The Influence of the Equatorial Quasi-Biennial Oscillation on the Global Circulation at 50 mb[1]

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ABSTRACT

Monthly mean Northern Hemisphere 50 mb geopotential heights for a 16-year period (1962–77) are composited with respect to the phase of the equatorial quasi-biennial oscillation (QBO). The observed zonal mean geopotential height at high latitudes is significantly lower during the westerly phase of the equatorial QBO than during the easterly phase in all months composited.

For this 16-year sample we find that in early winter (November–December) the amplitude of planetary wavenumber 1 is nearly 40% stronger during the easterly phase of the equatorial QBO. In late winter (January–March) the amplitude of planetary wavenumber 2, on the other hand, is nearly 60% stronger during the westerly phase of the equatorial QBO. Data from an additional 6-year sample show a similar wavenumber 1 signal during the November–December period. However, an additional 4-year sample does not support our conclusions concerning wavenumber 2 during the January–March period. Composites based on zonal wind data from a longitudinal network of Southern Hemisphere stations show a significant QBO in the zonal wind component in the spring but not in the summer.

We hypothesize that shifts in the latitude of the zero mean zonal wind line (critical line) associated with the equatorial QBO may be responsible for the planetary wave portion of the extratropical 50 mb QBO.

1. Introduction

The quasi-biennial oscillation (QBO) in the equatorial lower stratosphere has been the subject of a number of observational studies including papers by Veryand and Ebdon (1961), Reed *et al.* (1961), Reed and Rodgers (1962), Reed (1965) and Coy (1979). The observations indicate that the equatorial QBO is characterized by alternating downward propagating patterns of westerly and easterly mean zonal winds which repeat with a somewhat irregular period averaging about 26 months. The oscillation is observed to have an approximate Gaussian distribution in latitude with the maximum amplitude at the equator and a latitudinal half-width of about 12°. The zonal wind oscillation has an approximately constant amplitude of ~ 20 m s^{-1} from above 10 mb to the vicinity of 50 mb, but decays rapidly below the 50 mb level. It is now generally believed that the equatorial QBO is a nonlinear oscillation produced by the vertical transfer of momentum by equatorial waves (Lindzen and Holton, 1968; Holton and Lindzen, 1972; Plumb, 1977).

A number of studies have attempted to confirm the existence of QBO's in extratropical latitudes (Angell and Korshover, 1970, 1975; Belmont *et al.*, 1974; Tucker and Hopwood, 1968; Trenberth, 1975; Tucker, 1979; and others). In some instances the analyses have included the troposphere and/or the mesosphere in addition to the stratosphere. In most of these studies the data records used have been quite short. (A mere four years in one study of mesospheric winds!)

Unfortunately, the irregularity of the period of the equatorial QBO, and the relatively short period for which observations have been available, have made it difficult to determine whether the various types of QBO's found in the analysis of extratropical data have any direct relationship to the equatorial QBO or merely reflect the interannual variability characteristic of the general circulation. An exception is the study of Ebdon (1975), who composited monthly mean Northern Hemisphere surface pressure fields according to the phase of the equatorial QBO at 30 mb. He found that in January the surface pressure in polar regions was significantly lower when the equatorial QBO was westerly than when it was easterly. A similar result was found in a July composite, but not in composites for spring and autumn months. Ebdon also mentioned that a very limited (6 year) data sample suggested that a similar signal was present at 30 mb. However, the results were not displayed in his paper.

In the past a primary motivation in the search for midlatitude QBO's was the hope that some type of midlatitude forcing might turn out to be the source

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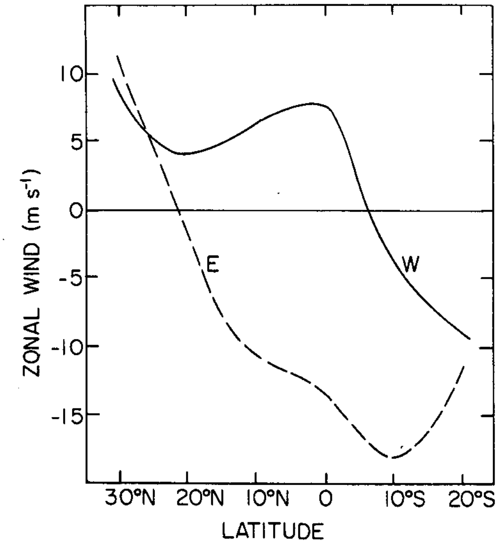

FIG. 1. Composite meridional profiles of the January mean zonal wind component at 50 mb for the westerly (W) and easterly (E) phases of the equatorial QBO.

TABLE 1. Deviations from the long-term (16-year) mean of the November–December mean zonal wind component at 50 mb over Balboa (9°N) for each year used in the winter composite.

Westerly category		Easterly category	
Year	$\bar{u}$ (m s^{-1})	Year	$\bar{u}$ (m s^{-1})
1963	9.3	1962	−4.5
1964	5.7	1965	−13.1
1966	8.1	1968	−12.4
1967	1.0	1970	−14.4
1969	5.9	1972	−19.7
1971	6.5	1974	−13.0
1973	6.2	1976	−3.0
1975	9.6	1977	−19.7
Average	6.5	Average	−12.5

of the equatorial QBO. However, it is now reasonably clear that the equatorial QBO is forced locally by vertically propagating equatorial wave modes. It is thus reasonable to pose the problem in reverse and attempt to determine whether there are extratropical QBO's driven by the equatorial QBO.

