Global QBO in Circulation and Ozone. Part I: Reexamination of Observational Evidence

K. K. TUNG AND H. YANG

Department of Applied Mathematics, University of Washington, Seattle, Washington

(Manuscript received 6 August 1993, in final form 18 February 1994)

ABSTRACT

Observational evidence for a global quasi-biennial oscillation (QBO) pattern is reviewed. In particular, the presence of an extratropical, as well as an equatorial, component of the QBO signal in column ozone is established. It is found that the ozone interannual variability is such that as one moves away from the Tropics, the frequency spectrum of the anomaly changes from one that is dominated by the equatorial QBO frequency of 1/30 mo to a two-peak spectrum around the two frequencies: 1/30 mo and 1/20 mo. Instead of treating the 1/20 mo frequency as a separate phenomenon to be filtered away in extracting the QBO in the extratropics, as was previously done, the authors argue that both peaks are integral parts of the extratropical QBO phenomenon. The 1/20 mo frequency happens to be the difference combination of the QBO frequency 1/30 mo and the annual frequency 1/12 mo. Therefore, it can represent the result of the QBO modulating an annual cycle. The authors suggest that previous methods of extracting the extratropical QBO signal severely underestimated the contribution of the QBO to the interannual variability of ozone when data are filtered to pass only the component with the period of equatorial QBO.

Further, it is argued that the transport of equatorial QBO ozone anomaly by a non-QBO circulation can at most account for 6–8 Dobson units (DU) of the observed interannual variability of column ozone in the extratropics. The remaining variability (up to 20 DU) probably cannot be produced without an anomaly in the transporting circulation in the extratropics.

1. Introduction

The phenomenon of equatorial quasi-biennial oscillation (QBO) is well known. It has been the subject of a number of observational investigations (Veryand and Ebdon 1961; Reed et al. 1961; Reed and Rogers 1962; Reed 1965; Wallace 1973; Coy 1979), as well as theoretical and modeling studies (Lindzen and Holton 1968; Holton and Lindzen 1972; Plumb and Bell 1982; Plumb 1984). It is an irregular oscillation forced by equatorially confined waves. The period during the last dozen years averages to about 30 months. The earlier decades saw somewhat shorter periods (about 27 mo).

What is not as well known, but is increasingly becoming apparent observationally, is that a QBO signal also exists in the extratropical stratosphere in dynamical variables (Tucker and Hopwood 1968; Belmont et al. 1974; Angell and Korshover 1975; Tucker 1979; Holton and Tan 1980, 1982; Labitzke and Van Loon 1988; Dunkerton and Baldwin 1991) and tracer fields: water vapor (Hyson 1983; Mastenbrook and Oltmans 1983) and column ozone (Angell and Korshover 1964, 1973, 1983; Hilsenrath and Schlesinger 1981; Hasebe 1983, 1984; Oltmans and London 1982; Bojkov 1986; Garcia and Solomon 1987; Lait et al. 1989). There is as yet no generally accepted explanation of how the equatorial QBO anomaly is transmitted to the high latitudes, where, at least in the case of column ozone, the signal is actually stronger than in the equatorial region.

Because of the high seasonal and interannual variability of dynamical quantities at high latitudes, which often overwhelms the QBO signal, the correlation between these quantities and equatorial QBO is relatively low at high latitudes when compared to that at low latitudes. Therefore, the extracted signal is often underestimated, especially when one presumes that the "signal" is of the frequency of the equatorial QBO. We will reexamine available evidence for the phenomenon of extratropical QBO and in the process provide a broader definition for the phenomenon. We will use Total Ozone Mapping Spectrometer (TOMS) column ozone as an example to argue that the bulk of its observed interannual variability in the extratropics is probably caused by the QBO phenomenon in its broader definition. In section 2, however, we will show that even under the traditional definition, there is evidence that a QBO signal exists in the extratropics. We will then show in section 3 that this is only a relatively small portion of the signal. There is an additional signal that is very coherent in all extratropical latitudes but has a period of 20 months. We argue in section 4 that this should be expected for a QBO signal in latitudes where there is a prominent seasonal cycle.

Corresponding author address: Dr. Ka Kit Tung, Department of Applied Mathematics FS-20, University of Washington, Seattle, WA 98195.

2. Existence of extratropical QBO

More than 13 years of ozone anomaly (November 1978 to December 1991) are obtained by processing the daily TOMS column ozone data [version 6, Herman et al. (1991), courtesy of R. McPeters] in the following way: The time series is deseasoned (i.e., from each day of the data a time average for that calendar day is subtracted) and monthly means are taken to remove the variations in short timescale. Then a linear trend and an 11-year solar cycle variation are removed by a least-squares fit to a function of the form

$$A + Bt + C\sin(2\pi t/11\ \text{yr}) + D\cos(2\pi t/11\ \text{yr}).$$

The result for global ozone, integrated from 70°S to 70°N, is plotted in Fig. 1a together with the equatorial zonal wind at 30 mb over Singapore [Naujokat (1986), with updates]. The linear trend obtained for global ozone (B in the formula above) is about -0.8 Dobson units (DU) or -0.27% per year for the period investigated. This is smaller than the -0.41%/yr for global ozone (90°S to 90°N) reported by World Meteorological Organization Ozone Trends Panel (WMO 1989) for the period from November 1978 to December 1987, which was obtained without taking out a solar cycle component. The amplitude for sinusoidal solar cycle component ($\sqrt{C^2 + B^2}$) is 2.8 DU. Our results for linear trend and solar cycle amplitude are similar to those found by Stolarski et al. (1991) using a slightly different procedure.

