A Two-Dimensional Model of the Quasi-biennial Oscillation of Ozone

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ABSTRACT

The stratospheric quasi-biennial oscillation (QBO) in zonal wind, temperature and column ozone has been successfully modeled in a two-dimensional dynamical/chemical model by the introduction of a parameterization scheme to model the transfer of momentum to the zonal flow associated with the damping of vertically propagating Kelvin and Rossby–gravity waves. The largest amplitudes of the observed QBO in column ozone are found in high latitudes and this must be taken into account in any explanation of the increased depletion of ozone in the southern polar spring during the 1980s. A strong QBO signal in column ozone is evident in the model at all latitudes. The largest anomalies of approximately 20 DU are present at high latitudes. The equatorial ozone QBO is out of phase with the mid- and high-latitude ozone QBO. A positive (negative) ozone anomaly at the equator coincides with the presence of equatorial westerlies (easterlies) at 50 mb, in good agreement with observations. The modeled zonal wind at the equator varies from +20 m s⁻¹ to -18 m s⁻¹ at 25 km. The period of the modeled QBO is just over 2 yr throughout the model run except for one event when the period extends to almost 3 yr. This anomalously long period is explained in terms of the strong interaction between the modeled QBO and the seasonal cycle; in particular, the timing of the westerly phase of the QBO is influenced by the presence of the modeled semiannual oscillation (SAO). In view of this model behavior a mechanism is proposed to explain the large variability in the period of the observed QBO.

1. Introduction

The presence of a quasi-biennial oscillation (QBO) in zonal winds and temperature in the equatorial stratosphere is well known (Reed 1960, 1962, 1964, 1966; Veryard and Ebdon 1961; Angell and Korshover 1970; Wallace 1973; Coy 1979; Plumb 1984; Dunkerton and Delisi 1985; Naujokat 1986). A mechanism involving the transfer of momentum to the zonal flow associated with vertically propagating equatorial waves has been proposed to explain the oscillation (Lindzen and Holton 1968; Holton and Lindzen 1972). A QBO in zonal winds and temperature has also been observed in extratropical latitudes (e.g., Tucker and Hopwood 1968; Angell and Korshover 1975; Belmont et al. 1974; Tucker 1979; Trenberth 1980; Holton and Tan 1980, 1982) and a strong QBO signal in column ozone is observed at all latitudes (e.g., Angell and Korshover 1964, 1967, 1973, 1978; Tolson 1981; Hilsenrath and Schlesinger 1981; Oltmans and London 1982; Hasebe 1983, 1984). The relationship between the various signals in temperature, zonal winds, and ozone has been the subject of some debate. The largest amplitudes of the ozone QBO, however, are found in high latitudes and this must be allowed for in any explanation of the increasing depletion of ozone in the southern polar spring during the 1980s (Bojkov 1986; Garcia and Solomon 1987). Modeling studies of the QBO have concentrated on understanding the dynamical processes which give rise to the equatorial QBO. These have mostly employed one-dimensional models at the equator (Plumb 1977; Holton 1979; Hamilton 1981; Dunkerton 1981). Plumb and Bell (1982), using an equatorial beta-plane model, and Dunkerton (1985), using a model extending to ±30 deg lat have extended this work to two dimensions and have successfully simulated many features of the equatorial QBO. In this paper we describe a forcing of the equatorial QBO in zonal winds following the method of Lindzen and Holton (1968) in a model which extends from pole to pole and includes a comprehensive photochemical scheme. We are therefore able to investigate two aspects which have not, to our knowledge, been considered before; namely, the effects of the equatorial QBO on the extratropical dynamics of the model and, secondly, the relationship between the dynamical QBO and the distribution of ozone and other chemical species in a two-dimensional model. In section 2 we briefly summarize the morphology of the observed QBO and out-
line the dynamical theory upon which our parametrization scheme is based. In section 3 a description of the model and details of the parametrization scheme are provided. The modeled QBO in zonal winds and column ozone are described in sections 4 and 5, respectively. We conclude with a summary of the main results and a discussion in section 6.

2. The QBO: characteristics and theory

The QBO is the dominant feature of the equatorial lower stratospheric winds (Wallace 1973; Dunkerton and Delisi 1985; Coy 1979; Naujokat 1986). The oscillations from easterly to westerly winds are irregular; the period varies between 22 and 34 months and has an average of about 28 months. Although the average period is close to 2 yrs the oscillation is not believed to be controlled by the annual cycle. The oscillation has its maximum amplitude of approximately 20 m s\(^{-1}\) in the altitude region 25–30 km. The zonal wind reversals occur at higher levels initially, and gradually descend with time at a rate of approximately 1 km per month. Both easterly and westerly phases of the QBO display this feature, unlike the semiannual oscillation (SAO) in which the easterly phase starts at all heights simultaneously. The QBO in zonal wind also displays an easterly–westerly asymmetry (Wallace 1973) with a stronger westerly acceleration than easterly acceleration at any given height. The amplitude of the zonal wind QBO is largest at the equator and drops off rapidly with latitude with an e-folding width of approximately 15 deg. There is, however, evidence of a QBO in zonal winds at higher latitudes (Tucker and Hopwood 1968; Angell and Korshover 1975; Belmont et al. 1974; Trenberth 1980; Tucker 1979; Holton and Tan 1980, 1982). Holton and Tan found that during the westerly phase of the equatorial QBO the westerly jet near 60°N in the winter months was stronger and there was a smaller amplitude anomaly of the opposite sign at about 30°–40°N.