One possible link between the equatorial QBO and the extratropical circulation is provided by the vertically and meridionally propagating stationary planetary waves of the winter hemisphere. Tung and Lindzen (1979) have argued that the structure and amplitude of stationary planetary waves should be influenced by the latitude of the so-called critical surface along which the mean zonal wind vanishes ($\bar{u} = 0$). The position of this critical surface depends both on season and height. But in the lower stratosphere it is the phase of the equatorial QBO which primarily controls the location of the critical surface. For example, in January the latitude of the $\bar{u} = 0$ line at 50 mb shifts from about 6°S during the westerly phase of the equatorial QBO to 20°N during the easterly phase, as shown in Fig. 1 compiled from data in Newell *et al.* (1974). Because planetary waves interact with the stratospheric mean flow in a complex manner (Andrews and McIntyre, 1976), it is apparently not possible to predict the nature of the extratropical response to the equatorial QBO in a simple fashion. In this paper we simply present observational evidence that the equatorial QBO does modulate the extratropical circulation at 50 mb. Identification of the physical mechanisms involved will probably require careful studies with numerical models. At present we can only speculate that the latitudinal shift of the $\bar{u} = 0$ line *might* be an important link between the equatorial and high-latitude QBO's.

2. Analysis procedure

The primary data set for this study is a 16-year sequence of gridded National Meteorological Center daily Northern Hemisphere 50 mb geopotential height charts (1962–77). Monthly mean height fields for the months of November–April were composited with respect to the phase of the equatorial QBO at 50 mb. Although our study focuses primarily on the winter season, we have also, for comparison, formed a composite based on a 2-month summer mean (June–July).

The data were composited in an objective manner by placing the monthly means for each of the 16 years into either a westerly category (denoted by W) on an easterly category (denoted by E) depending on the sign of the mean zonal wind at 50 mb at Balboa, Canal Zone (9°N) as given in Fig. 1 of Coy (1979). Fortunately, there is a tendency for the change in phase of the QBO at 50 mb to occur during the Northern Hemisphere summer months so that 15 of the 16 years of winter monthly means could easily

TABLE 2. As in Table 1 except for the summer (June–July) composite.

Westerly category		Easterly category	
Year	$\bar{u}$ (m s^{-1})	Year	$\bar{u}$ (m s^{-1})
1962	5.6	1963	−12.4
1964	10.7	1966	−2.1
1967	5.7	1968	−4.5
1969	5.7	1970	−3.5
1971	2.8	1975	−3.0
1973	5.0	1977	−9.4
1976	7.7		
Average	6.2	Average	−5.8