Figure 1a demonstrates that the interannual variation of global total ozone contains a significant QBO component. Furthermore, the QBO signal in global ozone is negatively correlated with the equatorial 30-mb wind. The correlation coefficient for the two curves in Fig. 1a is -0.71. Global ozone contains, of course, an equatorial, as well as an extratropical, component. In Fig. 1b, the equatorial column ozone, processed in the same manner, is plotted along with the 30-mb Singapore zonal wind. The two equatorial time series appear very well correlated. The correlation coefficient is 0.73. Such in-phase relationship between column ozone and 30-mb Singapore wind holds true at other latitudes as well between 10°S and 10°N.

Recall that Fig. 1a shows that global ozone is negatively correlated with the phase of equatorial QBO. Since the global ozone contains tropical ozone, it follows then that there must exist a coherent QBO signal in extratropical ozone 180 degrees out of phase with the tropical ozone. In fact, contributions from variations between 50 and 70 deg in both hemispheres are in phase with the global signal, and account for one-half of the global signal in Fig. 1a (measured by area-weighted standard deviations), in spite of the small area involved.

It is also apparent from Fig. 1a that the year to year variation in the extratropics contains frequency components other than the frequency of equatorial QBO. In addition, we will show that there exists a significant 20-mo component in ozone anomaly that is antisymmetric about the equator and therefore does not appear in the global average. These have often been treated as noise to be filtered away in processing the signal. We will show that they are part of the QBO signal.

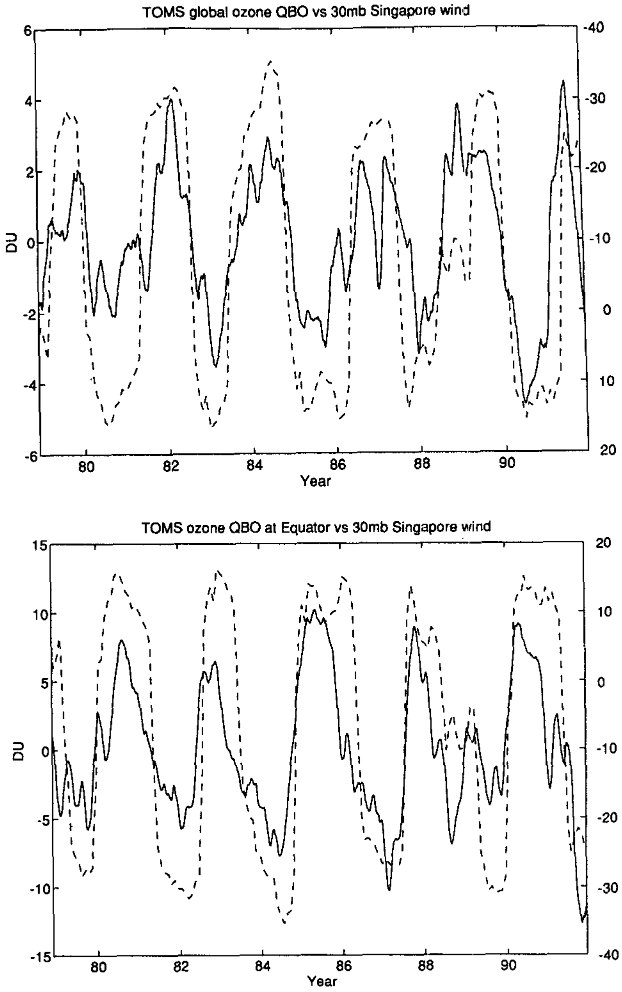


FIG. 1. (a) TOMS global ozone anomaly (solid line, left scale in DU) and 30-mb Singapore wind (dashed line, right scale in m s^{-1}) as a function of time. (b) Same as (a) except for TOMS equatorial ozone anomaly. Note that the wind in (a) is plotted upside down.

3. Latitudinal distribution and frequency spectrum

Figure 2 shows the latitudinal distribution of the ozone anomaly obtained by the aforementioned procedure. No further filtering has been applied, and so in principle it can contain other modes of interannual variability, such as the El Niño–Southern Oscillation, and anomalous chemistry not removed by the linear trend.

Despite the fact that the unfiltered signal is rather noisy, especially at high latitudes, a QBO pattern can be discerned from Fig. 2. The equatorial QBO signal

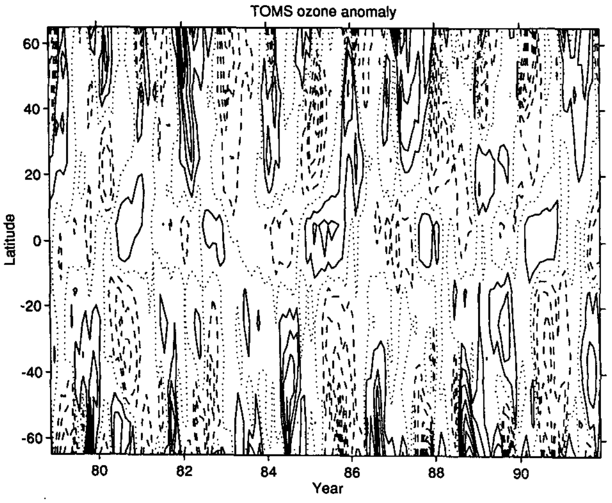


FIG. 2. Latitudinal distribution of TOMS ozone anomaly. Contour levels are 0 (dotted line), ±5 DU, ±10 DU, . . . , with solid (dashed) lines for positive (negative) contours.

