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On the phase propagation of extratropical ozone quasi-biennial oscillation in observational data

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Abstract. Global column ozone data from total ozone mapping spectrometer (TOMS), backscattered ultraviolet (BUV) and Dobson stations are analyzed to determine the pattern and phase property of the ozone quasi-biennial oscillation (QBO) signal. It is found that the ozone QBO signal is strongest in middle and high latitudes and is present mainly in the winter-spring season in both hemispheres. The extratropical ozone QBO signal is out of phase with the equatorial ozone QBO, which is itself in phase with the QBO in equatorial zonal wind. There are three distinctive regions, namely tropical, midlatitudinal, and polar regions, in each of which the ozone QBO signal has a fairly constant phase with respect to latitude. There is a phase reversal (sign change) between the equatorial and the extratropical regions associated with the return branch of the equatorial QBO secondary circulation, and this sign reversal occurs at $\pm 12°$ of latitude symmetric about the equator. In the northern hemisphere between the midlatitudinal and polar regions, there is another possible phase reversal in some (but not all) years possibly in connection with the presence or absence of midwinter sudden warming, which creates a positive or negative anomaly relative to the region outside the polar vortex. In the southern hemisphere polar latitudes, the ozone QBO signal is usually delayed until spring in connection with the final warming. These properties are found in all data sets analyzed by the same method. Evidence does not support a gradual phase propagation from the subtropical region to the high-latitude region. Previous reported evidence for phase propagation is reexamined and is found to be artifacts of data processing.

1. Introduction

The phenomenon of quasi-biennial oscillation (QBO) in total ozone at extratropical latitudes has been the subject of current research [e.g., *Tung and Yang*, 1994a, b, and references therein]. Considerable progress has been made in our understanding of the phenomenon, particularly since the availability of observational data with global coverage. However, there have been differing results drawn from analyses of earlier observational data concerning the property of phase propagation in the extratropical ozone QBO. A poleward phase propagation of 10 degrees of latitude per month in the northern midlatitudes and 7–8 degrees of latitudes per month in the southern midlatitudes was reported by *Hasebe* [1983] using filtered data from Nimbus 4 backscattered ultraviolet (BUV) and ground-based observations. Equatorward phase propagation was reported at northern high latitudes by the same author. *Zerefos et al.* [1992] also reported a poleward phase propagation (but at the half of the speed given by *Hasebe* [1983] in both hemispheres) by calculating the cross spectrum between 50-mbar zonal wind at Singapore and ozone data from total ozone mapping spectrometer (TOMS) and ground-based observations. On the other hand, the ozone QBO pattern obtained using a linear regression model by *Yang and Tung* [1994] from TOMS data showed little evidence of a gradual phase propagation. Since these seemingly conflicting results were obtained by different methods from various data sets, it is possible that the reported phase propagation feature in the extratropical ozone QBO is due to the different ways with which the data were processed. In this study, we shall reexamine all the ozone data available to us to determine the phase property of the extratropical ozone QBO and to reconcile the differences reported in the literature. The presentation is divided into two parts. In the first part (sections 2 and 3), we present our analysis of TOMS and Dobson station data. In the second part (section 4), we repeat previous analysis of TOMS, Dobson, and BUV data and reconcile the differences found.

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2. Ozone QBO Pattern and Phase Property

It is desirable to determine the properties of the ozone QBO before a specific method is used to extract the QBO signal, because conceivably the method adopted may distort the signal and its properties. On the other hand, accurate determination of its properties may not be possible before the signal is extracted by some method if the ozone QBO is buried in other signals and noise. Recognizing this difficulty, we shall use both approaches for our task and compare the properties of the original data with those of the extracted signal.

TOMS Data

Because of its continuous and global coverage, TOMS ozone data (version 6) may be the most appropriate data set available now for our purpose. *Yang and Tung* [1994] suggested that a linear regression model (LRM) with seasonally varying coefficients can be used to objectively extract the ozone QBO signal from the total ozone data. The model has the form of

$$O_3 = \alpha + \beta \cdot t + \gamma \cdot Q(t - \text{lag}) + \delta \cdot F(t) + \text{noise},$$

where $Q(t) \equiv U(t) - \text{mean}(U(t))$ and $U(t)$ and $F(t)$ are the 30-mbar Singapore wind and smoothed F10.7-cm solar flux, respectively. The mean value of the 30-mbar Singapore wind $U(t)$ (time average over the period considered) is subtracted from $U(t)$ so that the resulting QBO index $Q(t)$ is more or less symmetric about the zero line. The solar flux index is smoothed by a 13-month centered moving average. The LRM is applied to every month of the year (to all January data, February data, etc.) separately such that the least squares coefficients, α, β, γ, and δ, may vary from month to month. A time lag (or lead if lag is negative) of up to 8 months between the ozone and adjusted wind for each latitude is allowed and is determined by minimizing the residue ("noise") in the model. (Erratic single grid point phase changes are restricted by requiring the lag to be continuous with respect to at least one of the neighboring points. Such behavior may sometimes occur when the QBO signal is weak.) Note that the restriction to a maximum 8 months of allowable phase shift is done without loss of generality. A phase shift of π, or 15 months for the 30-month component of total ozone, can be accomplished by a change of sign in the regression coefficient of the model. A 9-month lead is represented by a 6-month lag together with a change in the sign of the regression coefficient.

The LRM-produced QBO signal, defined as $\gamma \cdot Q(t - \text{lag})$ and shown in Figure 1, preserves such important features as triple-peak spectrum [*Tung and Yang,* 1994a, b] and seasonal synchronization [*Hamilton,* 1989; *Gray and Dunkerton,* 1990] in the extratropical ozone QBO. It has the following phase property in the midlatitudes of both hemispheres: In the winter-spring season, there is a strong QBO signal that is out of phase with the equatorial ozone QBO; in other seasons, the signal is very weak. The summer signal, which may sometimes appear to be in phase with the equatorial ozone QBO, is below the level of statistical significance. Little evidence of phase propagation is present in the midlatitudes.

