present interpolated values of $\bar{u}$ at 6°S, 0° and 6°N for both the 30 and 50 mb levels. (These diagrams provide a direct test of the continuity of the present interpolated

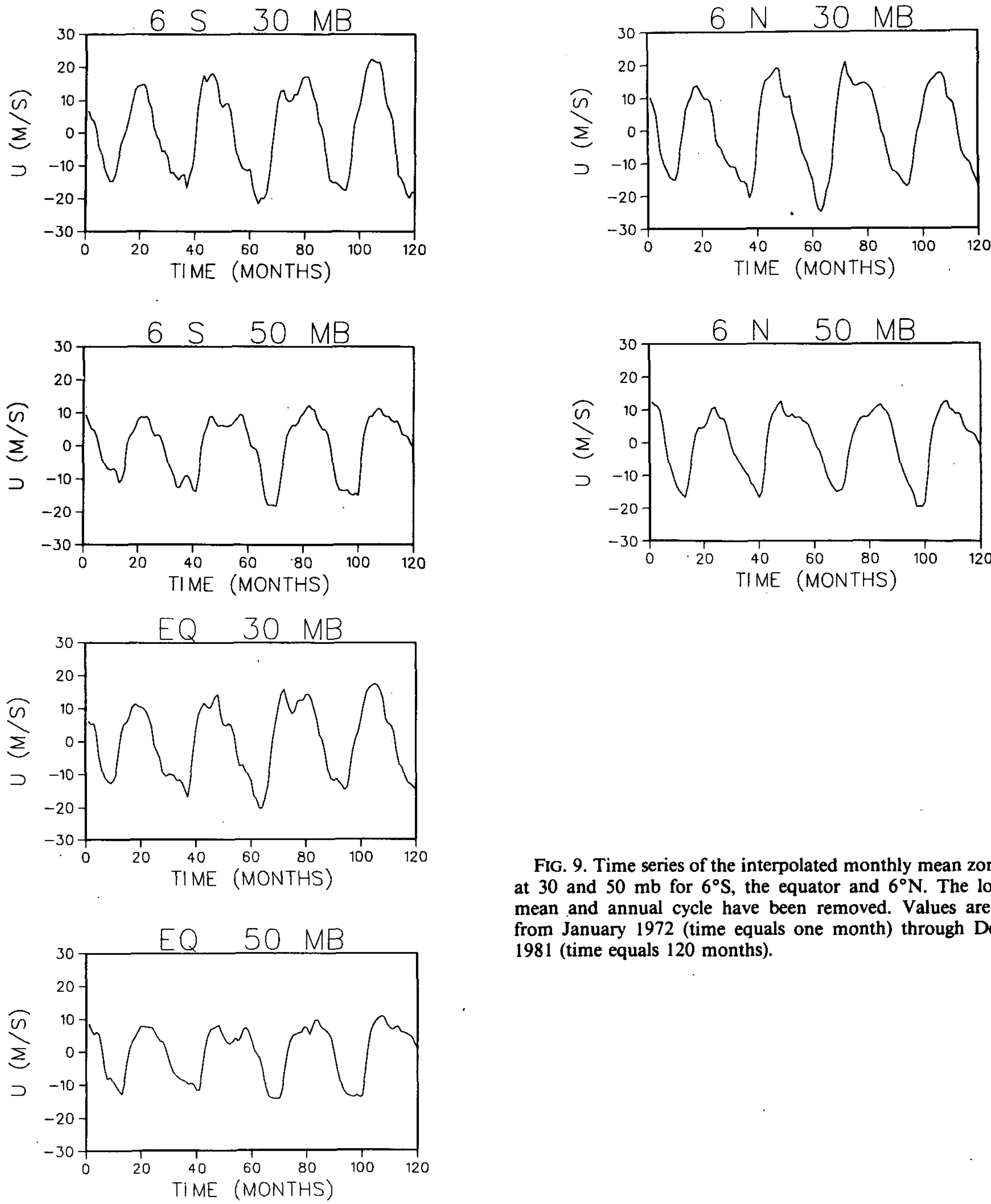

FIG. 9. Time series of the interpolated monthly mean zonal wind at 30 and 50 mb for 6°S, the equator and 6°N. The long-term mean and annual cycle have been removed. Values are plotted from January 1972 (time equals one month) through December 1981 (time equals 120 months).