is very clear. It also appears that there is an apparent phase reversal in the subtropics in both hemispheres, and this pattern appears to be somewhat coherent in most years to middle and high latitudes. We note two additional features of the extratropical ozone anomaly. The first feature is that the anomaly is strongest at high latitudes during winter in the Northern Hemisphere and during early spring in the Southern Hemisphere. This property of seasonal synchronization has previously been pointed out by Gray and Dunkerton (1990). It is a continuation of the feature that can first be discerned in the subtropics, as pointed out by Hamilton (1989) and Holton (1989). This feature is very clear in the unfiltered data, but becomes smeared out and loses its seasonal synchronization when filtering is applied to the time series [compare Fig. 2 with the narrow band-passed data of Hasebe (1984) and with both the narrow and broad band-passed data of Lait et al. (1989)]. The second feature is that the frequency spectrum of the ozone anomaly is such that in the Tropics and subtropics it is close to that of the equatorial wind (with a peak centered around 30 mo). As one moves to the middle and high latitudes, a second peak, around 20 months, emerges. This has previously been noted by Schuster et al. (1989) without further comment. Hilsenrath and Schlesinger (1981) found that the ozone QBO period is about 27 mo at the equator, decreasing to 20 mo at 40°N. Limited by short data record, they were not able to explain the "period decrease" and suggested the ozone QBO at high and low latitudes may not be directly related. These two features are interrelated, as we will show in more detail below.

The power spectra of the ozone anomaly time series at various latitude bands are calculated using a Tukey window with a window width of 120 months (Bloomfield 1976). A wide window width is used to preserve individual peaks at the expense of larger uncertainty in the resultant spectrum. (The multiplying constants for 95% confidence intervals for the true spectrum are 0.32 and 13.9, for lower and upper limits, respectively. They could be narrowed down to 0.54 and 2.5 if a 30-month lag window was used instead.) The results are shown in Fig. 3. The power spectrum is normalized so that its summation over all frequencies is equal to the sample variance.

Figure 3 shows that the dominant period for both global and equatorial ozone column anomalies is about 30 months—the QBO period. This is to be expected from the high correlations between the ozone anomalies and equatorial wind shown in Fig. 1. There are other smaller peaks; however, the data record is probably too short for us to make any meaningful statement about features like the four-year oscillation noticed by Hasebe (1984) in the 10-year record of BUV data.

The 30-month equatorial QBO period is still a dominant period in the subtropics (10 to 30 deg latitude north and south in Fig. 3), but an additional peak with period around 20 months now emerges. It is much stronger in the Northern Hemisphere than in the Southern Hemisphere.

The 20-month signal is coherent in all extratropical latitudes, all the way to the polar latitudes. Its amplitude increases as one moves poleward, and becomes comparable to, or even larger than, the 30-month oscillation in the middle and high latitudes.

The presence of this frequency component complicates the task of extracting the QBO signal from the raw data, with the consequence that the phenomenon of extratropical QBO is currently ill defined. We will argue that the 20-month part of the spectrum is an integral part of the extratropical QBO phenomenon, but previous attempts at defining the phenomenon have mostly involved filtering away periods different than the equatorial QBO period.

Figure 4 shows an example of such an extracted signal, representing the part of the variability in Fig. 2 that is only in the equatorial QBO frequency. It is obtained by fitting, in least squares, the time series of the data in Fig. 2 with the time series of the 30-mb Singapore wind, allowing for a possible phase shift for each latitude. The resulting global pattern is very clean but much diminished in amplitude in the extratropics. In the equatorial region, it contains most of the variance in the anomaly. The equatorial QBO pattern extends to 12° symmetrically on both sides of the equator, poleward of which there is a reversal of phase. This symmetry in QBO ozone anomaly is probably a reflection of the symmetric equatorial QBO secondary circulation, whose vertical velocity also reverses sign at ±12° of latitude. The amplitude of the QBO anomaly in Fig. 4 in middle and high latitudes is about 6 DU, about a quarter of the amplitude of the "unfiltered" anomaly. Furthermore, peak values at high latitudes are no longer synchronized with season. The direction of the phase