The TOMS ozone anomaly (not necessarily QBO), defined as deseasoned (by removal of monthly averaged composite) TOMS ozone with a linear trend and an 11-year solar cycle component removed, is shown in Fig-

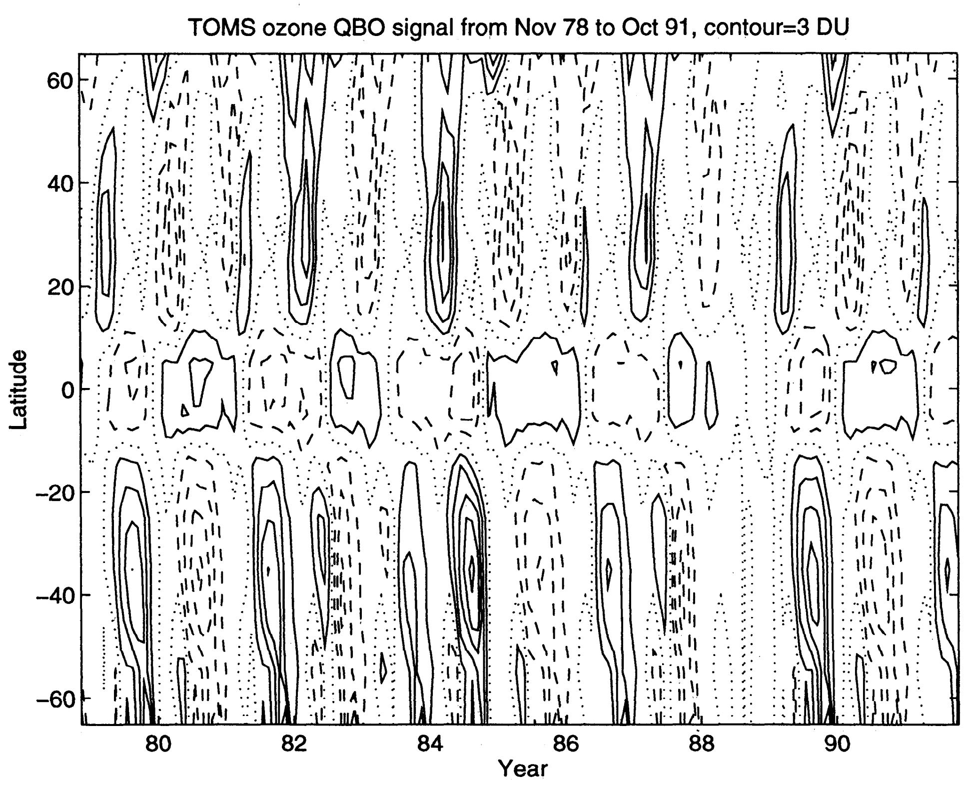

Figure 1. Ozone quasi-biennial oscillation (QBO) signal from total ozone mapping spectrometer (TOMS) data, obtained by a linear regression model. Contour levels are 0 (dotted line), ±3DU, ±6DU,..., with solid lines for positive contours and dashed lines for negative contours.

ure 2. This anomaly contains the QBO signal, plus other unidentified signals and noise. Note that it is very similar to Figure 1 and to the one obtained by *Tung and Yang* [1994a]. It has the same phase relationship discussed above as in the LRM-produced ozone QBO signal in the middle latitudes. At high latitudes, the anomaly is more varied and less coherent, possibly reflecting ozone variations associated with the polar vortex and sudden warming of the polar stratosphere. As a result, the QBO signal extracted by the linear regression model has an amplitude much smaller than that of the total anomaly.

Dobson Station Data

Next, we examine the phase properties of the ozone QBO revealed by the ground-based Dobson station data, which were provisionally revised by R. D. Bojkov and published in the Report of the International Ozone Trends Panel 1988 [*World Meteorological Organization* (WMO), 1989]. Although the revised data set covers a period of 30 years, we chose to use the last 20 years (from 1966 to 1985) as the period for data analysis, because for some of the stations involved the data series did not start until the early 1960s. The ozone QBO signal is extracted by our linear regression model.

The result for the southern hemisphere is shown in the upper two panels of Figure 3. Although it contains data at only three stations (MacQuarie Isle at 54°S, Aspendale at 38°S, and Huancayo at 12°S), Figure 3 shows a clear and coherent ozone QBO signal in the extratropics. The QBO pattern is in good agreement with that of TOMS data during the years when the two data sets overlap. The ozone QBO signal peaks during the winter at the midlatitudes, and there is little evidence to suggest a gradual (poleward or equatorward) phase propagation, although the spatial resolution here is too low to make a definite conclusion by the Dobson station data alone. The ozone QBO signal peaks during spring at high latitudes, in connection with the final warming and breakdown of the polar vortex in the southern hemisphere.

There are many more stations in the northern hemisphere. Instead of individual stations, we use the latitudinally banded data from the same source. The four latitudinal bands are 30°N–39°N, 40°N–52°N, 53°N–64°N, and 60°N–80°N. The LRM-produced ozone QBO signal is shown in the lower two panels of Figure 3, where each band is shown at its middle point. Again, the QBO pattern and phase property of the station data are in fairly good agreement with those of TOMS data during the years when the two data sets overlap. It is interesting to note that there is a sign change near 55°N for some of the years in the ozone QBO signal. We will return to this feature later in the discussion.

The corresponding ozone anomaly for both hemispheres is shown in Figure 4. Although much noisier, it has generally the same pattern as the LRM-extracted QBO signal. In particular, no notable phase propagation, poleward or equatorward, is evident in the extratropical data.