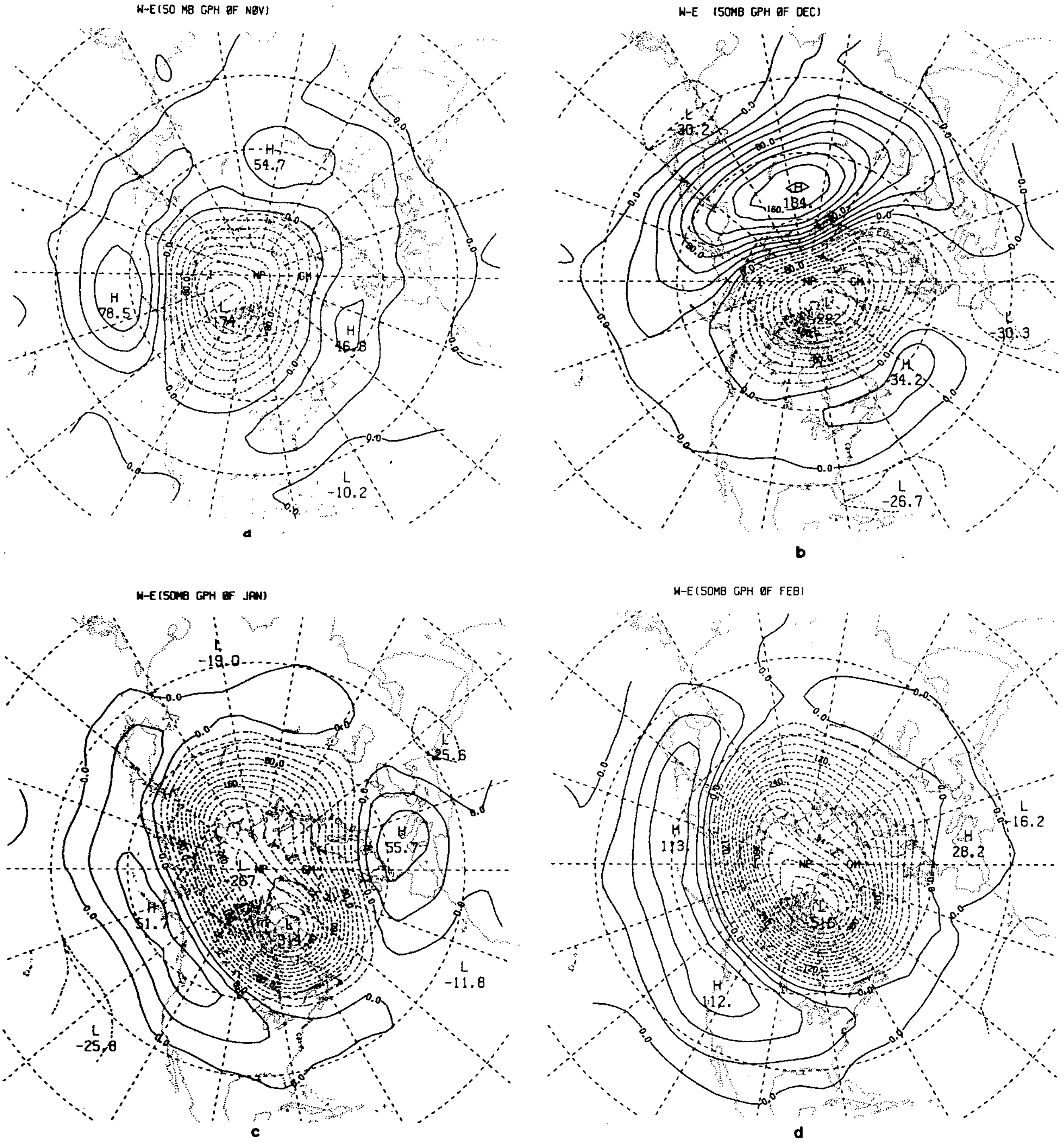

FIG. 2. Monthly mean 50 mb geopotential height differences (westerly category minus easterly category) for November–March. Units: geopotential meters.

be placed into either the W or E category. January–March 1968 was a change over period for the QBO at 50 mb, so these months were omitted from the composites. Table 1 shows the classification by category for the November–December period. In this period the mean zonal wind difference at Balboa between the W and E categories is 19 m s^{-1}. Similar differences between the two categories occur for other winter months. However, the June–July composite, shown in Table 2, has only a 12 m s^{-1} difference between the two categories, and three years had to be omitted from the composite because the QBO changed phase during the June–July period.

After completion of this analysis, we obtained an additional six years of November–December monthly mean data (1957–61 and 1978) and four

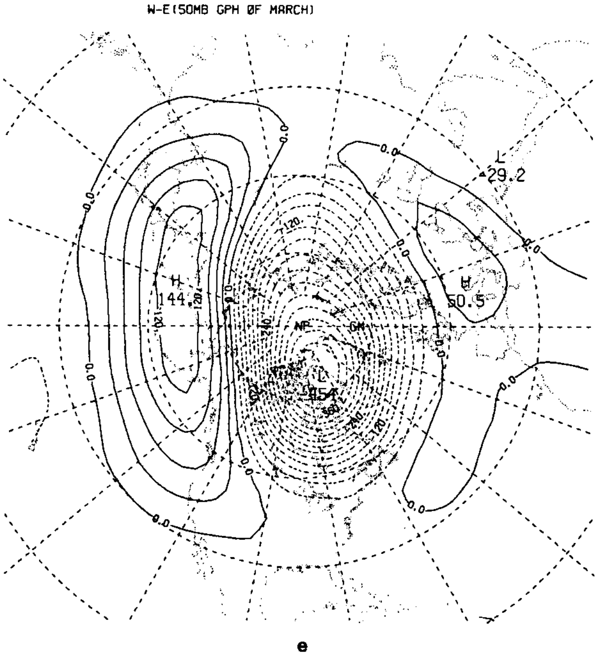

FIG. 2. (*Continued*)

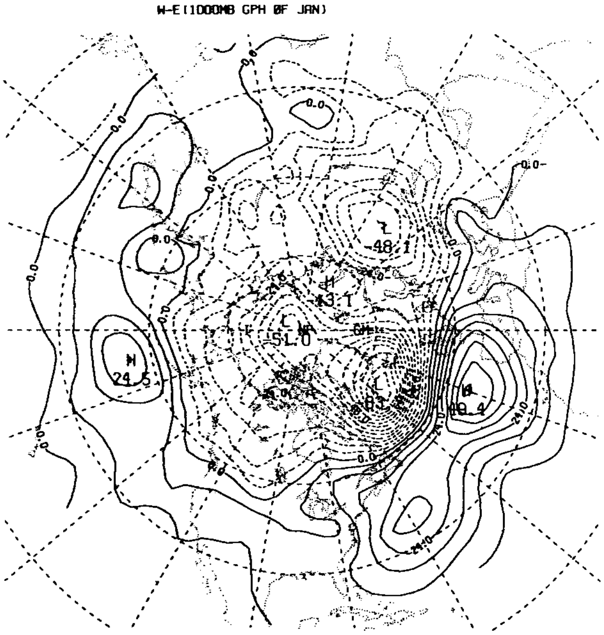

FIG. 3. January mean 1000 mb geopotential height difference (westerly category minus easterly category). Units: geopotential meters.

years of January–March data (1958–61). These extra data were used to further test the statistical significance of our results.

In addition to the analysis of Northern Hemisphere data described above, a much more limited study was undertaken using a 20-year record of station data from a Southern Hemisphere station network spanning latitudes 7–60°S along ~145°E. This data was previously analyzed by Tucker (1979) who used harmonic analysis to confirm the existence of an extratropical QBO in the Southern Hemisphere. In the present study the zonal wind component at the 50 mb level was composited according to the phase of the QBO for the spring (September–November) and summer (December–February) seasons in order to provide some information on possible seasonal variations in the Southern Hemisphere QBO.