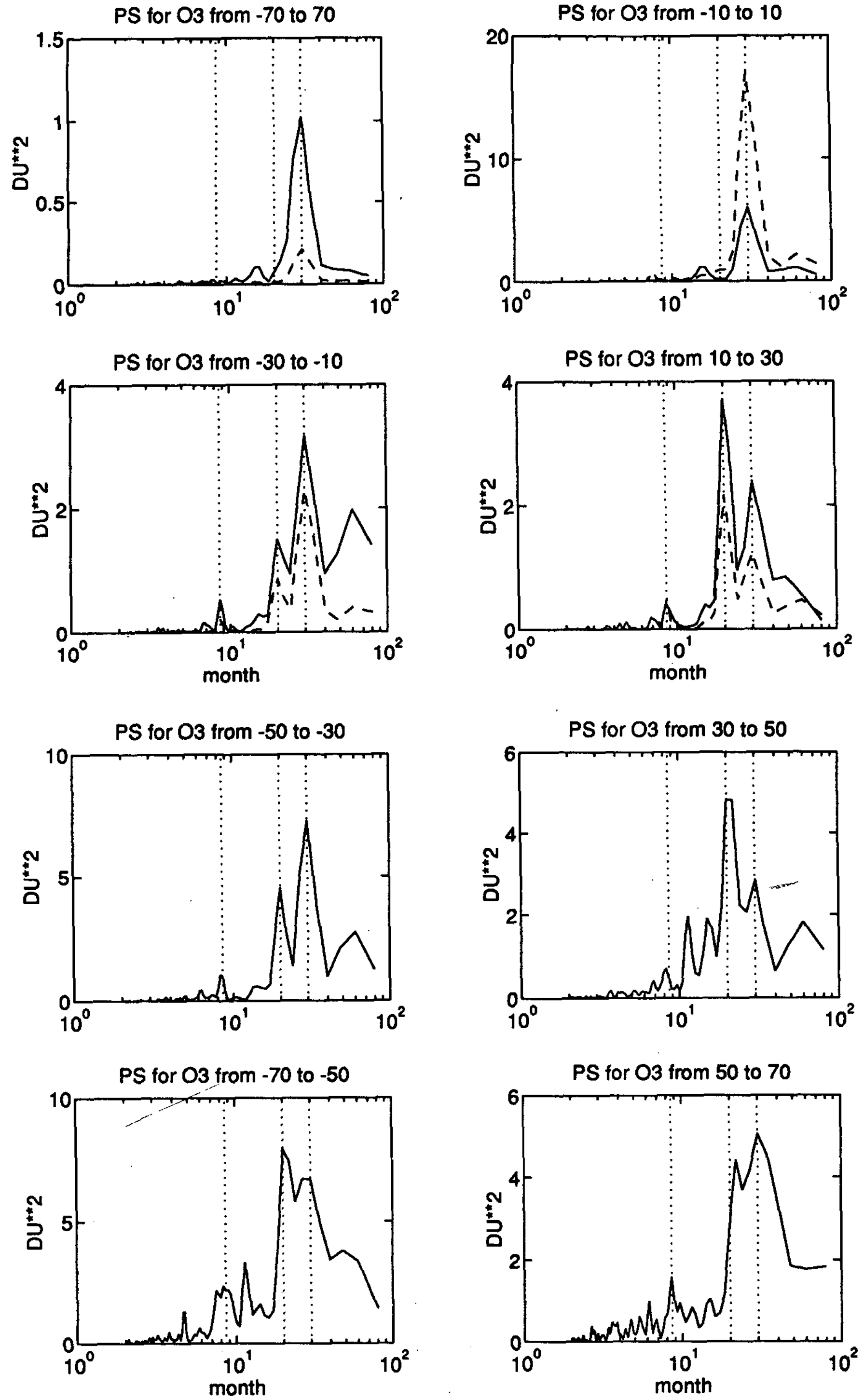


FIG. 3. Power spectra of TOMS ozone anomaly at various latitude bands. The vertical lines mark the positions of 8.6, 20, and 30 mo, respectively.

tilt with latitude is an artifact of data processing and does not indicate the direction of "propagation," as there is no systematic phase propagation evident in our unfiltered anomaly in Fig. 2. In the narrowband filtered BUV data of Hasebe (1984), reproduced in Fig. 5, lines of constant ozone anomaly in the Northern Hemisphere tilt to the right (apparent poleward propagation) south of the nodal line, and tilt to the left (apparent

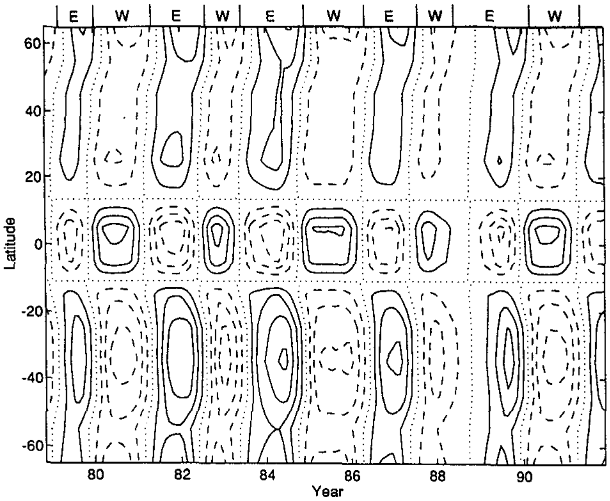


Fig. 4. Latitudinal distribution of TOMS ozone anomaly projected onto 30-mb Singapore wind by least squares fit, with possible phase shift at each latitude. Contour levels are 0 (dotted line), ±2 DU, ±4 DU, . . . , with solid (dashed) lines for positive (negative) contours.

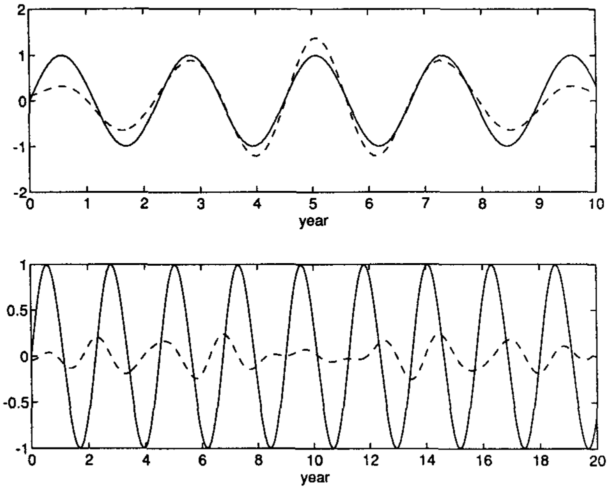


Fig. 6. A sinusoidal function with period of 27 mo (solid lines) and its projection (dashed lines) onto the 18-, 24-, and 30-mo harmonics (see text).

equatorward propagation) poleward of this line. In the Southern Hemisphere, the apparent phase propagation in Hasebe's data is equatorward to the north of the nodal line and poleward to the south of that line. In the Stratospheric Aerosol and Gas Experiment (SAGE II) data analyzed by Zawodny and McCormick (1991), there appears to be poleward propagation in the Northern Hemisphere in late 1985 and in the Southern Hemisphere in 1987 and 1988. It is possible that these features are sensitive to the method of filtering and that when these data are reprocessed with a broadband filter, these "propagation" features would largely disappear.