$\bar{u}$ values in successive months. In general the results appear reassuring in this regard.) The "classical" asymmetry is generally evident, although this feature is clearer in some cycles than in others. It is interesting that the evolutionary asymmetry in the present $\bar{u}$ time series is significantly altered by the removal of the seasonal cycle from the data. In particular, in the unfiltered zonal wind time series the classical asymmetry is much less evident than in the deseasonalized series. This result would suggest that, on average, there is some correlation between the timing of the QBO transitions and the annual cycle. It may also explain why the (unfiltered) zonal wind time series presented by Newell *et al.* (1974; see their Fig. 10.15) do not clearly display the classical evolutionary asymmetry.

d. Harmonic analysis

A standard analysis of both the interpolated $\bar{u}(\theta)$ values and the individual station data was conducted in order to determine the amplitude and phase of the "quasi-biennial harmonic." Before the analysis was performed, all records had the long term mean and seasonal cycle removed. Then a least-squares fit was performed to minimize the quantity

$$X = \sum_{t=1}^{120} \{\bar{u}(t) - A\cos[2\pi(t-\phi)/T]\}^2,$$

where t labels the months and T is the period in months. The minimum value of X was computed for various values of the assumed period. At almost all latitudes the best fit was obtained with $T = 28.6$ months.

The solid curves in Figs. 10 and 11 show the determinations of A and ϕ at 30 mb as a function of latitude based on the continuous representations of $\bar{u}$. The dots represent the A and ϕ values from individual stations (see also Table 3). Poleward of about 4° latitude, the general shape of the amplitude curve is similar to that found in earlier studies (e.g., Reed, 1964). In no previous paper, however, has any evidence been presented that supports the drop in A near the equator evident in Fig. 10.

There is generally good agreement between the individual station results and those obtained with the $\bar{u}(\theta)$ profiles. An important exception is the best fit harmonic for Singapore (1°20′N), which appears anomalously large and which has a phase that seems anomalously early. Now the continuous $\bar{u}(\theta)$ values in any month effectively represent arithmetic means over several stations randomly located within about 4° of latitude. Thus agreement can generally be expected between single station and continuous $\bar{u}(\theta)$ determinations of A and ϕ if there are not strong meridional gradients in the amplitude or phase of the QBO (assuming, of course, that there are not significant longitudinal variations of the QBO). On the other hand, if there are large meridional variations in the QBO over a latitude interval, then the mean value may not be representative, and thus there may be differences between single station and continuous determinations of A and ϕ. In particular, it may be that the QBO actually has a deep minimum in phase near the equator (or slightly north of the equator), as indicated by the Singapore result shown in Fig. 11. If this is so, then the use of the continuous representation of the mean flow would be expected to lead to underestimates of the phase gradient and also the amplitude near the equator. This may account for at

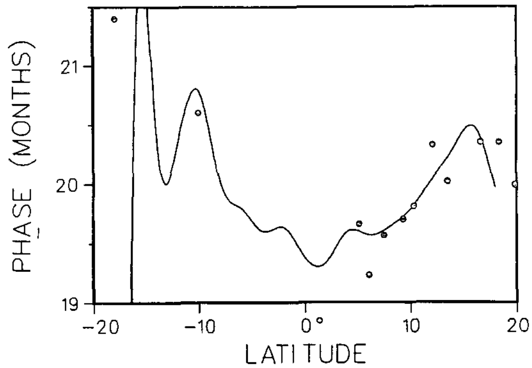

FIG. 11. As in Fig. 10 but for the phase. See text for details. Note that the point for Singapore (1°20′N) falls just below the border of the plotting rectangle.

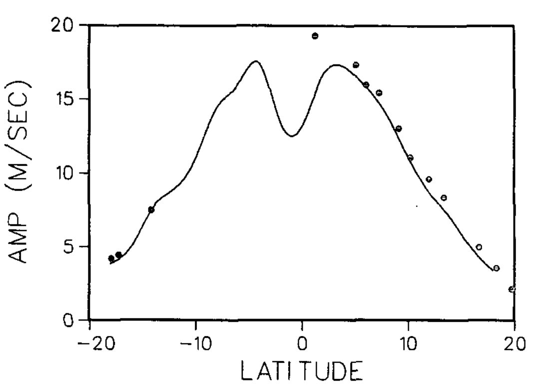

FIG. 10. The amplitude of the 28.6 month harmonic of the 30 mb zonal wind variation determined by a least-squares fit. The solid curve shows the results obtained using the interpolated wind fields for each month. The dots show results obtained from the individual stations listed in Table 3. To avoid crowding of points no values are plotted for Wake Island, Grand Cayman, Barbados, Truk, Majuro and Ponape.

TABLE 3. Results for the harmonic analysis at individual stations. The phases are in months from December 1971 and the amplitudes are in m s^{-1}.