3. Northern Hemisphere results

Polar stereographic projections of monthly mean 50 mb geopotential height differences (westerly category minus easterly category) for November–March are shown in Figs. 2a–2e for our basic data set (1962–77). In all cases there is a strong zonally symmetric component to the difference field with negative values poleward of about 60°N, and a belt of positive values equatorward of 60°N. Thus, 50 mb geopotential heights are lower in the polar region and higher in midlatitudes during the westerly phase of the equatorial QBO than during the easterly phase, with the maximum differences occurring in February and March. This "seesaw" oscillation between polar and middle latitudes is qualitatively similar to the QBO in surface pressure in January reported by Ebdon (1975). This similarity suggests that the polar QBO at 50 mb might in part be a barotropic response caused by an oscillation in the total atmospheric mass between the polar and middle latitudes. To test this hypothesis we prepared composites of monthly mean 1000 mb height difference fields corresponding to the 50 mb composites of Fig. 2. The January composite is shown in Fig. 3. All the 1000 mb composites showed negative height differences in the polar region surrounded by irregular patterns of positive differences. However, the patterns were far less regular than the 50 mb patterns and the height differences were often only 10–20% of the 50 mb height differences. Thus, we can conclude that the 50 mb extratropical QBO primarily reflects a change in 50–1000 mb thickness rather than a change in surface pressure. This is consistent with the conclusions of Angell and Korshover (1970) who found that a 6-year record of rocketsonde data showed a strong QBO in polar stratospheric temperatures out of phase with the QBO in equatorial temperature.

It is interesting to note that our January 1000 mb composite has a pattern which is very similar both in shape and amplitude to the surface pressure composite obtained by Ebdon. Since our composite was based on 15 years of data while Ebdon's was based on 10 years, and only 6 years were common to both composites, the similarity of the results increases

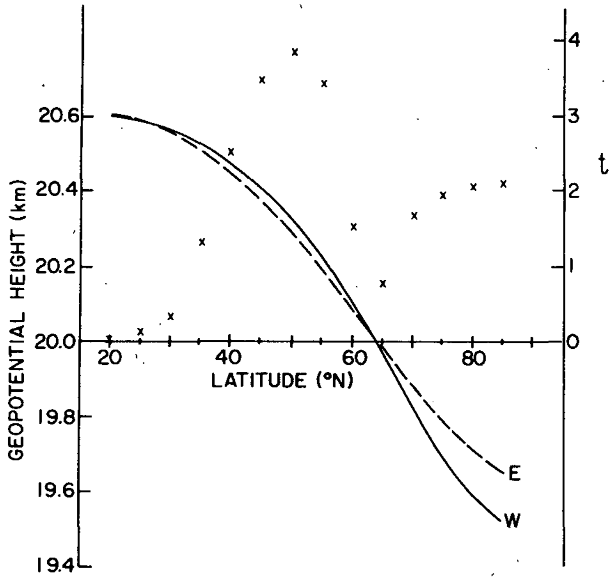

FIG. 4. Composite meridional profiles of the zonal mean 50 mb geopotential height for November–December. W and E denote westerly and easterly categories, respectively. Crosses denote Student's t values (right hand scale). t values of 2.15, 3.00 and 4.14 correspond to significance levels of 5, 1 and 0.1%, respectively (14 degrees of freedom).

our confidence that the observed signal is real and not simply a sampling fluctuation.

In order to examine the possible role of stationary planetary waves in the extratropical QBO at 50 mb, we have applied zonal harmonic analysis to the monthly mean height fields for the W and E categories and have also computed the corresponding zonal mean geostrophic winds. Differences between the W and E categories for the zonal mean height field and zonal mean geostrophic wind were similar for all months analyzed (November–March). However, the monthly mean results could be divided into two groups based on the planetary wave amplitudes. In the first group (November–December) planetary wavenumber 1 was substantially stronger for the E category, while there was relatively little difference between categories for wavenumber 2. In the second group (January–March) planetary wavenumber 2 was much stronger in the W category, while there was very little difference between categories for wavenumber 1. Thus, in the following discussion we have combined months to produce an "early winter" average (November–December) and a "late winter" average (January–March).

a. Early winter results

Fig. 4 shows the latitudinal profile of the November–December zonal mean geopotential heights for the two categories. Values of the Student's t statistic are plotted at 5° latitude intervals to indicate the statistical significance of the differences between the W and E categories. The zonal mean geopotential heights are lower in the polar regions and higher in midlatitudes during the westerly phase of the equatorial QBO, as was already evident from the plots of Fig. 2. The corresponding zonal mean geostrophic winds exhibit dramatic differences between the W and E categories as shown in Fig. 5. During the easterly phase of the equatorial QBO the mean zonal winds have a broad latitudinal extent and are rather weak. During the westerly phase of the equatorial QBO, on the other hand, there is a comparatively strong polar night jet centered near 60°N. This pattern was evident in each of the five monthly composites. The striking difference between the mean zonal wind distributions in the two categories introduces a complication in the interpretation of the composite planetary wave results. It is difficult to know whether the differences which occur in the amplitudes and phases of the waves in the two categories arise from the shift in the latitude of the critical line or from the differing mean zonal wind distributions, or both.