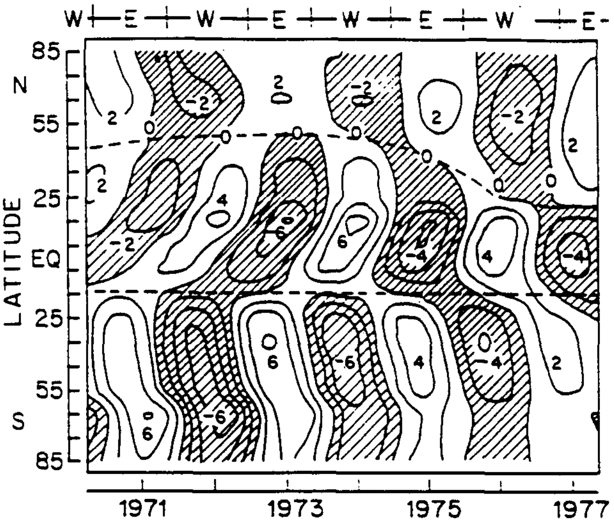


Fig. 5. Latitudinal distribution of ozone anomaly (DU) derived by Hasebe (1983, 1984) using *Nimbus-4* BUV data.

The amplitude of the anomaly is also affected by the degree of filtering. For the same TOMS data, narrowband filtered around the QBO frequency by Lait et al. (1989), the ozone variability yields an amplitude of 8 DU (their Fig. 7c), an increase of 2 DU from our Fig. 4, which passes only the QBO frequency. Their broad band–filtered data (their Fig. 7b) show a still larger amplitude of 12 DU. These are, however, all significantly smaller than the amplitude of the unfiltered anomaly shown in Fig. 2, which is about 25–30 DU.

The method of analysis adopted by Zawodny and McCormick using only a few discrete harmonics (18, 24, and 30 mo) with which to reconstruct the data leads to another artifact: the creation of a longer-period beat frequency, with the consequence that the amplitude of the filtered anomaly appears to be periodically stronger in some years and weaker in others. Figure 6 serves to illustrate this point. It depicts a sinusoidal function with period of 27 months and its projection onto the harmonics of 18, 24, and 30 months. In Fig. 6a, the projection is based on a 10-year "data" record. The long period (over 10 yr) signal in the projection is evident with large amplitude in year 5 and small amplitude in year 0 and year 9. The second projection, based on 20-year data and shown in Fig. 6b, has the additional problem of severely underestimating the amplitude all the time.

4. Discussion of the spectrum

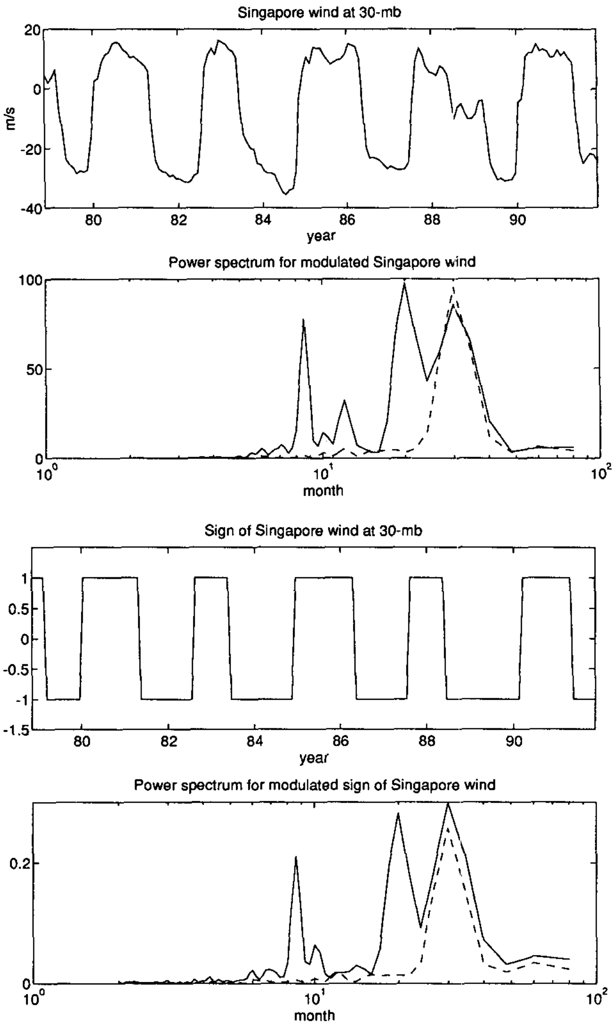
Ozone is a transported quantity and should reflect the variability of the transporting circulation. Away from the equatorial region the seasonality of the circulation is evident and it becomes increasingly prominent as one approaches the high latitudes. It is clear that the interaction of the equatorial QBO frequency with the annual frequency cannot be ignored.

Ozone anomaly in the extratropics can in principle result from the transport of equatorial anomaly by the climatological (non-QBO) Brewer–Dobson circulation [as proposed by Holton (1989)] or it can be created in situ by a QBO circulation anomaly in the extratropics [as proposed by Tung and Yang (1993)]. Given the fact that the ozone QBO anomaly is an order of magnitude less than the climatological ozone distribution, the generation of the ozone anomaly in the extratropics could easily be produced by the anomaly circulation provided that the anomaly circulation is of the same order of magnitude as the climatological circulation in the lower stratosphere. This turns out to be the case as we will discuss in more detail in Part II, based on the fact that the QBO anomaly Eliassen–Palm flux divergence of Dunkerton and Baldwin (1991) is about the same order of magnitude as the climatological values (see Edmon et al. 1980; Yang et al. 1990).