A QBO signal is also present in various other stratospheric measurements, in particular, those of temperature and column ozone. The amplitude of the temperature oscillation is approximately 2 K and also has its maximum value in the equatorial lower stratosphere, but with a phase reversal at about ±15° lat (Angell and Korshover 1962, 1964, 1967). The observations support the idea that the QBO oscillations are in approximate thermal wind balance (e.g., Plumb 1984; Andrews et al. 1987). A QBO in column ozone has been observed at all latitudes, and is well documented (Angell and Korshover 1964, 1967, 1973, 1978; Tolson 1981; Hilsenrath and Schlesinger 1981; Oltmans and London 1982; Hasebe 1983, 1984). There have also been measurements which suggest a possible QBO in water vapor (Hyson 1983).

The presence of westerly acceleration at the equator during one phase of the QBO implies the existence of an eddy-induced zonal force on the mean flow. The proposed mechanism by which this is thought to take place is the damping of vertically propagating equatorial waves (Lindzen and Holton 1968; Holton and Lindzen 1972). Kelvin waves, which have a westerly phase speed, may give rise to the westerly phase of the QBO while Rossby–gravity waves, which have an easterly phase speed, are proposed to account for the easterly phase. The transfer of momentum to the zonal flow due to the damping of Kelvin waves is precisely the same as that proposed to account for the westerly phase of the semiannual oscillation (SAO) except that the relevant waves are those with smaller phase speeds so that damping occurs lower in the atmosphere. This process by which the Kelvin and Rossby–gravity waves interact with the mean flow provides a plausible explanation for the gradual downward propagation of both the westerly and easterly phases of the QBO. Plumb (1977) conducted a simple numerical experiment to illustrate the mechanism. Successful simulations of the QBO have been carried out in more detailed models with a restricted latitudinal domain using this theory by Plumb and Bell (1982) and Dunkerton (1985). Other possible mechanisms for the momentum transfer have been suggested; for example, the role of equatorially propagating planetary waves in the easterly phase has been investigated by Dunkerton (1983) and contributions to both easterly and westerly phases from gravity waves have been suggested (Hamilton, personal communication). It seems likely that the QBO arises from a combination of the above mechanisms. In this study we have chosen, for simplicity, to confine ourselves to the modeling of momentum transfer associated with Kelvin and Rossby–gravity waves only. A more detailed review of the dynamics of the QBO may be found in Plumb (1984) and Andrews et al. (1987).

3. The Model

The two-dimensional model of Harwood and Pyle (1975, 1977, 1980) is employed in the study. Zonal mean values of temperature, wind components, and chemical constituent mixing ratios are calculated with a resolution of \(\pi/19\) in latitude, 0.5 ln\((p_0/p)\) in the vertical (where \(p\) is pressure and \(p_0\) is the surface value), and a 4 h time step. The model extends from pole to pole and from the ground to approximately 100 km. The model configuration and gas kinetic data are the same as employed by Gray and Pyle (1987a; hereafter referred to as GP). Note that the photochemical scheme contains none of the mechanisms (polar stratospheric clouds, CIO dimer, etc.) which are believed to play a special role in the springtime Antarctic ozone loss. There are two changes in the model compared with GP. Firstly, for the sake of simplicity, the gravity wave breaking parametrization scheme introduced in GP is not included. The simple Rayleigh friction scheme employed by Gray and Pyle (1986) was
used in order to close the jets at mesospheric levels. The region in which the Rayleigh friction acts was considered sufficiently far from the levels of interest in this study not to affect the results. (The presence of the QBO (and SAO) will, in fact, influence the propagation of gravity waves through the modeled equatorial stratosphere and hence influence the nature of the modeled mesosphere and upper stratosphere.) The parametrization of the SAO described by GP has been retained in the majority of the model runs to be described, but with a reduced forcing of the Kelvin wave at the lower boundary (see Table 1). Secondly, the improved radiation scheme described by Haigh (1984) has been employed in most of the model runs. In this scheme, band models of five spectral regions in the infrared are used to cover the 15 μm carbon dioxide band, the 9.6 μm ozone band, and a number of rotation and vibration–rotation bands of water vapor. The calculations are carried out from the tropopause into the mesosphere. The major advantage of this treatment is that an interactive dynamical/radiative balance can now be calculated in the lower stratosphere whereas previously, with fixed, specified heating rates in the lower stratosphere, an important potential feedback could not be included. Moreover, with the Haigh scheme, feedback exists between ozone concentration and heating rates in the infrared as well as in the ultraviolet.

The QBO in zonal winds has been modeled by including the momentum deposition associated with the presence of thermally dissipating Kelvin and Rossby–gravity waves. The formulation follows that of Dunkerton (1979) as employed by GP in the modeling of the SAO. A WKB approximation is used to derive an expression for the wave-induced zonal force per unit mass:

\[
F = A \exp \left( \frac{z - z_0}{H} \right) R(z) \exp(-P(z))
\]

where

\[
R(z) = \frac{\alpha(z)N}{k(\tilde{u} - c)^2}
\]

and

\[
P(z) = \int_{z_0}^{z} R(z') \, dz'.
\]

Here \( A \) is the vertical momentum flux at \( z_0 = 16 \) km, \( \alpha(z) \) the thermal damping rate, \( N \) the Brunt–Väisälä frequency, \( k \) the horizontal wavenumber, \( c \) the phase speed and an overbar denotes a zonal average. The equation is solved with parameter values appropriate to the Kelvin and Rossby–gravity waves shown in Table 1. Note that two Kelvin waves are forced which are identical apart from their phase speeds. The zonal force per unit mass associated with the faster phase speed, \( c = 60 \) m s\(^{-1}\), occurs at higher levels in the modeled atmosphere and gives rise to the westerly phase of the SAO. (The easterly phase of the SAO is produced in the model by a specified periodic easterly zonal force per unit mass—see GP.) It is the slower phase speed Kelvin wave which drives the westerly phase of the QBO.