However, whatever the cause, there certainly is a significant difference between the amplitude of stationary wavenumber 1 in the two categories for the early winter period. As shown in Fig. 6, wavenumber 1 has nearly 40% greater amplitude in the E category years than in the W category years. The t-test results indicate that at 60°N this difference is significant at the 1% level. When the additional 6-year sample mentioned in Section 2 is included in the composite, the wavenumber 1 amplitude difference increases to more than 50% at 60°N. This difference proves to be significant at the 0.1% level. Wavenumber 2 is also slightly stronger in the E category years, but the difference is not statistically significant.

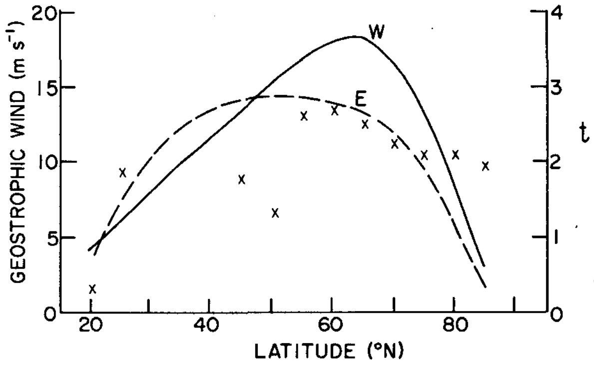

FIG. 5. Composite meridional profiles of the zonal mean geostrophic wind at 50 mb for November–December. W and E denote westerly and easterly categories, respectively. Crosses denote Student's t values (right-hand scale). From 30–40°N t values are in excess of 4 (crosses omitted). For significance levels see caption of Fig. 4.

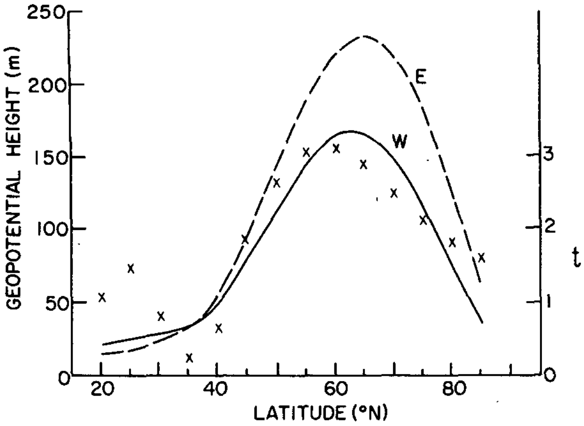

FIG. 6. Composite meridional profiles of the amplitude of the 50 mb planetary wavenumber 1 geopotential height field for November–December. W and E designate westerly and easterly categories, respectively. Crosses denote Student's t values (right-hand scale). For significance levels see caption of Fig. 4.

b. Late winter results

Figs. 7 and 8 show the meridional profiles of the zonal mean geopotential heights and corresponding geostrophic winds for the January–March period. The profiles are similar in structure to those of the early winter period, but the differences between the W and E categories are even more dramatic. This is especially true for the zonal mean geostrophic wind (cf. Figs. 5 and 8). In this period the planetary wavenumber 1 profiles showed no significant differences between the two categories. The wavenumber 2 amplitudes for our basic data set, however, were ~60% stronger during the *westerly* phase of the equatorial QBO as shown in Fig. 9. Despite this large difference in wavenumber 2 amplitude between the W and E categories, the signal is statistically significant only at about the 4% level. Furthermore, when the additional 4-year sample (1958–61) is added to the composite, the signal is significant at only the 10% level. Thus, there is a strong possibility that the wavenumber 2 signal is a result of sampling fluctuations rather than a real difference between the W and E categories.

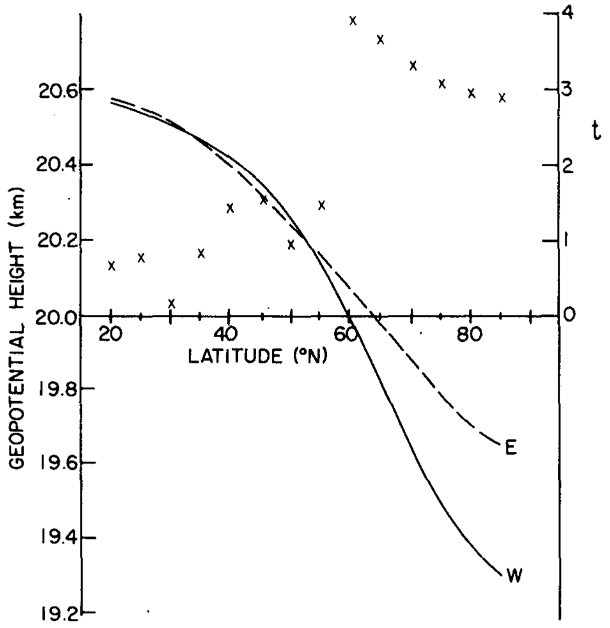

FIG. 7. As in Fig. 4 except for the January–March average. t values of 2.16, 3.01 and 4.22 correspond to significance levels of 5, 1 and 0.1%, respectively (13 degrees of freedom).