If there is an *anomaly circulation* in the extratropics that is the result of the *modulation* of the tropical QBO on the winter–spring transport, as we propose in Part II, then this anomaly circulation should have two extra frequencies: the sum and difference of the tropical QBO frequency and the annual frequency, in addition to the tropical QBO frequency. This can be easily demonstrated by considering the following simple mathematical formula:

$$\left[A + B\sin\left(\frac{2\pi t}{12\text{ mo}}\right)\right]\sin\left(\frac{2\pi t}{30\text{ mo}}\right) \approx A\sin\left(\frac{2\pi t}{30\text{ mo}}\right) + \frac{B}{2}\cos\left(\frac{2\pi t}{20\text{ mo}}\right) - \frac{B}{2}\cos\left(\frac{2\pi t}{8.6\text{ mo}}\right).$$

We see that a three-peak (30 mo, 20 mo, and 8.6 mo) spectrum emerges. The first part of the product on the left side of the formula has a constant (A) and an annually varying (B term) component. The constant component is present if the anomaly circulation has a nonzero annual mean. This is a relevant case when the anomaly occurs, for example, only during winter and not during summer. The annual mean then is not zero. The second part of the product, a sinusoidal function with a 30-month period, represents the equatorial QBO. It does not matter that the equatorial QBO is not a perfect sinusoid. We show the power spectra in Fig. 7 when the sinusoidal function is replaced by the 30-mb Singapore wind or the sign of the 30-mb Singapore wind. The spectra have the same characteristic three spectral peaks at 30, 20, and 8.6 months.


Singapore wind at 30-mb

Power spectrum for modulated Singapore wind

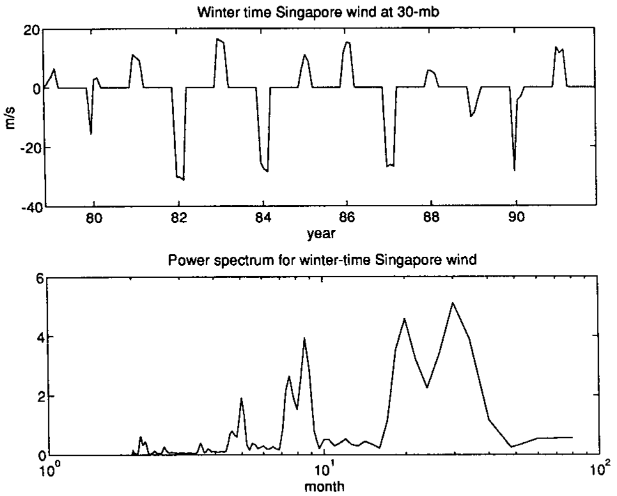
Sign of Singapore wind at 30-mb

Power spectrum for modulated sign of Singapore wind

FIG. 7. (a) Upper panel: 30-mb Singapore wind (U); lower panel: power spectra of U (dashed line) and of the function $[1 + 2\sin(2\pi t/12\text{ months})]U$ (solid line). (b) Same as (a) except for the sign of 30-mb Singapore wind [sign(U)] replacing U in (a).

The next example is more interesting, as it is probably closer to what happens in reality. Consider the case of an anomaly (in extratropical circulation, say) that is correlated with the equatorial QBO as measured by the Singapore wind, but is present only during the winter months (DJF) and is zero in other months. Since such an on–off switch is annually periodic, the result is equivalent to multiplying the 30-month term by a 12-month term. The product should have the same three-peak spectrum we discussed above. This case is plotted in Fig. 8, which is simply the spectrum of a function with values of Singapore wind in winter and zero for other seasons. We see the same three spectral peaks at 30, 20, and 8.6 months, as expected.

The three-peak spectrum at periods of 30, 20, and 8.6 months is a *signature of a QBO circulation anomaly in the extratropics.* Such a circulation anomaly should *generate* in situ an *ozone anomaly* with the same spectral signature in the extratropics. Note that peaks at 8.6 months in Figs. 7 and 8 have smaller values


Winter time Singapore wind at 30-mb

Power spectrum for winter-time Singapore wind

FIG. 8. Upper panel: wintertime 30-mb Singapore wind (U_w), defined as 30-mb Singapore wind in the December, January, February period and zero for other seasons; lower panel: power spectrum of U_w.

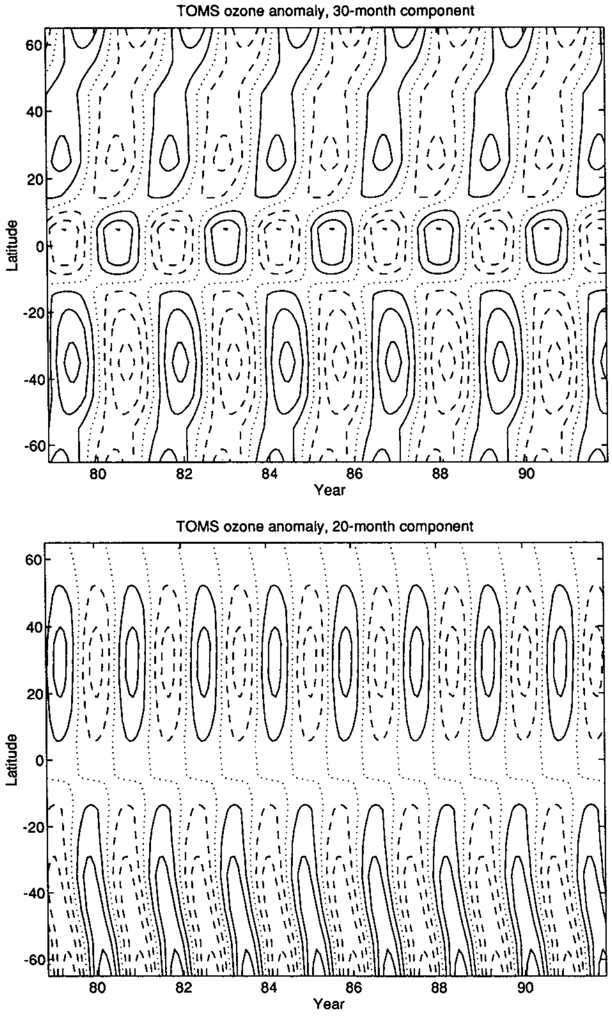
mainly because the data windowing that we have adopted reduces amplitudes at higher frequencies more than at lower frequencies.

