Influence of the Annual Cycle in Meridional Transport on the Quasi-biennial Oscillation in Total Ozone

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ABSTRACT

The equatorial stratospheric quasi-biennial oscillation (QBO) in zonal wind and temperature is observed to be symmetric about the equator. The QBO in column ozone, although it is believed to be caused primarily by vertical displacements due to the meridional circulation associated with the equatorial temperature QBO, is asymmetric with respect to the equator, and is strongly linked to the phase of the annual cycle. In this note a simple one-layer model is used to demonstrate that the gross features of the observed QBO in total ozone can be attributed to meridional advection of the ozone perturbation by the annually reversing mean meridional Hadley circulation. This advection causes a displacement of the equatorial ozone anomaly towards the winter hemisphere, and thus produces an asymmetry with respect to the equator. It also modulates the amplitude of the ozone QBO, since the phase of the equatorial wind QBO with respect to the annual cycle may produce either constructive or destructive interference between the effects of the annually reversing meridional transport and the vertical advection by the equatorial wind QBO.

1. Introduction

A number of authors have reported observational evidence for quasi-biennial oscillations in total ozone in the tropics and extratropics (e.g., Angell and Korshover 1973; Oltmans and London 1982; Hasebe 1983; Hamilton 1989). It is clear from these and other studies that at least in the tropics the ozone QBO is associated with the well-known QBO in temperature and zonal wind. (For a review of the equatorial QBO see Andrews et al. 1987.) Ling and London (1986) used a one-dimensional model to show that the QBO in equatorial temperature generates a QBO in the upper stratosphere due to the temperature dependence of rate coefficients in the photochemistry of ozone, while in the lower stratosphere an ozone QBO is generated through vertical transport by the mean meridional circulation associated with the temperature QBO. The roles of both transport and chemistry in generating the QBO in total ozone were studied in a two-dimensional model by Gray and Pyle (1988), who showed that transport processes dominate in the total column perturbation, although chemical processes are crucial above about 25 km.

Reed (1964) first deduced the nature of the mean meridional circulation driven by the temperature QBO. He pointed out that the temperature QBO in the tropics is symmetric about the equator and has phase reversals at about ±15° latitude. In order to maintain this temperature anomaly pattern in the presence of radiative damping, a vertical circulation is required whose adiabatic heating and cooling balances the radiative damping. Thus, in the QBO westerly shear zone, which by thermal wind balance requires a positive temperature anomaly near the equator and a negative temperature anomaly poleward of ±15° latitude, there will be subsidence near the equator and rising poleward of ±15°, as shown schematically in Fig. 1. This vertical motion pattern acting on the mean positive vertical gradient of ozone mixing ratio in the lower stratosphere will then tend to produce a positive ozone anomaly near the equator and a negative anomaly poleward of ±15°. In the easterly shear zone of the equatorial QBO, on the other hand, the sense of the forced meridional circulation is reversed so that the signs of the equatorial and subtropical ozone anomalies produced by the vertical circulation of the equatorial QBO will also be reversed. Since the ozone concentration in the lower stratosphere represents the major contribution to the total column ozone it might be expected that the observed QBO in total ozone would have a latitudinal structure similar to that of the mean meridional circulation associated with the temperature QBO, and hence be symmetric about the equator with phase reversals at ±15° latitude.

The observed ozone QBO at low latitudes differs from this predicted structure in two important ways. First, it is strongly modulated by the seasons so that the maximum perturbation in each hemisphere tends to occur in winter. Second, the phase reversal does not generally occur at 15° latitude. During the 1970s, as
2. Model description

The model developed here is based on a number of simplifying assumptions:

1) The QBO in total ozone is due primarily to ozone perturbations in the layer between 100 and 50 mb (about 16 to 21 km) where the chemical lifetime of ozone is in excess of one year. In this layer the mean tropical ozone content is about 25 DU (Dobson Units, where 1 DU = 2.142 × 10^{-5} kg m^{-2}) compared to an observed QBO in total ozone of about ±5 DU.