Station	Latitude	50 mb amplitude	50 mb phase	30 mb amplitude	30 mb phase
Hilo	19°43′N	1.1	23.3	1.8	19.9
Wake Island	19°17′N	1.3	23.5	2.5	19.9
Grand Cayman	19°15′N	1.7	23.1	2.9	19.7
San Juan	18°26′N	2.0	23.3	3.5	20.4
Johnston Island	16°44′N	3.1	23.5	5.2	20.3
Guam	13°33′N	6.1	24.1	8.4	20.0
Barbados	13°04′N	6.8	23.6	8.1	20.0
Curacao	12°12′N	7.2	24.0	9.7	20.3
Piarco	10°36′N	8.6	24.2	11.2	19.8
Yap	9°29′N	10.1	24.4	13.1	19.7
Truk	7°28′N	12.2	24.2	15.5	19.5
Koror	7°20′N	11.9	24.3	15.5	19.6
Majuro	7°05′N	12.6	24.1	16.0	19.3
Ponape	6°58′N	12.7	24.2	16.4	19.5
Kota Kinabalu	5°57′N	12.2	24.4	15.8	19.2
Penang	5°18′N	12.5	24.6	17.4	19.7
Singapore	1°20′N	15.1	24.1	19.6	18.8
Darwin	12°26′S	7.3	23.9	—	—
Pago Pago	14°20′S	5.2	23.8	7.5	20.6
Tahiti	17°33′S	2.7	23.8	4.5	7.2
Hao	18°04′S	2.6	23.2	4.2	21.4

least some of the difference between the single station result at Singapore and the values based on the interpolated $\bar{u}$. In this view, one would have to place more confidence in the single station results and thus discount the equatorial minimum in A indicated by the solid curve in Fig. 10.

It is hardly surprising that there is strong poleward propagation of the QBO phase near the equator, given the "early start" that the westerly acceleration has at low latitudes. From Fig. 11 it can be seen that the poleward phase propagation extends out to about 15° latitude. This phase variation is just the opposite of what might be naively anticipated if eddy fluxes from stationary planetary waves are important in the QBO dynamics (Dunkerton, 1983a).

Figures 12 and 13 show the A and ϕ values determined at 50 mb. At this level also there is an indication of strong poleward phase propagation near the equator that is underestimated in the continuous $\bar{u}(\theta)$ representation. A major difference between the 30 and 50 mb results occurs north of 5°N where there does seem to be some equatorward phase propagation at 50 mb, although the amplitudes here are fairly small and thus the significance of this result may be questioned. The roughly four-month difference in phase between the 30 and 50 mb surfaces is supported by the results at individual stations given by Reed (1964).

5. Conclusion

The mean zonal wind evolution at 30 and 50 mb between 20°S and 20°N during the 10-year period 1972–81 has been studied using a large number of monthly mean radiosonde observations from stations throughout the world. This study has differed from many earlier investigations in being focused directly on a number of issues involved in current theoretical work on the dynamics of the QBO. Despite serious data limitations it has been possible to shed some light on the questions that were posed in the Introduction. In particular, the following conclusions can be drawn:

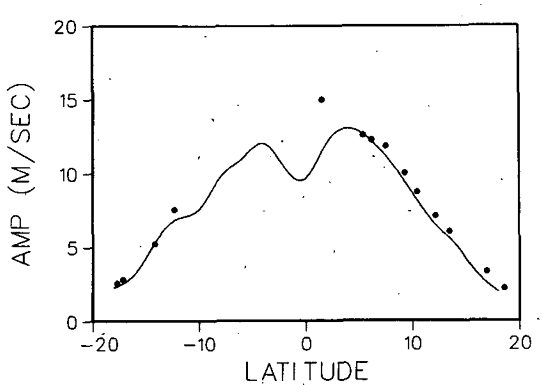

FIG. 12. As in Fig. 10 but for 50 mb.

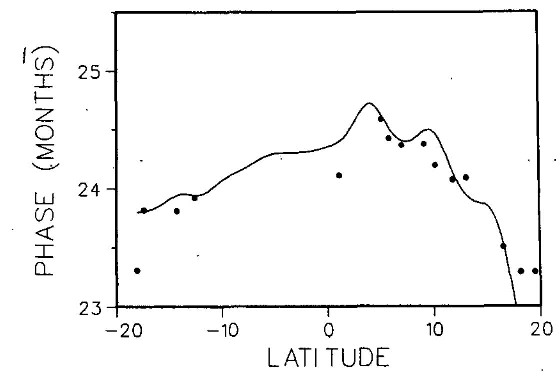

FIG. 13. As in Fig. 11 but for 50 mb.

1) The initial westerly mean flow acceleration away from the extreme easterly phase of the QBO is concentrated in a very narrow region around the equator. It is very difficult to reconcile this feature with the mean flow evolution that would result from the eddy momentum flux convergence associated with a vertically propagating Kelvin wave (at least a Kelvin wave satisfying the usual "slowly varying" scaling relations).

2) In each cycle of the QBO there appears to be a considerable period of time near the maximum easterly phase when the total mean flow vorticity gradient is negative in a region or regions near the equator.

3) There is little evidence for equatorward propagation of the phase of the zonal wind QBO in the tropics. In fact, at 30 mb there appears to be some poleward phase propagation near the equator.

Acknowledgments. The author would like to thank Tim Dunkerton for helpful comments. This work was supported by the Canadian Natural Sciences and Engineering Research Council through Grant U0219.

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