3. Discussion of the QBO Pattern Found

A consistent QBO pattern emerges from both TOMS and Dobson data sets. This pattern is obtained by applying the same objective procedure uniformly to the data sets. We now summarize the QBO pattern char-

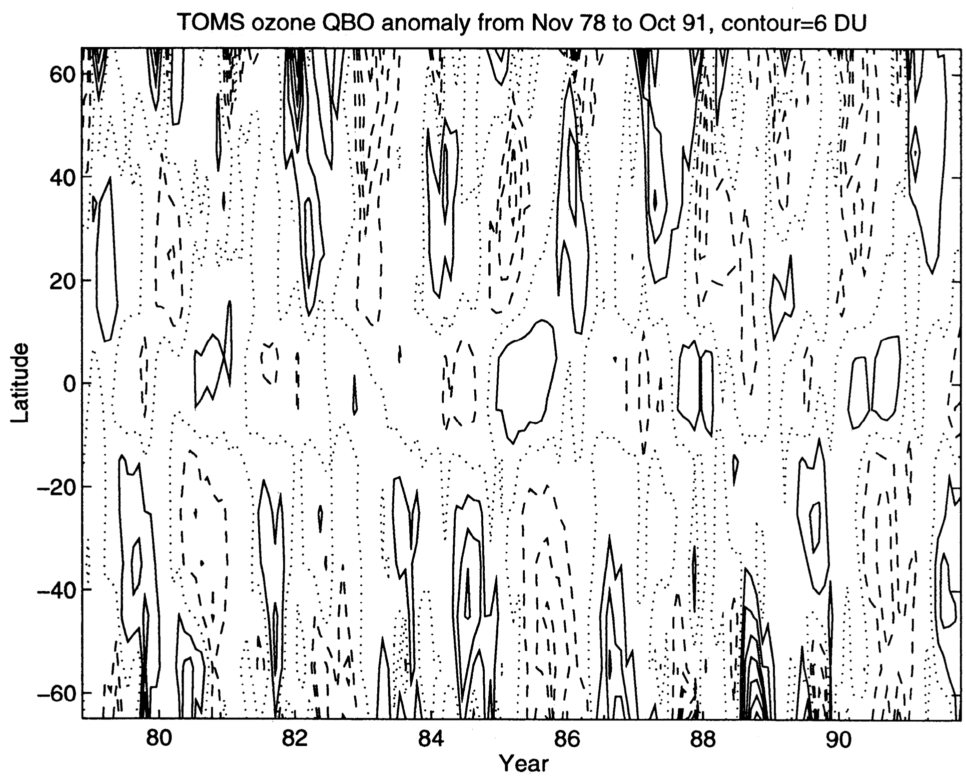

Figure 2. Ozone QBO anomaly from TOMS data (see text). Contour levels are 0 (dotted line), ±6DU, ±12DU,..., with solid lines for positive contours and dashed lines for negative contours.

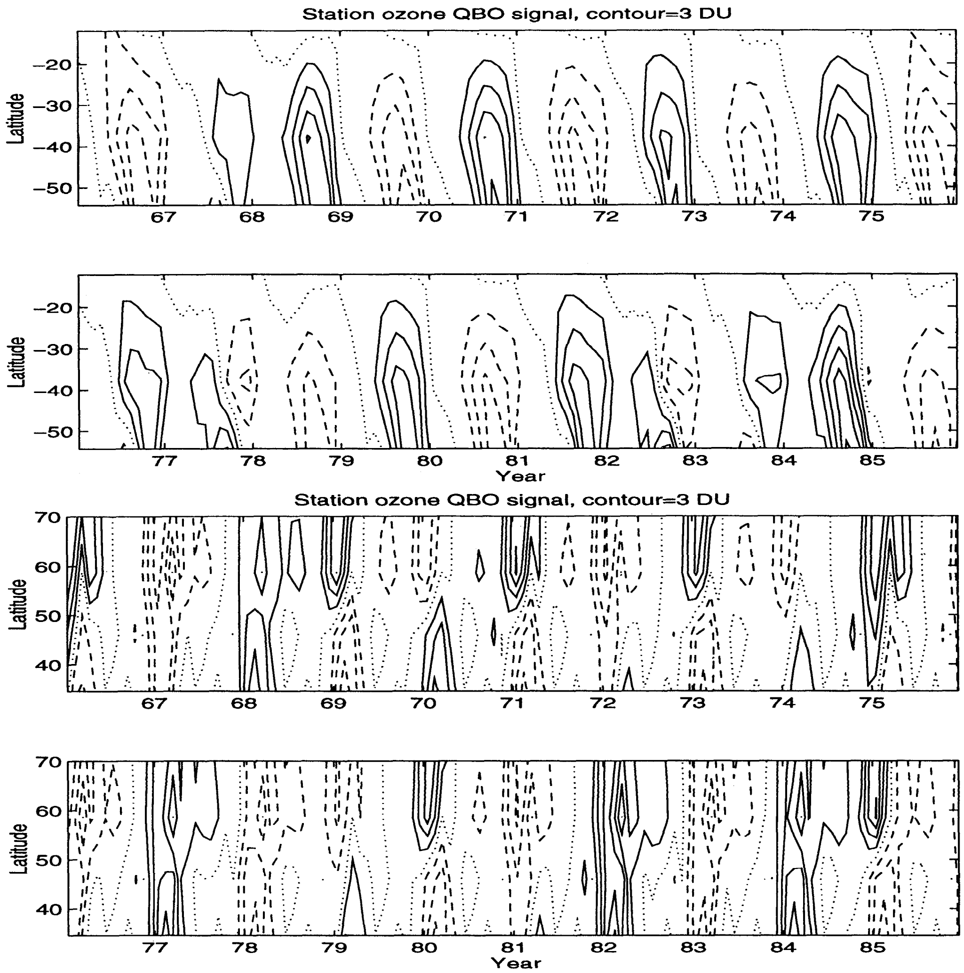

Figure 3. Ozone QBO signal from Dobson station data. The upper two panels plot data from three stations (MacQuarie Isle at 54°S, Aspendale at 38°S, and Huancayo at 12°S); the lower two panels plot data from four slightly overlapping latitudinal bands: 30°N–39°N, 40°N–52°N, 53°N–64°N, and 60°N–80°N, and each band is shown at its middle point. Contour levels are 0 (dotted line), ±3DU, ±6DU,..., with solid lines for positive contours and dashed lines for negative contours.

acteristics that are found by us to be common to both data sets.

There exist three distinct latitudinal bands. (Please refer to Figure 1.)