2) The seasonally reversing Hadley cell in the lower tropical stratosphere represents an extension of the upper tropospheric Hadley cell that has the same temporal and latitudinal structure as the observed tropospheric cell, and decays upward into the stratosphere with a scale height given by the equatorial Rossby depth, $H$. Here, $H \sim \beta L^2/N$, where $\beta$ is the rate of change of the Coriolis parameter with latitude evaluated at the equator, $L$ is the characteristic meridional width of the Hadley cell, and $N$ is the buoyancy frequency. With $L \sim 2000$ km and $N = 0.02$ s^{-1}, $H$ is about 5 km. The monthly mean data of Oort (1983) indicates that at 200 mb the mean meridional velocity in the equatorial region is $\sim 3$ m s^{-1}. Thus, it seems reasonable to estimate that the average value in the 50–100 mb layer is about 0.2 m s^{-1}.

3) It is assumed that the Hadley circulation flows northward for the months of October through March and southward for the months of April through September. Oort's (1983) data indicates that the tropospheric Hadley circulation switches very quickly between northern and southern winter cells and that there is little evidence for an equinontial circulation with two cells symmetric about the equator.

4) The QBO in equatorial ozone mixing ratio has a small anomaly of opposite sign overlying the lower stratosphere anomaly (Ling and London 1986), which tends to cause a partial cancellation of the equatorial total ozone signal. It is assumed here that because of the decay with height of the upper branch of the Hadley cell, and the shorter chemical time scale in the upper region, that the upper level anomaly will not be advected into the subtropics to any significant extent.

Using these assumptions a one-dimensional model can be developed by starting from the zonally averaged continuity equation for ozone mixing ratio:

$$\frac{\partial X}{\partial t} = -\frac{\partial}{\partial y} (Xv) - \frac{1}{\rho_0} \frac{\partial}{\partial z} (\rho_0 Xw) + G. \quad (1)$$

Here, $X$ is the mass mixing ratio of ozone, $v$ and $w$ are the mean meridional and vertical transport velocities, $\rho_0(z)$ is a basic state density, and $G$ represents the net effects of eddy diffusion and chemical sinks. (Since all variables considered here are zonally averaged we omit the conventional overbars.)

shown by the analysis of BUV satellite data by Hasebe (1983), the oscillation tended to have rapid phase changes near 10°S and 25°N latitude. Analysis of TOMS data for more recent years indicates that this asymmetry does not always favor the Northern Hemisphere (Lait, Schoebel and Newman, unpublished manuscript).

Hamilton (1989) has suggested that this behavior can be accounted for if the equatorial zonal wind QBO modulates the meridional propagation of winter hemisphere planetary waves to provide a QBO in the eddy transport. Indeed there is indirect evidence from previous studies (e.g., Holton and Tan 1982) suggesting that the equatorial QBO may modulate planetary wave activity, and that this may produce QBOs in the winter season temperature and wind distributions at middle and high latitudes. It seems likely that this process may also play a role in the QBO in ozone, especially at high latitudes.

However, it is not necessary that the meridional velocity field itself have an asymmetric QBO component in order to produce an asymmetric QBO in ozone. A time mean or annually varying meridional transport velocity that is asymmetric with respect to the equator can in principle advect the symmetric equatorial ozone anomaly produced by the equatorial QBO, and hence produce the observed asymmetry. In fact, the two-dimensional model of Gray and Pyle (1988) clearly shows the influence of the annual cycle.

In this paper a very simple one-dimensional model is used to demonstrate qualitatively that meridional advection by the lower stratospheric branch of the annually reversing Hadley circulation can account for many of the observed features of the asymmetry of the QBO in ozone at least in the latitude range of ±40°.
We now assume that we can separate the mixing ratio field into a basic state (height dependent) part and a QBO anomaly:

\[ \chi(y, z, t) = \chi_0(z) + \chi_B(y, z, t) \]

where \( \chi_0(z) \) is the mean tropical ozone profile and \( \chi_B \) is the quasi-biennial perturbation.