The values in Table 1 are based on data summarized by Wallace (1973). The damping of the waves has been restricted to thermal damping, as in the SAO parametrization of GP. Above 30 km, the damping rate \( \alpha(z) \) was chosen to be the “slow” damping rate of Dunkerton (1979) which peaks at approximately \( 2 \times 10^{-6} \) s\(^{-1}\) at 50 km; below this level a constant value of \( 0.35 \times 10^{-6} \) s\(^{-1}\) was specified. Note that this thermal damping rate and the zonal mean heating rates, which follow Haigh (1984), are independent. Although no mechanical damping was explicitly employed in the QBO parametrization scheme, the model includes a vertical diffusion operating on the model wind fields with a constant value of \( K_{z2} = 1.0 \) m\(^2\) s\(^{-1}\) at all latitudes and heights.

A Gaussian distribution about the equator was applied to the forcing associated with the two types of waves, with a functional dependence of \( \exp(-y^2/Y_L^2) \) where \( y \) is the distance in the meridional direction and

\[
Y_L = \left( \frac{2\nu}{k\beta} \right)^{1/2}
\]

for the Kelvin waves and

\[
Y_L = \left[ \frac{2\nu/\beta (\frac{c}{\nu} - k)}{k} \right]^{1/2}
\]

for the Rossby–gravity waves where \( \nu/k = c \) (Holton 1972), \( \beta \) is the meridional gradient of the coriolis parameter, \( c \) is the phase speed and \( k \) the horizontal wavenumber. It is important to note that the parametrized forcing associated with the Kelvin and the Rossby–gravity waves specified by Eq. (1) are both present at all times of the modeled year. It is, therefore, changes in \( \tilde{u} \) which influence the changing momentum deposition; the period of the QBO depends on the parameters chosen in Table 1 and is not specifically imposed on the model.
4. The zonal wind QBO

Results are presented here from a model integration (run 1) which included both the SAO and QBO parametrizations. The time–height section of the zonal wind at the equator from model run 1 is shown in Fig. 1. Note that this differs slightly from the zonal wind time-series shown in Gray and Pyle (1987b) as a result of the different radiation scheme employed. Four cycles of the QBO are evident. The semiannual oscillation is dominant above 35 km and the QBO is the dominant signal between 10 and 30 km, in good agreement with observations. Both phases of the QBO exhibit a gradual descent with time (at an average rate of just over 1 km per month); this behavior is also characteristic of the westerly phase of the SAO and illustrates the similarity in mechanisms of the forcing. The period of the modeled QBO is just over 24 months for three of the oscillations but extends to almost 36 months in the oscillation that commences with a westerly phase in yr 7 and 8. This variability in the period of the modeled QBO is discussed more fully below. Note that although the period of the modeled SAO is imposed on the model by the introduction of easterlies at 6 monthly intervals, the period of the QBO is not imposed on the model—it is determined internally and depends entirely upon the parameter values and assumptions described in the previous section. The amplitude of the modeled QBO is a maximum at approximately 25 km where the winds vary between 20 and \(-18 \text{ m s}^{-1}\). In general, the westerly wind maximum is larger than the corresponding easterly maximum at a given level. The westerly phase descends rather more rapidly in the region of 25–30 km than the easterly phase, in good agreement with observations (Wallace 1973), although the asymmetry reverses at lower levels. This asymmetry arises as a result of induced circulations in the model equatorial region: a sinking motion induced below the leading edge of the westerly phase aids the descent of the westerlies while a rising motion associated with the easterly phase impedes the descent (Dunkerton 1983).

The regions of easterly and westerly acceleration associated with the QBO in Fig. 1 at around 25–30 km are significantly correlated with the phase of the SAO. For example, the maximum westerly acceleration of the QBO always occurs as a downward extension of the SAO westerlies. This behavior compares well with observations; for example, the zonal wind time-series measured at Ascension Island (Hirota 1978). Plumb (1977) noted that the parametrization of the thermal damping of Kelvin and Rossby–gravity waves is such that the mean flow acceleration at any level depends only on the parameter values at that level and lower levels. The presence of the SAO is therefore not essential to the simulation of the QBO. However, the SAO has a substantial influence on the character of the modeled QBO at about 30 km via its control of the term \((\bar{u} - c)\) at this level and due to the sinking (rising) motion below the leading edge of the SAO westerlies (easterlies) which will aid the development of the westerly (easterly) phase of the QBO. Figure 2 shows the equatorial zonal wind time-series from a model run identical to run 1 except that it did not include the SAO (run 1A). Although the main characteristics of the QBO in this model run are similar to run 1, the westerly acceleration at 30 km does not always occur.

![Figure 1](image-url)  
**Fig. 1.** Time–height section of the equatorial zonal wind from model run 1 which included both the QBO and SAO parametrizations. Contour interval 10 m s\(^{-1}\); dashed contours are easterlies. Note that for clarity the zero contour has been omitted.
at the same time of year; in run 1 the westerly phase of the QBO always commences during March–April whereas in run 1A, for example, the westerly phase begins in September in yr 4 and June of yr 6. The phase reversal of the QBO from easterlies to westerlies in run 1A, therefore, does not lock onto the seasonal cycle in the same way as in run 1. Note also that there is no anomalously long period oscillation in run 1A. The importance of the SAO in our model runs ties in with the work of Hamilton (1984), who concluded that the structure of the initial westerly mean flow at about 30 mb was difficult to reconcile directly with eddy momentum flux convergence associated with a vertically propagating Kelvin wave, and suggested that mean vertical advection of westerlies from above was important, at least in the initial few months of the westerly acceleration.