The first is the equatorial region (12°S–12°N). The QBO signal in this region is symmetric about the equator and has strong latitudinal coherence. There is no notable phase propagation. The QBO signal goes through a node at 12 degrees of latitude in both hemispheres. There does not appear to be a hemispheric difference in the location of this nodal line, in contrast to some previous reports [e.g., *Hasebe*, 1983]. We believe that the equatorial QBO in column ozone is caused by the induced secondary circulation of the equatorial QBO phenomenon itself. Since such a circulation is symmetric about the equator and reverses its sign at around 12 degrees of latitude north and south; the ozone QBO signal exhibits the same features.

The second band is the midlatitudes (12°N–50°N, 12°S–55°S). The pattern is continuous between the subtropics and the middle latitudes. Therefore the subtropical region is grouped together with the midlatitude region. The strong anomaly in the extratropics is synchronized with the late winter-early spring period and is 180° out of phase with the equatorial ozone anomaly. During the rest of the year and especially in summer, the QBO signal is very weak, and a statistical analysis (not shown) suggests that it may be indistinguishable from zero. Therefore we will simply describe the extratropical QBO signal as out of phase relative to the equatorial signal and present only during the winter-spring season. The features are quite broad latitudinally in this region, with a relative maximum occurring near 35 degrees in both hemispheres. The subtropical circulation poleward of 12 degrees is simply the return branch of the equatorial QBO secondary circulation and so is opposite in sense to that equatorward of 12 degrees.

The last band is the polar regions (50°N–90°N, 55°S–90°S). We have a somewhat incomplete picture for the polar regions because of the absence of satellite data during the polar night. The Dobson station at Resolute (74°N) also has some gaps during winter. Nevertheless,

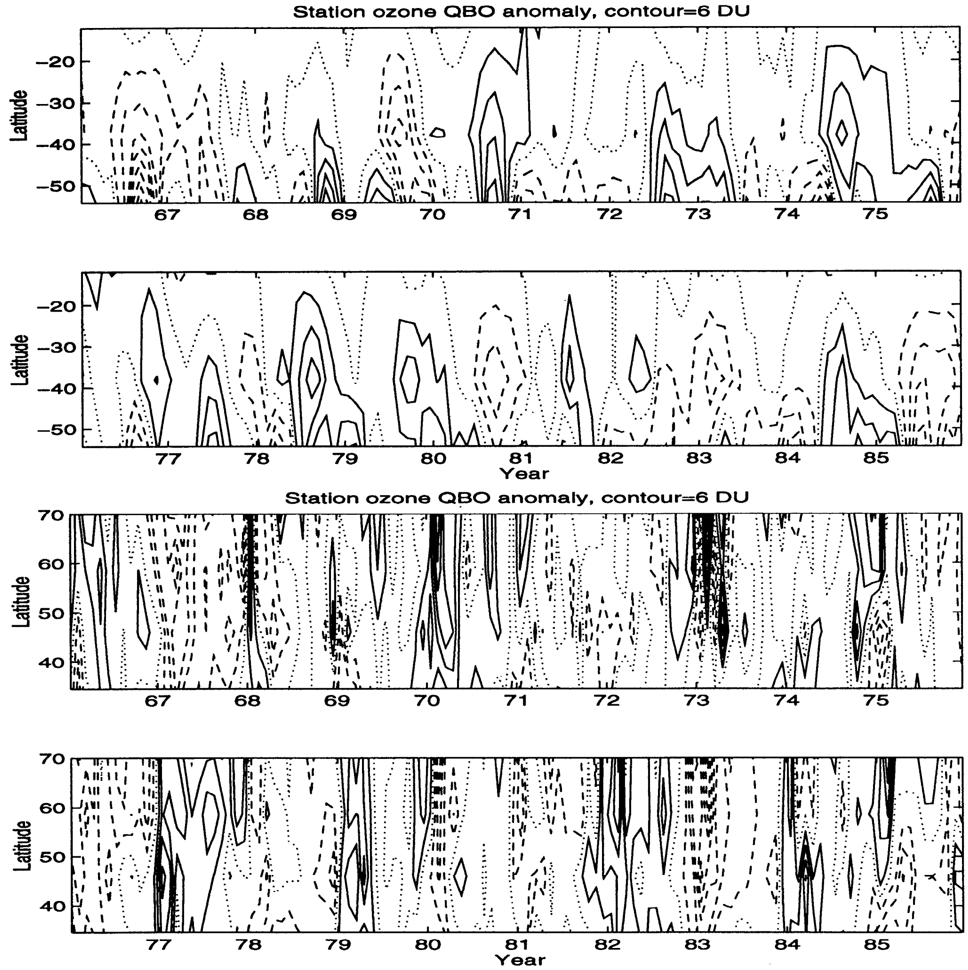

Figure 4. Same as in Figure 3, except for ozone QBO anomaly. Contour levels are 0, ±6DU, ±12DU,...

some interesting features of the QBO signal can still be noted.

The QBO anomaly appears to reach a relative minimum somewhere around 50 degrees of latitude. The location of this minimum varies with year but on average is located at 50 degrees in the northern hemisphere and more poleward, at 55 degrees, in the southern hemisphere. This is roughly where the edge of polar vortex is located. Inside the polar vortex, the peak anomaly occurs after the final warming in the southern hemisphere. The anomaly is more variable in the northern polar region than is the case for the southern polar region. In some years, it has a different sign than that in the middle latitudes. We attribute this extravariability to the presence of the polar sudden warming phenomenon. More discussion on this can be found in the next section.

Although there is some phase difference between the QBO signal in different regions for reasons discussed above, there does not appear to be any significant phase difference for the signal within each region.

4. Comparison With Previous Results

We have analyzed TOMS and Dobson station ozone data, which were obtained by different instruments and covered different periods of time. The periods covered in our analysis are 1978–1991 for TOMS and 1966–1985 for Dobson stations. Both data sets, either in the form of unfiltered ozone anomaly or in the form of LRM-produced QBO signal, show the same seasonally synchronized QBO pattern that is out of phase in the winter-spring season in both hemispheres. No phase propagation was found in the middle latitudes, where the signal is strongest. This result is different from the previous reported phase propagation property of the extratropical ozone QBO. Here we attempt to reconcile the differences.