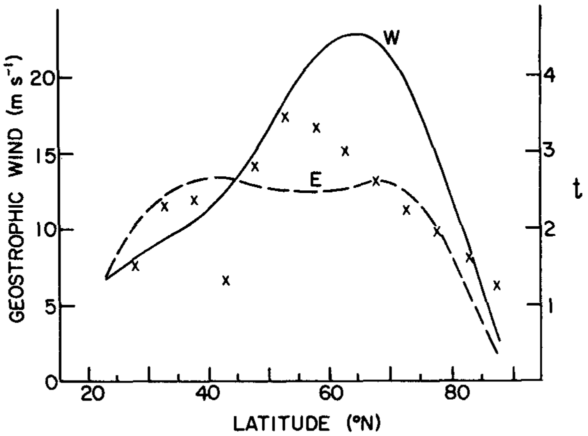

FIG. 8. As in Fig. 5 except for the January–March average. For significance levels see caption of Fig. 7.

During the January–March period irregularly occurring sudden stratospheric warmings cause very large year-to-year variations in the Northern Hemisphere 50 mb circulation. Labitzke (1965) showed evidence that during the period 1958–64, the synoptic character of sudden warmings was modulated

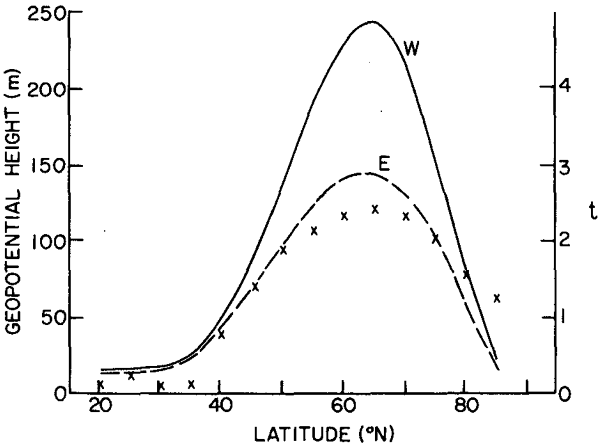

FIG. 9. Composite meridional profiles of the amplitude of the 50 mb planetary wavenumber 2 geopotential height field for January–March. W and E designate westerly and easterly categories, respectively. Crosses denote Student's t values (right-hand scale). For significance levels see caption of Fig. 7.

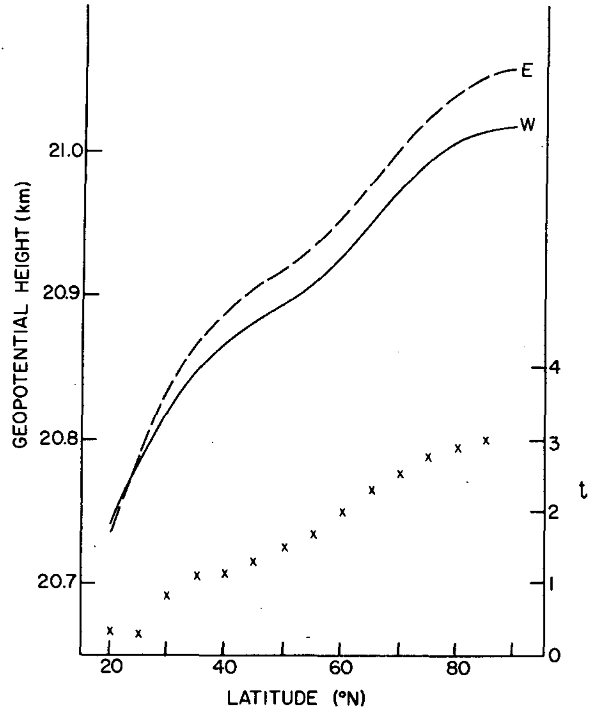

FIG. 10. Composite meridional profiles of the zonal mean 50 mb geopotential height for June–July. W and E denote westerly and easterly categories, respectively. Crosses denote Student's t values (right-hand scale). t values of 2.2, 3.11 and 4.44 correspond to significance levels at 5, 1 and 0.1%, respectively (11 degrees of freedom).

by the equatorial QBO. In more recent years there has apparently been no simple connection between the QBO and sudden warmings. Sudden warmings, however, are the likely cause of the large variances present in both the W and E categories for wavenumber 2 in the January–March period. Apparently, a much longer data record is required before we can definitely conclude that the equatorial QBO modulates planetary wavenumber 2 during this period.

At present we have no theoretical explanation for the apparent seasonal dependence of the planetary wave response to the equatorial QBO. Nor can we say what the cause-effect relationship may be between the zonally symmetric and wave components of the extratropical QBO. However, it seems likely that the latitudinal shift of the critical line, and the oscillation in the profile of the mean zonal wind at extratropical latitudes are both important factors in understanding the planetary wave response.

To further explore the possible seasonal dependence of the extratropical QBO we have carried out a similar composite for the June–July period using the categories shown in Table 2. As mentioned in Section 2, three years had to be omitted from this composite because the 50 mb mean zonal wind at Balboa changed sign during the period. During the summer months the stationary wave components at 50 mb are simply weak upward extensions of vertically decaying tropospheric waves. Not surprisingly, zonal harmonic analysis of the W and E categories for the June–July period failed to reveal any significant difference in wave amplitudes or phases. However, the zonal mean geopotential height (Fig. 10) does show a statistically significant difference between categories with the lower height at the pole occurring in the W years just as was the case in the winter composites. The height difference in this case, however, is much less than in the winter.