There is evidence in Fig. 2 of a QBO signal as high as 50 km, although Hamilton (1981) found no significant QBO in the observed wind data above about 40 km. This suggests that our model may display too strong an overlap between the height regions in which the SAO and QBO are dominant, compared with the real atmosphere. (This feature of the model would probably be improved by the use of a wavelength dependent thermal damping rate following Hamilton 1981 and Fels 1982.)

The tendency of the QBO in run 1 to lock onto the seasonal cycle is particularly well illustrated by the third oscillation in Fig. 1 (yr 7–10), in which the period extends to 3 yr. We suggest the following sequence of events to explain this behavior: the period of the modeled QBO as determined internally by the various parameter values described in section 3 (see Table 1) is just over 2 yr. This period is modulated externally, however, by the 6 month period of the SAO, so that the resulting QBO period is constrained to be a multiple of the SAO period. In most cases this results in a QBO with a 24 month period but occasionally conditions are such that the QBO locks onto a longer period (which is, nevertheless, still a multiple of the SAO period). The suggestion that the period of the SAO may influence the period of the QBO was first made by Lindzen and Holton (1968). We suggest that this influence of the SAO on the period of the modeled QBO may be a clue to understanding the large variation in the period of the QBO in the real atmosphere from 22 to 34 months. While such a large variability may be explained in terms of the year-to-year variability in the amplitude of the wave forcing that gives rise to the QBO, it is perhaps more easily understood in terms of a variability around two preferred periods in the manner outlined above. It is not clear, however, why the model has locked onto a 36 month and not a 30 month period in yr 7–10. It seems more likely that the variability of the period of the QBO in the atmosphere (i.e., from 22 to 34 months) is actually a variability around the two preferred periods of 24 and 30 months.

A forcing of the zonal wind at the equator in the model implies a corresponding temperature adjustment to maintain thermal wind balance. In Fig. 3, the time-series of temperature (Fig. 3i) and zonal wind (Fig. 3ii) anomaly at the equator is shown for one period of the modeled QBO. (The appropriate monthly mean for each calendar month averaged over the whole run has been subtracted from each data point in order to remove the annual cycle.) As expected, the temperature anomaly displays a gradual descent with time in a sim-
ilar manner to that of the zonal winds, with the maximum positive anomaly occurring below the maximum westerlies. A maximum anomaly of 4 K is present at approximately 22 km which is consistent with the maintenance of the thermal wind balance (Plumb 1984; Andrews et al. 1987). These time-series compare well with the temperature/zonal wind relationship obtained by Hitchman and Leovy (1985) in the westerly acceleration phase of the SAO using temperature measurements from the LIMS satellite instrument.

Thermal wind balance is maintained in the model by the development of a meridional circulation with adiabatic heating (cooling) in the cold (warm) region driving upward (downward) motion (Reed 1964; Plumb and Bell 1982). Thus the direction of the induced circulation depends upon the phase of the QBO. During a westerly (easterly) phase, descending (ascending) motion is present at the equator just below the level of maximum vertical wind shear, with rising (sinking) motion at midlatitudes. A much weaker meridional cell of the opposite direction is also induced above the level of maximum vertical wind shear.

The latitudinal extent of this induced meridional circulation in the model is restricted to latitudes less than about 30 deg from the equator, in good agreement with theory (Plumb 1982). Figure 4 shows the vertical velocities associated with this induced circulation for March of yr 5 and 6 of run 1. [Note that this is the instantaneous response solely to the equatorial body force specified in Eq. (1), that is, it is the linear response (see, e.g., Dunkerton 1988), and does not indicate the possible effects of a feedback of the QBO forcing on the ozone and temperature distributions and hence on the heating of the atmosphere and on the eddy transport of temperature.] The influence of such an induced equatorial circulation on the zonal flow at midlatitudes was discussed by Plumb (1982), who investigated the linear response of the atmosphere to a localized equatorial thermal forcing which he proposed to be a model of the diabatic heating of a cold thermal anomaly at the equator associated with the QBO. Thermal wind balance implies easterlies above and westerlies below such a temperature anomaly; however, the induced zonal wind acceleration maximum in the subtropics was of the opposite sign. The meridional structure of the modeled QBO in this present study exhibits a similar feature; Fig. 5 shows the latitude-time distribution of zonal wind from model run 1 at 22 km for a 2 yr period. The monthly mean values averaged over the whole model run have been subtracted from each month so that the annual cycle and shorter periods have been removed. A prominent QBO is visible not only in equatorial regions, as expected, but also at midlatitudes, particularly in the Northern Hemisphere. The zonal velocity is of opposite sign in the midlatitudes compared with the equatorial wind, in agreement with Plumb (1982). The direct forcing of the zonal flow due to the damping of Kelvin and Rossby–gravity waves via Eq. (1) dominates the equatorial region out to approximately 25° lat, but polewards of this, zonal velocities of the opposite sign associated with the induced circulation are evident (to approximately 45° lat). A
corresponding plot of temperature anomaly versus latitude shows similar features, as a result of the maintenance of thermal wind balance in the model. Dunkerton (1985) also found an induced zonal wind of opposite sign poleward of his direct QBO forcing. The amplitude of the midlatitude QBO in Fig. 5 agrees well with the study by Holton and Tan (1980, 1982) of 16 yr of monthly mean geopotential data for the Northern Hemisphere; they found a weak oscillation at 30°-40° which had the opposite phase to the equatorial oscillation.