The previous studies that reported phase propagation [*Zerefos et al.,* 1992; *Hasebe,* 1983, 1984] all defined the extratropical ozone QBO signal as having the same frequency as that of the equatorial QBO. As pointed out by *Yang and Tung* [1994], this is only a component of the extratropical ozone QBO. The phase property of our LRM-extracted QBO, which is the same as that of the unfiltered anomaly, represents the phase property of the entire QBO signal, while the previous results represent the phase property of a component of the QBO signal. Nevertheless, a legitimate question can still be asked: Does the QBO component with the frequency of the equatorial QBO have a finite phase propagation speed from the tropics to the extratropics? To answer this question, we repeat and reexamine the same data sets using the same methodology as adopted by the previous authors.

TOMS Data

Following *Zerefos et al.* [1992], we obtain the phase of ozone QBO by calculating the cross spectrum between the ozone time series and the 30-mbar Singapore wind. The phase represents the amount of phase lag of ozone with respect to the Singapore wind that yields a maximum correlation between the two series. It is a function of frequency. Shown in Figure 5 are the phases at the period of 30 months for TOMS total ozone (monthly and zonally averaged version 6 TOMS ozone data, with no further processing for this calculation) at the resolution of one degree of latitude.

At the period of 30 months, TOMS ozone in the equatorial region is leading the Singapore wind by 1–2 months (see *Tung and Yang* [1994b] for a discussion). A change of phase occurs at about 12 degrees of latitude in both hemispheres symmetric about the equator. This phase transition is relatively sharp as seen in Figures 1 and 2 but shows up as a smooth transition in Figure 5. At middle latitudes (20°N–45°N, 20°S–50°S), the phase is fairly constant and is lagging the equatorial ozone QBO by about 15 months or out of phase with the equatorial ozone QBO (with a 30-month period). There is a phase shift of a few months at about 50 degrees of latitude in both hemispheres for the 30-month component.

Our calculation agrees well with the calculation of *Zerefos et al.* [1992], reproduced here in Figure 6, except for one point at the southern high latitude. Note that they used 50-mbar Singapore wind and showed the result at the period of 27 months, which accounts for the

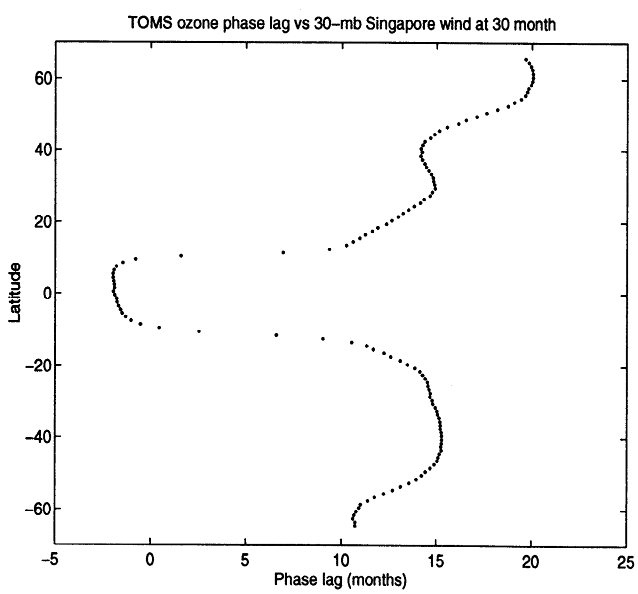

Figure 5. The phase lag with respect to the 30-mbar Singapore wind of the 30-month component of TOMS total ozone.

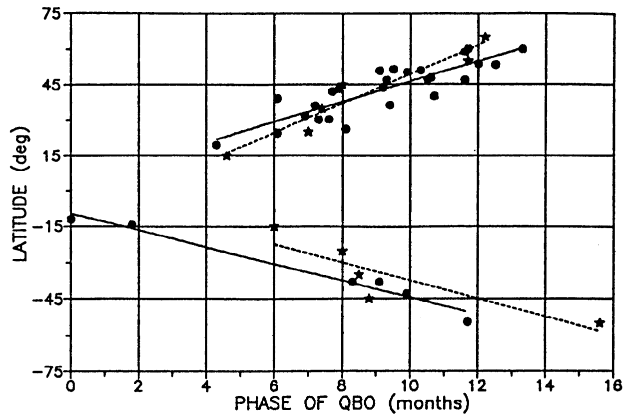

Figure 6. The phase lag with respect to the 50-mbar Singapore wind of the 27-month component of TOMS total ozone (stars) and Dobson station total ozone (circles). The straight lines are least squares fits to the Dobson station data (solid lines) and the TOMS data (dashed lines). Taken from *Zerefos et al.* [1992].

different scales on the time axes. However, it appears to be a misinterpretation to conclude that a gradual phase propagation exists based on a least squares line fitted to the data. In each of the three regions that we described, the 30-month component of TOMS total ozone has a fairly constant phase. There are phase changes (or phase shift) at the boundaries between these regions. The phase change in the subtropics, which is actually a sign change, is associated with the return branch of the symmetric QBO secondary circulation induced by the equatorial QBO in zonal winds. The phase shift between middle and high latitudes needs more explanation.

The top panel of Figure 7 shows the TOMS total ozone at the 10-degree latitude bands centered at 45°N and 65°N. It is seen that the seasonal variations at the middle and high latitudes are of the same sign and in phase with each other. It is also evident that ozone variation in the polar region has a larger amplitude than that in the middle latitudes. When the seasonal cycle is removed, positive or negative anomalies are created in the deseasoned data, shown in the middle panel of Figure 7. There still does not appear to be a phase shift in the overall anomaly patterns between middle and high latitudes. However, the sign of the anomaly may be different between middle and high latitudes during some years. This different behavior inside and outside of the polar vortex can be attributed to the tightness of the polar "containment vessel" with respect to the transport across the edge of the polar vortex.