We next define a layer mean ozone perturbation (kg m\(^{-2}\)) for the 50–100 mb layer:

\[ M(y, t) = \int_{z_B}^{z_T} \rho_0 \chi_B dz = -\int_{p_B}^{p_T} \chi_B g^{-1} dp \tag{2} \]

where subscripts \( b \) and \( t \) refer to the 100 and 50 mb levels, respectively. If (1) is integrated vertically from \( z_b \) to \( z_t \), we obtain

\[ \frac{\partial M}{\partial t} \approx -\frac{\partial}{\partial y} \langle M v \rangle - [\rho_0 \chi_0 w]_z - \gamma M \tag{3} \]

where

\[ \langle v \rangle = M^{-1} \int_{z_b}^{z_T} \rho_0 \chi_B dz \]

is a layer mean meridional velocity. We have also assumed that \( \chi_0(z) \) dominates over \( \chi_B \) in the vertical flux term and that the vertical ozone flux vanishes at \( z_b \) (100 mb). Finally, we assume that the eddy diffusion and chemical loss terms can be parameterized by linear relaxation with rate constant \( \gamma \) (\( \gamma^{-1} = 1 \) year).

Equation (3) can be solved for \( M(y, t) \) provided that \( \langle v \rangle \) and \([\rho_0 \chi_0 w]_z\) are specified. We here assume that the vertical flux at 50 mb is controlled by the vertical velocity associated with the equatorial QBO, which is specified by a modification of Reed's (1964) model as

\[ w(z_t) = w_0 \exp(-\eta^2/2)(1 - \eta^2) \cos \nu t \tag{4} \]

where \( w_0 = 10^{-4} \) m s\(^{-1}\) is the equatorial amplitude of \( w(z_t) \), \( \eta = \phi/\phi_B \) with \( \phi_B = 15^\circ \), and \( \nu \) is the QBO oscillation frequency.

For the annually reversing mean meridional circulation we base the distribution on Oort's tropospheric data, but with the exception that the meridional extent of the cell is extended into the winter hemisphere to reflect the fact that it is really the residual circulation rather than the conventional Eulerian mean that is most relevant for transport. Although these will be similar near the equator where eddy meridional heat fluxes are small, the influence of winter hemisphere eddies will extend the residual circulation into high latitudes in winter (see for example Edmon et al. 1980).

A simple analytic representation that has the desired properties is the following:

\[ \langle v \rangle = \begin{cases} v_0 \exp[-(\phi - \phi_0)^2/\phi_0^2], & \text{for } \phi < \phi_0 \\ v_0 \exp[-(\phi - \phi_0)^2/\phi_0^2], & \text{for } \phi > \phi_0 \end{cases} \tag{5} \]

Here, \( v_0 = 0.2 \) m s\(^{-1}\); for the months of October–March, \( \phi_0 = +5^\circ, \phi_B = 15^\circ \), and \( \phi_N = 40^\circ \); for April–September, \( \phi_0 = -5^\circ, \phi_B = 40^\circ \), and \( \phi_N = 15^\circ \).

Solutions are obtained by finite differencing (3) using second-order centered differencing in time with 1 day time steps, and fourth-order differencing in space with a 2\(^{\circ}\) grid spacing. The domain is taken to be the region between ±40° latitude and it is assumed that the meridional gradient in ozone flux vanishes at the boundaries.

3. Results

As a control experiment we have set \( v_0 = 0 \) so that the ozone perturbation is driven only by the specified QBO vertical velocity. The QBO period is set at 28 months and the model integrated for 10 years. In all figures that follow, the first 2 years of the integration are not shown in order to allow transients to damp out. A time–latitude plot of the total ozone QBO given by this simple model is shown in Fig. 2. A period of 7 years is displayed since that is the period for a 28-month oscillation to synchronize in phase with the annual cy-

![Fig. 2. Time-latitude section for the total ozone anomaly driven by a 28 month period equatorial vertical velocity QBO for a control case in which the meridional transport by the Hadley circulation is neglected. (Contour interval of 2 DU, anomalies greater than +2 DU are stippled, those less than −2 are striped.)](image)
cle. As expected the ozone perturbations are symmetric about the equator and have phase reversals at ±15° latitude.