As we have mentioned, the 20-month spectral peak is very prominent and coherent in the observed column ozone anomaly in all extratropical latitudes. The 30-month spectral peak is also present. The 8.6-month spectral peak is much fainter than those at 20 and 30 months but is nevertheless also present in all extratropical latitudes. Apart from the reduction in the 8.6-month spectral amplitude due to data analysis mentioned above, the *response* of ozone to forcing in wave driving is also damped more severely at higher frequencies than at lower frequencies due to dynamical and chemical damping. Thus, smaller ozone amplitude at an 8.6-month period is to be expected. Our analysis of ozone data is inconclusive about the presence of an 8.6-month period. It would be interesting to see whether this period is present in dynamical variables like wave driving and circulation. Our theory, if valid, predicts the presence of such a period. Modeling of the anomaly circulation mentioned above and the resulting ozone anomaly will be attempted in Part II.

The transport of equatorial QBO anomaly by the annual mean climatological circulation can in principle also produce a QBO anomaly with the 30-month period. This component is quite small (about 1 DU) in the extratropics, according to our model results in Part II. Without the help of models, however, we are unable to separate this component of the 30-month spectrum from the contribution of in situ generation. Nevertheless, even lumping both 30-month components together amounts to about 4–6 DU in the extratropics.

The seasonally varying part of the climatological circulation transporting an equatorial 30-month ozone anomaly should theoretically also produce a 20-month anomaly in the extratropics and add to the anomaly produced in situ by the 20-month circulation anomaly discussed earlier. Such a mechanism was pointed out by Gray and Dunkerton (1990) previously, although they were not specific about the period of the resulting anomaly. However, this contribution is extremely small, based on tests we have performed with our mechanistic model discussed in Part II. The presence of a 20-month peak in TOMS ozone spectrum supports the existence of an *extratropical anomaly circulation* as suggested above.

It is instructive to examine the latitudinal structure of the 30-month and 20-month components of the extratropical QBO phenomenon in more detail. Figure 9 shows these components as a function of latitude and


TOMS ozone anomaly, 30-month component

TOMS ozone anomaly, 20-month component

FIG. 9. (a) Latitudinal distribution of TOMS ozone anomaly projected onto a sinusoidal function with a 30-month period. Contour levels are 0 (dotted line), ±2 DU, ±4 DU, . . . , with solid (dashed) lines for positive (negative) contours. (b) Same as (a) except for 20-mo period.

time obtained by least squares fitting the TOMS data with 30-month and 20-month harmonics. The 30-month component is very similar to that obtained by fitting the ozone anomaly with the 30-mb Singapore wind. Note that the pattern of the 30-month component is also similar to that of the lag coefficients for DJF season in the Northern Hemisphere and for austral spring season (SON) in the Southern Hemisphere presented by Bowman (1989). The 30-month component shows extratropical QBO amplitude of 4 DU in the Northern Hemisphere and 6 DU in the Southern Hemisphere, both out of phase with the equatorial QBO. The 20-month oscillation, on the other hand, has a very different pattern. It is almost antisymmetric between the two hemispheres, suggestive of a circulation component that has a global pattern from one hemisphere to another. Because of this antisymmetry, the 20-month ozone column oscillation largely cancels itself when globally integrated. Therefore, the 20-month period does not show up in the global ozone spectrum (see Fig. 3). The amplitude of the 20-month oscillation is comparable to that of the 30-month oscillation: about 4–6 DU. The two harmonics, when combined, yield only half of the anomaly amplitude in the extratropics. This is because the observed oscillations are not pure harmonics. There are, however, no other prominent spectral peaks other than those of 30 and 20 months. In Part II, we point out that it is necessary to compare model results with unfiltered data as far as the amplitude of the interannual variability is concerned. The filtered data or the simple harmonics presented here serve only to shed some light on the *patterns* of the transports responsible for the anomaly.

5. Conclusions

Previous methods of extracting the QBO signal from the extratropical ozone distribution have focused mostly on the part of the signal that is at or near the period of the equatorial QBO. This approach often leads to the conclusion that the QBO signal in ozone "falls apart" or that the correlation coefficient drops below statistical significance poleward of the midlatitudes. The part of the ozone variability near the period of the equatorial QBO is found to be about 4–6 DU (6–8 DU if nearby periods are admitted in a narrow-band filter) in the extratropics, as compared to the observed amplitude of ozone anomaly of 20–30 DU. We argue here that it is reasonable to expect that the signal of ozone interannual variability in the extratropics, where the seasonal cycle is prominent, should contain a 20-month period in addition to the 30-month equatorial QBO period, and that such a 20-month period oscillation, as well as the 30-month oscillation, in column ozone can be produced in situ by the modulation of the winter–spring transport in the extratropics by the equatorial QBO.

The existence of such an anomaly circulation is consistent with (and is in fact demanded by) the existence of a wintertime Eliassen–Palm flux divergence difference between the two phases of the equatorial QBO that is reported by Dunkerton and Baldwin (1991). The effect of such an anomaly circulation on ozone will be tested in Part II using a simple mechanistic model.

Acknowledgments. This research is supported by NSF Grant ATM-8903340, and by NASA Grants NAGW-1605 and NAG-1-1404.

REFERENCES

Angell, J. K., and J. Korshover, 1964: Quasi-biennial variations in temperature, total ozone, and tropopause height. *J. Atmos. Sci.*, **21**, 479–492.

——, and ——, 1973: Quasi-biennial and long term fluctuations in total ozone. *Mon. Wea. Rev.*, **101**, 426–443.

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

——, and ——, 1983: Global variation in total ozone and layer-mean ozone: An update through 1981. *J. Climate Appl. Meteor.*, **22**, 1611–1627.