Holton and Tan also found a second phase reversal at high latitudes in the data. Several possible mechanisms have been suggested to explain the high latitude zonal wind QBO. The location of the zero wind line in the subtropics, which is directly influenced by the phase of the QBO, has been speculated to be important in the development of stratospheric warmings (McIntyre 1982), and is therefore a possible mechanism by which the equatorial QBO may influence the circulation at high latitudes. However, Holton and Tan did not observe a significant QBO signal in Eliassen–Palm fluxes in their study, so that at present there is little direct evidence to support this theory.

Alternatively, the observed QBO is column ozone may be sufficient to produce a thermal anomaly via absorption in the 9.6 μm ozone band (which produces net heating in the polar lower stratosphere) and this would lead to a QBO signal in zonal winds with the correct phase relationship to the column ozone QBO. The high latitude QBO in zonal winds does not appear to be reproduced in Fig. 5. The feature at 60° lat is rather noisy and does not appear to be biennial in nature. A more coherent high latitude signal is present at higher levels in the model and this aspect of the modeled QBO is under further investigation.

5. The QBO in ozone

The QBO is a modulation of the low latitude circulation of the lower stratosphere, a region where the photochemical time constant of ozone becomes long compared with dynamical timescales. It may be expected then that the ozone record would show a quasi-biennial signal. This is indeed the case (Angell and Korshover 1964, 1967, 1973, 1978; Tolson 1981; Hilsenrath and Schlesinger 1981; Oltmans and London 1982; Hasebe 1983, 1984) but, interestingly, the amplitude of the observed ozone QBO is largest in high latitudes. Observations of large ozone reductions in high southern latitudes during spring (Farman et al. 1985) make the understanding of the latitudinal variation of the ozone QBO particularly important. Garcia and Solomon (1987), for example, have speculated that the QBO is relevant to the understanding of the temporal variation of the springtime column ozone in southern polar latitudes during the 1980s. In this section we present results of the modeled ozone QBO and attempt to explain the high latitude behavior.

Before discussing the QBO it is appropriate to review the main features of the ozone budget in the stratosphere. The photochemical time constant of ozone decreases with increasing altitude and generally, at any given height, with decreasing latitude. In Fig. 6 contours indicating the approximate lifetime of odd oxygen in our model (based on the photochemical destruction time) for the month of March are shown as a function of latitude and height. (Below 50 km the concentration
of odd oxygen is dominated by its ozone content.) With a lifetime of hours in the upper equatorial stratosphere the distribution of ozone is expected to be close to its steady state. However, the ozone concentration in the polar lower stratosphere can be far from its equilibrium value since the photochemical time scale is long in that region and dynamics exert a major influence. Between these two regions is a portion of the atmosphere where dynamical and photochemical time scales are roughly comparable. The boundaries of this transition zone are to some extent arbitrary. Typical dynamical time scales for changing trace distributions obviously depend not just on the wind components but also on the gradients of the tracers involved. For ozone, and indeed many tracers, a dynamical time scale of a month or two for meridional transport can be assumed in the stratosphere (Brasseur and Solomon 1984). We have therefore chosen to call the ozone transition zone the region between the 20 and 50 day photochemical time constant (see Fig. 6); this region should be regarded loosely as being under equal dynamic and photochemical influence. It is the morphology of this transition region that defines the ozone budget and distribution.

Figure 7 shows the time-series of ozone anomaly from run 1. (The appropriate monthly mean averaged over the whole model run has been subtracted from each point.) A prominent QBO signal is present at all latitudes. The largest anomaly is in high latitudes, reaching 20 Dobson units (DU) in some cases. A phase reversal is present at approximately 20° lat so that high latitude anomalies are out of phase with the equatorial anomalies. There is some asymmetry between the hemispheres which is discussed more fully below. There is no evidence for in situ photochemical control of the high latitude ozone anomaly. This is not surprising given that the photochemical time constant of ozone is long there. The overall behavior of the modeled ozone QBO compares favorably with the zonally averaged observations of the QBO derived by Hasebe (1983, 1984) using Nimbus-4 BUV data (reproduced in Fig. 8) and by Schoeberl using TOMS data (personal communication). Hasebe noted that the positive ozone anomalies occur at the equator at approximately the same time as the westerly phase of the equatorial zonal wind QBO at 50 mb. The modeled ozone QBO in run 1 also shows this relationship. (The phases of the zonal wind QBO at approximately 50 mb are marked on both Figs. 7 and 8.)

The modeled QBO in ozone arises as a result of the interaction of dynamics and photochemistry in the following sequence of events. The QBO in equatorial zonal winds produces a rising and sinking motion at the equator as described in section 4. This induced circulation may be expected to modulate the strength of both the vertical motion and the horizontal divergence of the Hadley circulation in the lower stratosphere. During a westerly phase the strength of the equatorial ascent in the Hadley cell is reduced and during an easterly phase it is increased. Hence, there exists a mechanism for a QBO in ozone at the equator: during an easterly phase the vertical transport out of the lower stratosphere is increased. This upward motion lowers the total ozone column by reducing the lower stratosphere mixing ratios, since the mixing ratio profile in the lower stratosphere increases with altitude up to about 32 km; conversely, during a westerly phase a reduction in the strength of the ascent in the upward branch of the Hadley cell increases the total ozone column. Thus during a westerly (easterly) phase a positive (negative) ozone anomaly will result. The return arm of the QBO-induced circulation in the subtropics has the opposite vertical direction to that at the equator and so it is expected to produce, by the same mechanism, a column ozone anomaly in subtropical latitudes of the opposite sign to that at the equator. Once an ozone anomaly is present at subtropical latitudes we
shall show that the region of anomalous ozone is then extended to higher latitudes.