The 1000 mb difference field for June–July (not shown) also shows a negative W minus E field in the polar area. However, the amplitude is only about one-third of the 50 mb difference. Thus, although a portion of the summer season 50 mb extratropical QBO may be accounted for by barotropic mass adjustment, changes in the 50–1000 mb thickness still are required to explain about two-thirds of the 50 mb signal. Because of the near absence of planetary waves in the summer hemisphere, the weak summer season QBO in the 50 mb height field is probably driven by a hemispheric scale mean meridional circulation related to the equatorial QBO. During the winter season, however, the extratropical QBO can probably not be understood without taking account of wave-mean flow interaction processes.

4. Southern Hemisphere results

Tucker (1979) has shown that there is an extratropical QBO in the zonal wind component for a network of stations in the Australian sector of the Southern Hemisphere. Since the stations used in Tucker's analysis all lie along approximately the same longitude, it is impossible to distinguish between zonal mean and planetary wave related signals. However, if the extratropical QBO reported by Tucker is related to planetary wave activity, there should be a seasonal dependence just as was found in our analysis of the Northern Hemisphere data. Thus, it is of some interest to apply the compositing method to the Southern Hemisphere data.

The data available consisted of daily wind observations for the period 1957–76. However, in many cases soundings did not reach the 50 mb level until about 1961. Therefore, the data set actually covers approximately the same period as the Northern Hemisphere data. At high latitudes monthly mean data proved to be highly variable from year to year. Thus, in order to obtain statistically significant results, it proved necessary to composite three-month seasonal averages. Since, as previously mentioned, the equatorial QBO tends to change sign at 50 mb during the June–August period, we decided to base our composites on spring (September–November) and summer (December–February). According to

Leovy and Webster (1976), planetary waves in the Southern Hemisphere stratosphere have large amplitudes from early winter until November and then die out rapidly. Thus the spring composite should be representative of a period with active planetary waves, while the summer composite should be relatively unaffected by wave disturbances. The westerly and easterly categories for the Southern Hemisphere composites are based on the same set of years as the Northern Hemisphere winter composite (Table 1), except that 1957, 1959 and 1961 were added to the W category, while 1958 and 1960 were added to the E category.

The results of the Southern Hemisphere composites are shown in Tables 3 and 4. Both seasons show ~20 m s^{-1} differences between the W and E categories at the equatorial station (Lae). In both cases there is a rapid decrease in amplitude of the QBO away from the equator with a minimum at Sydney (33°S) as previously discovered by Tucker (1979). However, poleward of Sydney significant differences between the W and E categories occur only in the spring season composite, *not* in the summer season. Although this result is consistent with the hypothesis that the Southern Hemisphere extratropical QBO is associated with planetary waves, just as in the case for the Northern Hemisphere, analysis of data from other longitudes would be required for definitive proof. We did attempt to composite the meridional wind component for the Southern Hemisphere stations. However, the strong variability in this parameter precluded us from obtaining statistically significant results.

TABLE 3. Spring (Sep–Nov) seasonal means of the zonal wind at 50 mb composited according to the phase of the equatorial QBO at 50 mb for a network of Southern Hemisphere stations centered along 145°E longitude. Columns headed W and E give zonal winds for the westerly and easterly phase of the QBO, respectively. Numbers in parentheses are standard deviations. The column headed W − E gives the zonal wind difference (westerly years minus easterly years), and the column headed t gives the value of the Student's-t statistic for the difference (t values of 1.76 and 2.15 correspond to 10% and 5% significance levels, respectively).

Station	Latitude (°S)	W (m s^{-1})	E (m s^{-1})	W − E (m s^{-1})	t
Lae	7	6.5 (4.9)	−16.7 (6.5)	23.2	8.44
Darwin	12	−1.3 (5.2)	−14.8 (2.8)	13.5	6.65
Townsville	19	−6.6 (3.1)	−9.9 (1.2)	3.3	2.90
Brisbane	27	−5.6 (2.3)	−7.2 (1.6)	1.6	1.52
Sydney	33	−3.8 (2.6)	−4.1 (4.9)	0.3	0.18
Melbourne	38	−1.2 (3.3)	−3.7 (2.0)	2.5	1.86
Hobart	43	8.7 (3.4)	6.3 (2.5)	2.4	1.63
Macquarie Island	55	23.9 (5.3)	21.6 (10.1)	2.3	0.54
Casey	66	36.1 (5.8)	33.1 (3.2)	3.0	1.03

TABLE 4. As in Table 1 except for summer season (DJF).