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

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

Bojkov, R. D., 1986: The 1979–1985 ozone decline in the Antarctic as reflected in ground level observation. *Geophys. Res. Lett.*, **13**, 1236–1239.

Bowman, K. P., 1989: Global patterns of the quasi-biennial oscillation in total ozone. *J. Atmos. Sci.*, **46**, 3328–3343.

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

Dunkerton, T. J., and M. P. Baldwin, 1991: Quasi-biennial modulation of planetary-wave fluxes in the Northern Hemispheric winter. *J. Atmos. Sci.*, **48**, 1043–1061.

Edmon, H. J., Jr., B. J. Hoskins, and M. E. McIntyre, 1980: Eliassen–Palm cross sections for the troposphere. *J. Atmos. Sci.*, **37**, 2600–2616; Corrigendum, **38** (1981), 1115.

Garcia, R. R., and S. Solomon, 1987: A possible relationship between interannual variability in Antarctic ozone and the quasi-biennial oscillation. *Geophys. Res. Lett.*, **14**, 848–851.

Gray, L. J., and T. J. Dunkerton, 1990: The role of the seasonal cycle in the quasi-biennial oscillation of ozone. *J. Atmos. Sci.*, **47**, 2429–2451.

Hamilton, K., 1989: Interhemispheric asymmetry and annual synchronization of the ozone quasi-biennial oscillation. *J. Atmos. Sci.*, **46**, 1019–1025.

Hasebe, F., 1983: Interannual variations of global ozone revealed from NIMBUS 4 BUV and ground based observations. *J. Geophys. Res.*, **88**, 6819–6834.

——, 1984: The global structure of the total ozone fluctuations observed on the time scales of two to several years. *Dynamics of the Middle Atmosphere*, J. R. Holton and T. Matsuno, Eds., D. Reidel, 445–464.

Herman, J. R., R. Hudson, R. McPeters, R. Stolarski, Z. Ahmad, X.-Y. Gu, S. Taylor, and C. Wellemeyer, 1991: A new self-calibration method applied to TOMS and SBUV backscattered ultraviolet data to determine long-term global ozone change. *J. Geophys. Res.*, **96**, 7531–7545.

Hilsenrath, E., and B. M. Schlesinger, 1981: Total ozone seasonal and interannual variations derived from the 7 year *Nimbus 4* data. *J. Geophys. Res.*, **86**, 12 087–12 096.

Holton, J. R., 1989: Influence of the annual cycle in meridional transport on the quasi-biennial oscillation in total ozone. *J. Atmos. Sci.*, **46**, 1434–1439.

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

——, and H. C. Tan, 1980: The influence of the equatorial quasi-biennial oscillation on the global circulation at 50 mb. *J. Atmos. Sci.,* **37,** 2200–2208.

——, and ——, 1982: The quasi-biennial oscillation in the Northern Hemisphere lower stratosphere. *J. Meteor. Soc. Japan,* **60,** 140–148.

Hyson, P., 1983: Stratospheric water vapor over Australia. *Quart. J. Roy. Meteor. Soc.,* **109,** 285–294.

Labitzke, K., and H. Van Loon, 1988: Associations between the 11-year solar cycle, the QBO, and the atmosphere. Part I: The troposphere and stratosphere in the Northern Hemisphere in winter. *J. Atmos. Terr. Phys.,* **50,** 197–206.

Lait, L. R., M. R. Schoeberl, and P. A. Newman, 1989: Quasi-biennial modulation of the Antarctic ozone depletion. *J. Geophys. Res.,* **94,** 11 559–11 571.

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

Mastenbrook, H. J., and S. J. Oltmans, 1983: Stratospheric water vapor variability for Washington, D.C./Boulder, CO: 1964–82. *J. Atmos. Sci.,* **40,** 2157–2165.

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

Oltmans, S. J., and J. London, 1982: The quasi-biennial oscillation in atmospheric ozone. *J. Geophys. Res.,* **87,** 8981–8989.

Plumb, R. A., 1984: The quasi-biennial oscillation. *Dynamics of the Middle Atmosphere,* J. R. Holton and T. Matsuno, Eds., D. Reidel, 217–251.

——, and R. C. Bell, 1982: A model of the quasi-biennial oscillation on an equatorial beta-plane. *Quart. J. Roy. Meteor. Soc.,* **108,** 335–352.

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.

——, and W. J. Cambell, 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.

Schuster, G., R. Rood, and M. Schoeberl, 1989: Quasi-biennial and interannual variability in high resolution total ozone data (TOMS). *Ozone in the Atmosphere,* Göttingen, R. D. Bojkov and P. Fabian, Eds., Deepak, 260–264.

Stolarski, R., P. Bloomfield, R. D. McPeters, and J. R. Herman, 1991: Total ozone trends deduced from NIMBUS 7 TOMS data. *Geophys. Res. Lett.,* **18,** 1015–1018.

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 H. Yang, 1993: On global quasi-biennial oscillation in column ozone. *Coupling Processes in Middle and Lower Atmospheres,* E. V. Thrane, T. A. Blix, and D. C. Fritts, Eds., Kluwer Academic, 1–24.

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

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

WMO, 1989: Report of the International Ozone Trends Panel 1988. World Meteorological Organization Global Ozone Research and Monitoring Project, Rep No. 18, Vol. 1, 441 pp.

Yang, H., K. K. Tung, and E. P. Olaguer, 1990: Nongeostrophic theory of zonally averaged circulation. Part II: Eliassen–Palm flux divergence and isentropic mixing coefficients. *J. Atmos. Sci.,* **47,** 215–241.

Zawodny, J. M., and M. P. McCormick, 1991: Stratospheric Aerosol and Gas Experiment II measurements of the quasi-biennial oscillations in ozone and nitrogen dioxide. *J. Geophys. Res.,* **96,** 9371–9377.