In order to elucidate the mechanism which causes the QBO in column ozone at high latitudes in the model, a budget study of the rate of change of ozone number density has been carried out. In the following discussion, we analyze results from the month of March because this month shows the strongest high latitude QBO signal in the Northern Hemisphere. Before the budget study was conducted, a classification of the years of the model run was made according to the phase of the equatorial zonal wind QBO and composites were calculated. Hence, for example, the relevant quantities in March of yr 3, 5 and 10 were averaged to produce March statistics that were typical of a year in which the easterly phase of the zonal wind QBO dominated.

Fig. 5. Latitude–time series of the zonal wind anomaly for one period of the QBO from run 1. (The appropriate monthly mean averaged over the whole of the model run has been subtracted from each data point to obtain the anomaly.) Contour interval 5 m s⁻¹; dashed contours are negative anomalies.
the equatorial lower stratosphere. Similarly, the relevant quantities in March of yr 4, 6 and 11 were averaged to characterize the years in which the westerly phase of the zonal wind QBO dominated the equatorial lower stratosphere. Years 7–9 were omitted from this procedure due to the uncharacteristically long period of that cycle of the QBO. In the following discussion these statistics will be referred to as March (easterly phase) and March (westerly phase), respectively.

Figure 9 shows the rate of change of ozone number density due to mean motions for March (westerly phase) minus the equivalent field from March (easterly phase).
i.e., March of yr 6 in Fig. 4) would give an increase in the upwelling at the equator in the region 20–25 km and a decrease in the upwelling below 20 km. This has resulted (see Fig. 9) in a net increase in the rate of change of ozone number density at the equator due to mean motions below 20 km and a net decrease above 20 km, with the maximum decrease situated at about 28 km. Corresponding distributions of the opposite sign are evident in the subtropics extending to approximately 40° lat, as expected from the theory outlined above.

There is also a contribution to the rate of change of ozone number density due to mean motions poleward of 40° lat in Fig. 9. This contribution is not predicted by linear theory; the extent of the QBO-induced circulation in Fig. 4 extends to approximately 30° lat only and does not show the complicated structure poleward of that latitude which is present in the lower stratosphere in Fig. 9. This feature is discussed in more detail later in this section.

A similar plot showing the contribution to the rate of change of ozone number density due to eddy motions, is shown in Fig. 10. In March (westerly phase), for example, a negative ozone mixing ratio anomaly is present in the lower stratosphere at around 30° lat (as a result of the QBO-induced mean motions) and hence the eddy parametrization in the model, which...
is based on a simple diffusive principle, acts to smooth out the anomaly. (Note that the eddy diffusion acts on mixing ratio and not on number density; mixing ratio is a conserved quantity whereas number density, which depends on temperature and pressure, is not.) Hence, Fig. 10 shows a positive rate of change centered at 30° lat in the lower stratosphere and a negative rate of change both at the equator and in mid- and high latitudes. Note that the rates of change due to the mean motions and to eddy motions are generally of the opposite sign in the lower stratosphere and hence there is some cancellation of these terms.

In Fig. 11 the corresponding plots of the rate of change of ozone number density due to photochemical effects is shown. The major contributions are to be found above about 25 km. The large rates of change at the equator in the region 25–30 km are opposite in sign to, and of approximately the same magnitude as, the rates of change due to the mean motions shown in Fig. 9. Hence there is some cancellation of those terms in that region. Below 20 km, however, there is no such cancellation, because the photochemical lifetime is long there and a parcel of air that is advected by mean motions does not rapidly adjust (photochemically) to its new environment. This is an illustration of the importance of the morphology of the transition region in determining the distribution of ozone in the stratosphere.

Figure 12 shows the corresponding resultant rate of change of the ozone number density in the model, which is the sum of the contributions due to mean motions, eddy motions and photochemical effects. The resultant distribution of the rate of change of ozone number density is the small residual of the summation of several large terms that have opposite signs. A comparison with Fig. 7 indicates that the rates of change shown in Fig. 12 are those required to give rise to the modeled ozone QBO. For example, Fig. 12 shows that in March (westerly phase) the vertically averaged rate of change of ozone number density is negative at the equator; this corresponds to the transition from a positive to a negative anomaly in the column ozone in yr 4, 6 and 11 (see Fig. 7). In the subtropics a positive vertically averaged rate of change in Fig. 12 corresponds with a positive rate of change of column ozone in the subtropics of those years in Fig. 7.

Interestingly, in polar regions Fig. 12 indicates a negative rate of change in the Northern Hemisphere and a positive rate of change in the Southern Hemisphere. This agrees well with a hemispheric asymmetry in the timing of the maximum ozone anomaly at high latitudes in Fig. 7. In yr 4, 6, and 11, the maximum negative anomaly in the Northern Hemisphere does not occur until about March (or slightly later); hence the negative rate of change of ozone number density in that hemisphere. Conversely, in the Southern Hemisphere in those years, the maximum negative anomaly occurs several months before March and hence the rate of change is positive in March. Figures 9–12 illustrate the close interaction of mean and eddy
Fig. 11. As in Fig. 9 but for photochemical effects.