Figure 8, taken from *Dunkerton and Baldwin* [1991], shows the average temperature north of 72°N at 50-mbar level for the October–April months from 1976 to 1988, with the timing of major warmings noted. During the winters when there is an early major warming in January, such as in 1985 and 1987, more ozone is transported from middle latitudes to the polar region as compared to a "normal, average" year. As a result, a positive anomaly in total ozone is created in the high-

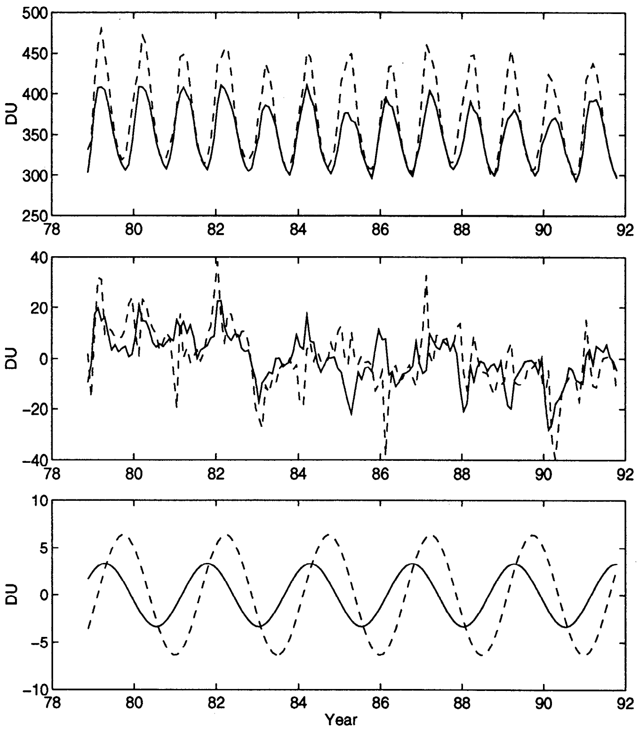

Figure 7. TOMS ozone data at the 10-degree latitude bands centered at 45°N and 65°N. Top panel shows TOMS total ozone; middle panel shows deseasoned TOMS total ozone; and bottom panel shows the projections of the deseasoned TOMS total ozone onto a 30-month harmonic function.

latitude region and simultaneously a negative anomaly is created in the middle-latitude region. The opposite is true during a quieter-than-normal winter when there is no midwinter sudden warming, such as in 1986. The anomaly is then negative in the polar region and positive in the middle latitude region. Although the timing of sudden warming is also affected by the phase of equatorial zonal wind QBO [*Labitzke*, 1982; *McIntyre*, 1982], the strength of the warming is not entirely determined by it, hence the presence of some "abnormal" years.

As can be seen from Figures 7 and 8, the ozone variations in the middle and high latitudes tend to be in phase during a normal, average year and out of phase during an abnormal (either dynamically more active or dynamically less active) year for the northern winter season. When such variations are projected onto a 30-month harmonic function, a single phase shift somewhere between 0° and 180° is created so that the overall pattern can best be fitted into a sinusoid. Such a procedure does not allow a sign change (180° phase shift) for some years but not for other years between the middle and high latitudes. For example, the projections of the two curves in the middle panel of Figure 7 onto a 30-month harmonic function, shown in the bottom panel of Figure 7, seem to suggest that the high-latitude ozone lags the midlatitude ozone by about 5 months. This phase shift is an artifact of data analysis because such a shift in phase is not seen in the original data.

The following example serves to illustrate this point further. In Figure 9, the 30-mbar Singapore wind in winter (December-January-February) season (upper panel) and its projection onto a 30-month harmonic function (lower panel) are plotted in solid lines. Also plotted, in dashed lines, are the same wind with the sign reversed for the four winters from 1984 to 1987 and its projection onto a 30-month harmonic function. Because of the sign change during some of the years in the original data, their projections differ in phase by about 5 months and differ in amplitude by more than a factor of 3. A narrowband filter used to extract ozone QBO signal may create similar artifacts, severely underestimating the amplitude of the QBO signal at high latitudes and producing a misleading phase in the extracted signal.

In summary, aside from a sign change near 12 degrees of latitude in both hemispheres for all years and a possible second sign change near 50°N during some abnormal years, there is little phase change in the global ozone QBO signal. The large (5 months) phase shift that is found in its 30-month harmonic component near 50°N is likely an artifact of the projection method and should not be interpreted as a real phase shift. Furthermore, it is misleading to draw a least squares straight line across the three distinct regions and to then conclude the existence of a gradual poleward phase propagation.

Dobson Station Data

Next, we repeat the above calculation for ozone data from individual Dobson stations. All the stations where the revised Dobson ozone data are available for the entire 20-year period from 1966 to 1985 are included in our calculation. The result is shown in Figure 10, where the phase of 30-month ozone harmonic with respect to

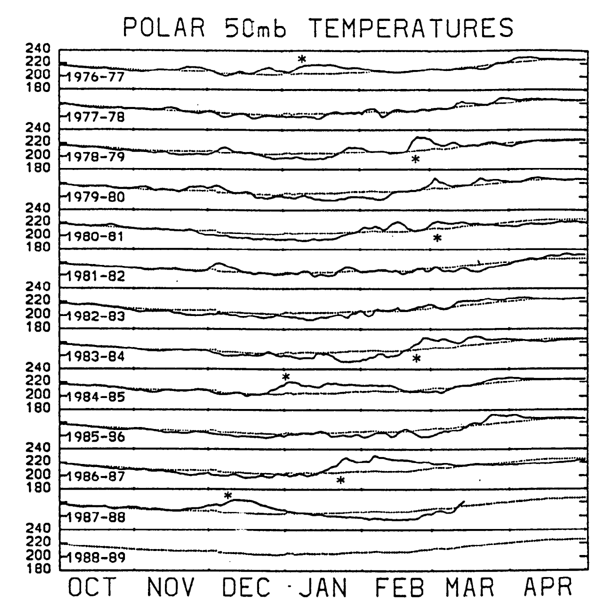

Figure 8. Average temperature (in degrees Kelvin) north of 72°N at 50-mbar level. Climatological average is shown as dotted line. Asterisks denote major warmings. Reprinted from *Dunkerton and Baldwin* [1991].