Station	Latitude (°S)	W (m s^{-1})	E (m s^{-1})	W − E (m s^{-1})	t
Lae	7	0.2 (3.5)	−21.5 (7.5)	21.7	7.77
Darwin	12	−9.6 (2.9)	−22.8 (2.6)	13.2	10.15
Townsville	19	−14.2 (1.8)	−18.1 (1.7)	3.9	4.70
Brisbane	27	−10.8 (2.1)	−12.1 (2.0)	1.3	1.30
Sydney	33	−6.4 (2.3)	−6.7 (1.0)	0.3	0.40
Melbourne	38	−4.4 (2.1)	−5.0 (1.5)	0.6	0.73
Hobart	43	2.7 (3.0)	2.3 (3.0)	0.4	0.30
Macquarie Island	55	2.5 (2.3)	2.2 (3.4)	0.3	0.29
Casey	66	−0.1 (1.2)	−0.0 (1.4)	−0.1	0.10

5. Conclusions

We have presented strong evidence that the equatorial QBO modulates the global circulation at 50 mb. In the Northern Hemisphere the zonal mean geopotential at the poles is lower during the westerly phase of the equatorial QBO in both summer and winter monthly mean composites. The mean zonal wind and planetary wave components of the geopotential field, however, are significantly modulated by the QBO only during the winter season when the mean wind is westerly and vertically propagating planetary waves are present.

We found that during November–December, the stationary planetary wavenumber 1 is substantially stronger during the easterly phase of the equatorial QBO, but that there is little evidence of a QBO in wavenumber 2. In the January–March period wavenumber 2 is stronger during the westerly phase of the equatorial QBO, and there is little evidence of a QBO in wavenumber 1. However, the wavenumber 2 signal may be a result of sampling fluctuations. A substantially longer time series will be required for a definitive answer. Since the latitudinal position of the $\bar{u} = 0$ critical line and the meridional profile of the extratropical mean zonal wind are both strongly modulated by the equatorial QBO, it is not surprising to find a QBO in the planetary waves. However, at present we cannot explain the observed difference in the wave behavior between the early and late winter periods.

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REFERENCES

Angell, J. K., and J. Korshover, 1970: Quasi-biennial, annual, and semiannual zonal wind and temperature harmonic amplitudes and phases in the stratosphere and low mesosphere of the Northern Hemisphere. *J. Geophys. Res.*, **75**, 543–550.

——, and ——, 1975: Evidence for a quasi-biennial variation in the eccentricity of the north polar vortex. *J. Atmos. Sci.*, **32**, 634–635.

Andrews, D. G., and M. E. McIntyre, 1976: Planetary waves in horizontal and vertical shear: The generalized Eliassen-Palm relation and the zonal mean acceleration. *J. Atmos. Sci.*, **33**, 2031–2048.

Belmont, A. D., D. G. Dartt and G. Nastrom, 1974: Periodic variations in stratospheric zonal wind from 20-65 km at 80°N to 70°S. *Quart. J. Roy. Meteor. Soc.*, **100**, 203–211.

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

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

Holton, J. R., and R. S. Lindzen, 1972: An updated theory for the quasi-biennial cycle of the tropical stratosphere. *J. Atmos. Sci.*, **29**, 1076–1080.

Labitzke, K., 1965: On the mutual relation between stratosphere and troposphere during periods of stratospheric warmings in winter. *J. Appl. Meteor.*, **4**, 91–99.

Leovy, C. B., and P. J. Webster, 1976: Stratospheric long waves: Comparison of thermal structure in the Northern and Southern Hemispheres. *J. Atmos. Sci.*, **33**, 1624–1638.

Lindzen, R. S., and J. R. Holton, 1968: A theory of the quasi-biennial oscillation. *J. Atmos. Sci.*, **25**, 1095–1107.

Newell, R. E., J. W. Kidson, D. G. Vincent and G. J. Boer, 1974: *The General Circulation of the Tropical Atmosphere and Interactions with Extratropical Latitudes*, Vol. 2. The MIT Press, 371 pp.

Plumb, R. A., 1977: The interaction of two internal waves with the mean flow: Implications for the theory of the quasi-biennial oscillation. *J. Atmos. Sci.*, **34**, 1847–1858.

Reed, R. J., 1965: The quasi-biennial oscillation of the atmosphere between 30 and 50 km over Ascension Island. *J. Atmos. Sci.*, **22**, 331–333.

——, and D. G. Rogers, 1962: The circulation of the tropical stratosphere during the years 1954–1960. *J. Atmos. Sci.*, **19**, 127–135.

——, W. J. Campbell, L. A. Rasmussen and D. G. Rogers, 1961: Evidence of the downward-propagating annual wind reversal in the equatorial stratosphere. *J. Geophys. Res.*, **66**, 813–818.

Trenberth, K. E., 1975: A quasi-biennial standing wave in the Southern Hemisphere and interrelations with sea surface temperature. *Quart. J. Roy. Meteor. Soc.*, **101**, 55–74.

Tucker, G. B., 1979: The observed zonal wind cycle in the Southern Hemisphere stratosphere. *Quart. J. Roy. Meteor. Soc.*, **105**, 263–273.

——, and J. M. Hopwood, 1968: The 26-month zonal wind oscillation in the lower stratosphere of the Southern Hemisphere. *J. Atmos. Sci.*, **25**, 293–298.

Tung, K. K., and R. S. Lindzen, 1979: A theory of stationary long waves, Part I: A simple theory of blocking. *Mon. Wea. Rev.*, **107**, 714–734.

Veryand, R. G., and R. A. Ebdon, 1961: Fluctuations in tropical stratospheric winds. *Meteor. Mag.*, **90**, 125–143.