Fig. 12. Latitude–height section of the monthly averaged net rate of change of ozone number density in run 1 for the composite of March from yr 4, 6 and 11 minus the composite of March from yr 3, 5 and 10. The equatorial lower stratosphere in yr 4, 6 and 11 is dominated by westerly winds and in yr 3, 5 and 10 it is dominated by easterly winds.
motions in the model and the extent to which the column ozone distribution is determined by a degree of cancellation between the mean, eddy and photochemical terms. (This fact was illustrated by Harwood and Pyle 1977 who provide a detailed description of the factors that determine the distribution of column ozone in the model at various times of the year.)

The previous discussion has highlighted a hemispheric asymmetry in the timing of the maximum ozone anomaly in high latitudes in run 1 (Fig. 7). The anomaly maxima are displaced by several months and they tend to occur in spring/early summer which coincides with the column ozone maxima. This compares favorably with observations of the Southern Hemisphere ozone anomaly (Fig. 8), although the observed Northern Hemisphere signal is rather more complicated. The asymmetry in the modeled QBO is produced as a result of the relative timing of the change in phase of the equatorial ozone QBO and the direction of the net interhemispheric circulation. The induced QBO circulation, although itself symmetrical, is superimposed on an asymmetrical mean circulation which has rising motion in the summer hemisphere and sinking motion in the winter hemisphere. The phase of the modeled equatorial QBO in total column ozone tends to reverse during April/May of each year and the mean circulation in the stratosphere during the following months is from the Northern to the Southern Hemisphere. The effect of the change in sign of the equatorial column ozone anomaly is immediately observed in the Southern Hemisphere in the form of a change in the phase of the ozone anomaly at mid- and high latitudes, but a similar change is not observed in the Northern Hemisphere until several months later. Notice that the resultant rate of change of ozone number density shown in Fig. 12 displays a hemispheric asymmetry and that the origin of this can be traced to a strong asymmetry in the components due to the mean and eddy motions (Figs. 9 and 10). The corresponding plots from December (not shown) have an even larger hemispheric asymmetry with a similar latitudinal distribution. In June, however, a strong asymmetry of the opposite sense is present so that a larger signal is evident in the Southern Hemisphere subtropics than in the Northern Hemisphere subtropics.

We propose the following mechanism for this hemispheric asymmetry. In December, for example, the circulation induced by the QBO gives rise to an ozone anomaly in the subtropical regions of both hemispheres. However, at this time of the year the interhemispheric circulation is from the Southern to the Northern Hemisphere so that the ozone anomaly in the Southern Hemisphere is then advected upwards by the mean circulation towards the photochemically controlled region of the stratosphere where it loses its identity. In this way, the magnitude of the subtropical anomaly in the Southern Hemisphere is reduced. Similarly, 6 months later, in the months around June, the magnitude of the Northern Hemisphere subtropical anomaly will also be reduced.

In order to simulate the nature of the asymmetry in the distribution of the column ozone anomaly a second model run (run 2) was carried out. In this run, the terms in the model that describe the advection of ozone by the mean motions (i.e., $\bar{V}_3$ and $\bar{w}_3$) were adjusted artificially in the latitudes between 36°N and 36°S such that, commencing in March of yr 1 and 3 they were multiplied by 0.75 (at each time step) and commencing in March of yr 2 and 4 they were multiplied by 1.25. (A reversal in March was chosen in order to simulate run 1 as closely as possible.) This model run did not contain either the QBO or SAO forcing described in section 3. In this way we have simulated a QBO in the advection of ozone by the mean motions in the equatorial and subtropical regions of the model. Although the artificial forcing was applied equally at all latitudes between 36°S and 36°N, a hemispheric asymmetry is present in the transport of ozone in the model at any particular time of the year due to the seasonal changes in the direction of the net interhemispheric circulation.

Figure 13 shows the resulting time-series of column ozone anomaly from run 2. (The appropriate monthly mean averaged over the whole model run has been subtracted from each point.) This figure should be compared with Fig. 7, the equivalent plot from run 1. The main effect of the adjustment in equatorial regions was to increase the upward transport of ozone at the equator in yr 1 and 3, hence creating a negative equatorial column ozone anomaly during those years, and to decrease the strength of the upward transport of ozone in yr 2 and 4, creating a positive column ozone anomaly during those years. A corresponding subtropical anomaly of the opposite sign caused by the QBO-induced circulation is evident in Fig. 13 at approximately 30° lat. These subtropical anomalies were then transferred to higher latitudes in the same manner as in run 1 (a similar budget study of ozone number density was carried out on this run, but is not shown). Figures 7 and 13 share many characteristics. For example, the maximum column ozone anomalies are situated at high latitudes and there is a distinct hemispheric asymmetry between the time of the maximum anomalies in both runs. In the months following the reversal of the adjustment, for example in spring/summer of yr 3, there was a corresponding increase in the strength of the subtropical downwelling in the southern (winter) hemisphere (at approximately 30°S), resulting in a positive column ozone anomaly in the subtropics of the Southern Hemisphere; this was immediately communicated to higher southern latitudes via a combination of mean and eddy transport. Not until a few months later, when the mean circulation changed direction, did the positive ozone anomaly occur in the subtropical Northern Hemisphere (at approximately 30°N) and then similarly spread to high northern lat-
itudes. Hence, there is approximately a 6 month separation between the column ozone maxima in the two hemispheres, which compares well with both Fig. 7 and with observations.