The situation changes dramatically when the annually reversing meridional velocity is included, as shown in Fig. 3. The amplitude of the equatorial oscillation is reduced and it is displaced into either the Northern or Southern Hemisphere depending on the phase of the equatorial QBO relative to that of the annual cycle. Furthermore, the meridional advection enhances the amplitude of the subtropical oscillation, and causes the phase to lag with increasing latitude. These properties are very similar to those found in the BUV satellite ozone data by Hasebe (1983), although as previously mentioned, his data covered a period when the phasing of the equatorial QBO caused the advection to primarily favor the Northern Hemisphere.

In order to elucidate the role of the annual cycle we have carried out further integrations in which the equatorial QBO is specified to have a period of exactly 24 months and the time when the QBO vertical velocity reaches its maximum amplitude is varied. Figure 4 shows the results for cases in which the vertical velocity maximum occurs at (a) Northern Hemisphere autumn equinox, (b) winter solstice, and (c) spring equinox. Since the ozone QBO maximum lags the vertical velocity maximum by several months, it is not surprising to see that for case (a) the QBO is shifted to the Northern Hemisphere, with phase changes occurring at around 15°S and 30°N. Case (c) is essentially the mirror image of (a) but is shifted 6 months in time so that the equatorial maxima occur in the Southern Hemisphere winter. In case (b) the maximum in the equatorial QBO vertical velocity occurs at winter solstice and there is much less time for the northward meridional velocity to advect the ozone QBO signal before the meridional circulation reverses in the spring. Thus, although there is still a northward displacement, the magnitude of the anomaly and the extent of the equatorial asymmetry are both less than given in cases (a) and (c). When the maximum in the equatorial QBO vertical velocity is specified to occur at Northern Hemisphere summer solstice the results (not shown) are a mirror image of case (b), but shifted by six months.

4. Conclusion

A simple one-dimensional model is used to show that horizontal advection by the mean Hadley circulation can account for much of the observed meridional asymmetry of the QBO in total ozone. Although a number of assumptions are required to formulate the one-dimensional model, the results should provide at least a reasonable qualitative proof that the asymmetry observed in the total ozone QBO does not require that a QBO exist in the transport velocity, but that a QBO in ozone, or any other long-lived tracer, will be advected by the annually reversing Hadley cell and will thus produce a tracer QBO at latitudes beyond those where the equatorial QBO has a direct influence on the species concentrations. Because the amplitude of the subtropical QBO in ozone is greatly amplified by this process there will be a very strong tendency for the QBO in ozone outside the equatorial zone to be in phase with the annual cycle. This is consistent with Hamilton's analysis of the Dobson data from Mauna Loa, Hawai’i (19.5°N), which showed that the peak in the ozone anomalies nearly always occurred in the months of January through March.

In this model no attempt has been made to model differences between the northern and southern hemispheric winter residual circulations. The observed dominance of northward displacement for the QBO in ozone may reflect a greater strength of the northern winter subtropical residual circulation, or a tendency for the equatorial zonal wind QBO transition at 50 mb to occur during northern summer (Dunkerton and Delisi 1985).

Finally, it is interesting to speculate that interannual variability in the seasonally varying Hadley circulation driven by sea surface temperature changes might explain some of the observed interannual variability in extratropical QBO signals.
Fig. 4. Time–latitude sections for the total ozone anomaly driven by a 24 month period equatorial vertical velocity QBO and an annually reversing meridional Hadley transport. Panels (a), (b) and (c) correspond to cases with the maximum QBO vertical velocity occurring at Northern Hemisphere autumn equinox, winter solstice, and spring equinox, respectively. (Plotting convention as in Fig. 2.)
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