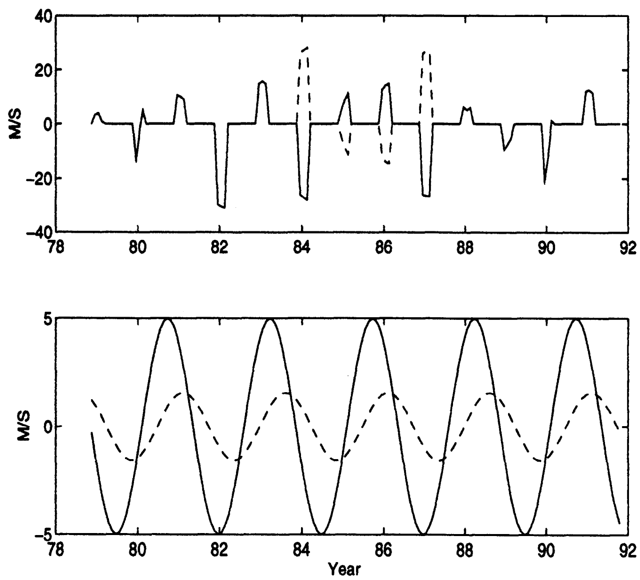

Figure 9. Upper panel: The solid line represents the wintertime 30-mbar Singapore wind; the dashed line represents the same wind except for during the four winters from 1984 to 1987, when the the sign of the wind is reversed. Lower panel: The data shown in upper panel is projected onto a 30-month harmonic function.

the 30-mbar Singapore wind is represented by a circle for each station (22 in all), along with those from the TOMS data (shown in dots).

The phase calculated from individual station data is less certain because data from an individual station are more varied than the zonally averaged data. This can be seen from Figure 6 and Figure 10, as the data points now are more scattered. Nevertheless, it is not inconsistent with the zonally averaged TOMS data, since the data points tend to scatter about the TOMS zonal average. There is no compelling reason to conclude the presence of poleward phase propagation based on the Dobson data. As pointed out earlier, one should not base one's conclusion of phase propagation on a least squares straight line that connects the three distinct (subtropical, middle, and high) latitudinal regions.

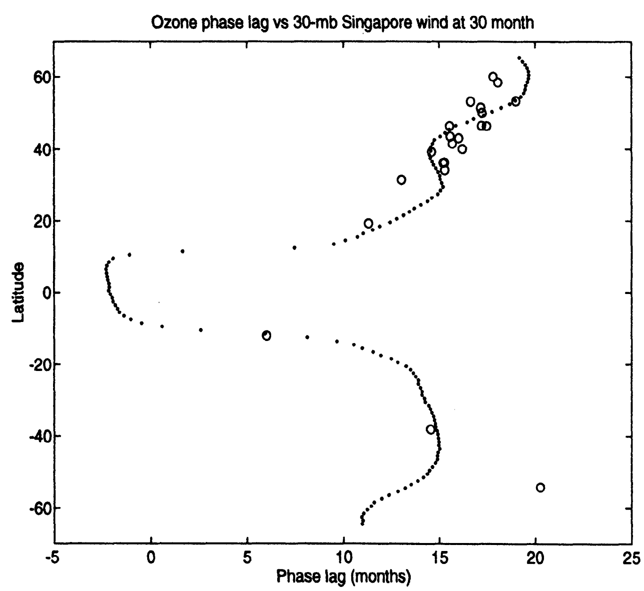

Figure 10. The phase lag with respect to the 30-mbar Singapore wind of the 30-month component of TOMS total ozone (dots) and Dobson station total ozone (open circles).

BUV Data

Hasebe [1983, 1984] presented an analysis of total ozone variation for the period from April 1970 to May 1977 based on a hybrid use of Nimbus 4 BUV and ground-based observational data by a modified scheme of the optimum interpolation. He has kindly provided us with his analyzed (deseasoned) ozone data before his narrowband filter is applied. The BUV ozone anomaly obtained by us from his data is shown in Figure 11. Little evidence of phase propagation in the midlatitudes in both hemispheres is present in the ozone anomaly.

Hasebe [1983, 1984] used a narrowband filter to extract the QBO signal. His result, reproduced by us and shown here in Figure 12, is often cited and taken to be the pattern of global ozone QBO. In his QBO signal, there are northward phase propagation in the entire equatorial region north of 10°S, poleward phase propagation in the middle latitudes, and equatorward phase propagation at high latitudes. These phase propagation features, however, are not apparent in the unfiltered BUV ozone anomaly (Figure 11).

A narrowband filter such as that used by *Hasebe* [1983, 1984] lacks the time resolution to resolve the seasonally synchronized QBO signal. Features narrow in time duration are projected onto broad features with periods of around 30 months. The weak summer-autumn signal is increased in amplitude by the projection. When this increased in-phase signal is connected

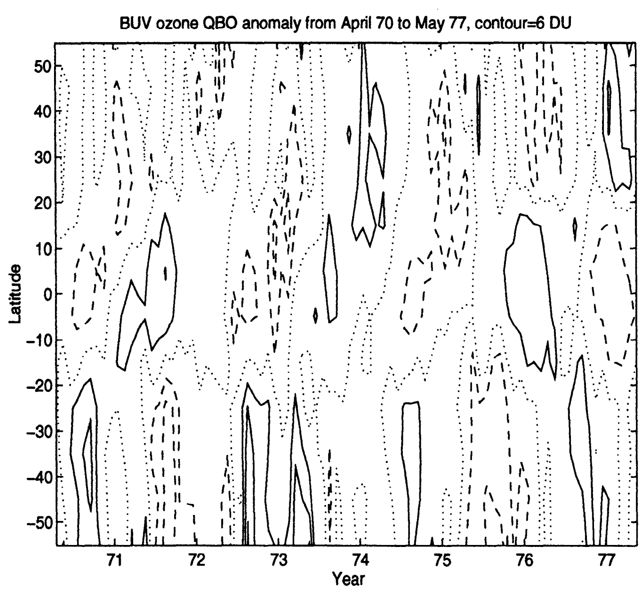

Figure 11. Ozone QBO anomaly from *Hasebe*'s [1983] analyzed backscattered ultraviolet (BUV) data. Contour levels are 0 (dotted line), ±6DU, ±12DU,..., with solid lines for positive contours and dashed lines for negative contours.

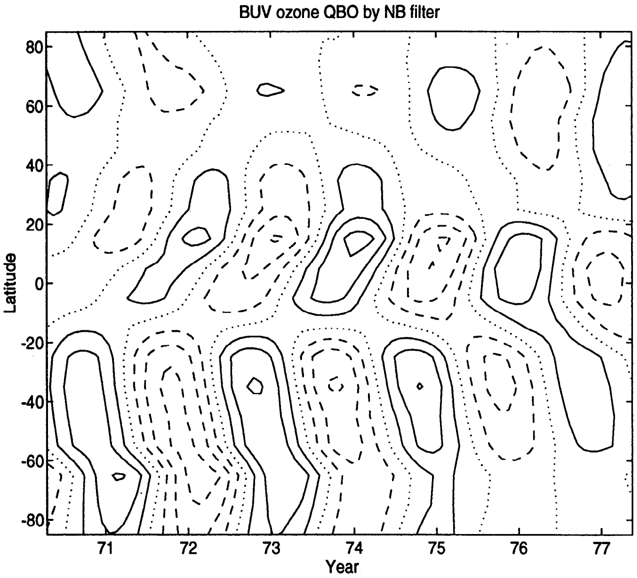

Figure 12. Ozone QBO signal extracted by Hasebe's narrowband filter from his analyzed BUV data. This is a reproduction of his earlier result [*Hasebe,* 1983]. Contour levels are 0 (dotted line), ±2DU, ±4DU,..., with solid lines for positive contours and dashed lines for negative contours.

with the equatorial signal in a contour plot (such as in the northern middle latitudes in Figure 12) it provides a visual impression of phase propagation, which may be misleading.

Second, the ozone QBO signal extracted by a filter may be sensitive to the properties of the filter used. If we change the order of the Hasebe's QBO filter (the number of terms in the convolution summation, see *Hasebe* [1980]) from 57 to 17 and keep all other parameters the same, the Hasebe narrowband filter becomes a broadband filter. When such a broadband filter is used to filter Hasebe's BUV data, the QBO obtained becomes the one shown in Figure 13, which differs in both amplitude and phase from the QBO shown in Figure 12.

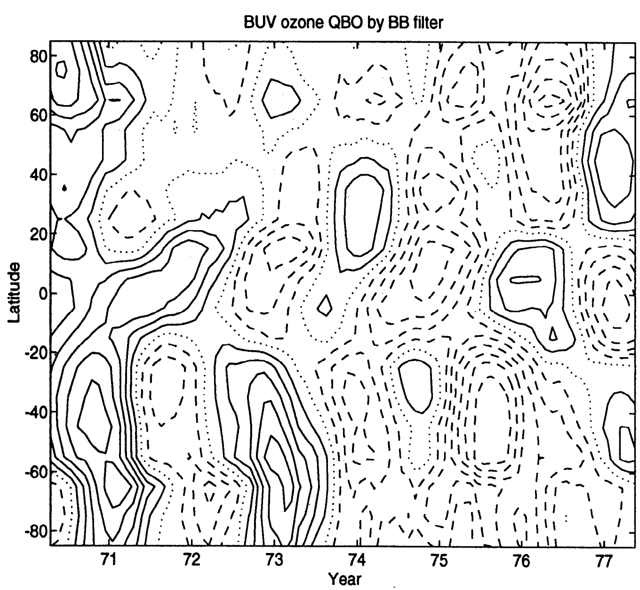

Figure 13. Ozone QBO signal extracted by a broadband filter from *Hasebe*'s [1983] analyzed BUV data. Contour levels are 0 (dotted line), ±2DU, ±4DU,..., with solid lines for positive contours and dashed lines for negative contours.

Lait et al. [1989] also used both narrowband and broadband filters to extract the ozone QBO from TOMS data. Their result showed an apparent poleward phase propagation in the southern midlatitudes and in the northern midlatitudes an apparent equatorward phase propagation in some years (1979, 1980, 1987) and no phase propagation in other years (1981–1986). *Zawodny and McCormick* [1991] used discrete Fourier modes to extract the ozone QBO from stratospheric aerosol and gas experiment (SAGE) II ozone data. Their result showed an apparent equatorward phase propagation in the southern hemisphere in 1985 and 1986, where an apparent poleward phase propagation was implied by *Lait et al.* [1989]. These features are probably artifacts of the data processing (see [*Tung and Yang,* 1994a].

5. Conclusions

Objective analysis of TOMS and Dobson station total ozone data using our linear regression model indicates a consistent pattern and phase property of extratropical ozone QBO. The extratropical ozone QBO is seasonally synchronized. The signal is strong in the winter-spring season and is out of phase with equatorial ozone QBO in the middle latitudes in both hemispheres. Evidence from TOMS, BUV, and Dobson station ozone data does not support a gradual phase propagation from subtropics to extratropics. Extratropical ozone QBO signal from all data sets shows an essentially constant phase with respect to latitude. Our finding is consistent with, though not a proof of, the theory that extratropical ozone QBO is created in situ by a QBO modulated circulation [*Tung and Yang,* 1994a, b]. Our result differs from earlier analyses by other authors. We repeated some of the earlier analyses and showed that the phase propagation in the extratropical ozone QBO reported previously in the literature appears to be an artifact of data processing. The artifact arises either from the analysis method that distorts the phase property or from misinterpretation.

We recommend the method of extracting global ozone QBO signal based on a linear regression model with seasonally varying coefficients. This method preserves the ozone QBO phase property discussed above. It also preserves the triple-peak spectrum and seasonal synchronization features [see *Yang and Tung,* 1994] of the extratropical ozone QBO.

It is interesting to note that there exists a minimum in the ozone QBO signal obtained by our linear regression model near 50 degrees in the northern hemisphere. Such a feature also exists at the same location in the linear trend obtained by the same method [*Stolarski et al.,* 1991; *Randel and Cobb,* 1994]. This feature may be caused by the difference in the degree of variability between the polar region and the middle latitude region across the edge of the polar vortex. The features of our LRM-extracted linear trend (not shown) turn out to be quite similar to the features discussed in this paper for the QBO signal. They will be discussed in more detail in a separate manuscript.

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