Figure 14, together with the analyses of Figs. 9–12, presents strong evidence that the QBO in ozone in the model arises as a result of (i) a modulation of the mean circulation equatorward of about 30° that creates a subtropical anomaly, and (ii) the poleward transfer of this anomaly by a combination of mean and eddy terms.

The modeled QBO in run 1 in both zonal winds (Fig. 1) and column ozone (Fig. 7) are extremely regular as a result of the constant values of the wave parameters employed in the parametrization; the period is very close to 2 yr (or, in one case, 3 yr) and therefore the pattern of asymmetry in Fig. 7 remains regular. However, a QBO period which is varying with time, as in the atmosphere, will produce a more variable pattern such as that displayed in Fig. 8.

In his analysis of the QBO signal in Nimbus-4 BUV data, Hasebe (1984) noted a northward shift of the equatorial anomaly so that the ‘equatorial’ anomaly sometimes extends to about 45°N (see Fig. 8). He proposed that this feature could be explained in terms of the transport by eddies (particularly those of wave-number 1) that penetrates from midlatitudes across the equator. Figure 7 displays some characteristics of this feature, particularly in yr 5 and 6, which suggests that the feature may, at least in part, be a result of the interaction of the QBO with the annual cycle.

We now return to a discussion of the unexpected contributions to the rate of change of ozone number density due to mean motions poleward of about 40° lat in Fig. 9. The nature of these contributions to the column ozone QBO is variable. At some latitudes the
The term has the same sign as the resultant rate of change and therefore acts to enhance the QBO in column ozone at those latitudes and times of year; at other latitudes it has the opposite sign to the resultant change in column ozone anomaly. Note, for example, that the rate of change due to mean motions in Fig. 9 enhances the column ozone anomaly at 60°–70°N and correlates well with the presence of the maximum QBO signal at 60 deg in the Northern Hemisphere.

Two distinct situations could give rise to the high latitude features in Fig. 9. One is the presence of an anomaly in high latitude ozone that is simply advected by the mean motions (that is, a QBO signal in the $\bar{v} \cdot \bar{O}_3$ component of the terms $\bar{v} \cdot \bar{O}_3$ and $\bar{w} \cdot \bar{O}_3$). We know that this is present, since a QBO is observed in column ozone in the model. The second possibility is a QBO signal in the mean winds (i.e., the $\bar{v}$ and $\bar{w}$ components of the terms $\bar{v} \cdot \bar{O}_3$ and $\bar{w} \cdot \bar{O}_3$). Figure 14 shows the vertical velocities in the model from March (westerly phase) minus March (easterly phase). The largest QBO signal is evident in the upper stratosphere and mesosphere. For example, there is a region of anomalous downwelling in the Northern Hemisphere poleward of 45°N and a region of anomalous upwelling in the Southern Hemisphere poleward of 45°S. This large-scale QBO-induced circulation in the model is due to a QBO signal in the thermal forcing of the atmosphere arising from the high latitude QBO in ozone amount. The mechanism and morphology of this QBO-induced circulation is being investigated further. In the present study, it is the smaller amplitude features in the lower stratosphere to which we wish to draw attention. Note that each feature in the lower stratosphere of Fig. 14 corresponds precisely to a feature in the rate of change of ozone number density due to mean motions shown in Fig. 9. For example, Fig. 14 shows greater upwelling in the region of 15 km during the westerly phase of the equatorial zonal wind QBO in the latitude bands 90°–75°S, 35°–25°S, 25°–40°N, and 55°–65°N; these latitude bands correspond to regions of negative rates of change of ozone number density. The region of anomalous upwelling centered at 60°N and the corresponding region of negative rate of change of ozone number density agrees well with the presence of the maximum QBO anomaly at 60°N in Fig. 7. The correspondence of the vertical velocities in Fig. 14 to the features in the lower stratosphere of Fig. 9 in March (and also at other times of the year, but not shown) strongly suggests that a QBO signal in the mean circulation as well as the advection of a QBO signal in high latitude ozone is an important factor in producing the features in Fig. 9 poleward of 40° lat.

6. Summary

A QBO in zonal wind, temperature and column ozone has been successfully simulated in a two-dimensional model, by the introduction of a parametrization
scheme to model the transfer of momentum to the zonal flow associated with the damping of vertically propagating Kelvin and Rossby–gravity waves. The zonal wind at the equator in the model varies from about 20 to $-18$ m s$^{-1}$ at 25 km. The period of the modeled QBO is about 2 yr except for one oscillation in which the period extends to 3 yr. Both phases of the modeled QBO exhibit a gradual descent with time, with the westerly descent generally more rapid than the easterly descent, in good agreement with observations. The model also includes a parametrization of the SAO, following the scheme described by Gray and Pyle (1987a). The relationship between the SAO and QBO compares well with observations (Hirota 1978); the westerly phase of the QBO has a strong tendency to evolve as a downward extension of the westerly phase of the SAO. The modeled SAO exerts a strong control over the QBO period, via its control of the term $(\bar{u} - c)$ at about 30 km and via the induced downward velocities at the equator below the level of maximum vertical wind shear during the westerly phase of the SAO. Because of this, the modeled QBO exhibits a period which is a multiple of the SAO period. A possible explanation of the large variability in the period of the observed QBO is proposed in terms of a variability about two “preferred” periods of 24 and 30 months.

The modeled zonal wind QBO is primarily confined to within approximately 25° lat of the equator, with a small signal of the opposite phase present at midlatitudes, agreeing well with observations. A second phase reversal at high latitudes is evident and is currently under investigation. A corresponding QBO in temperature is also observed as a result of the maintenance of thermal wind balance in the model.

A strong QBO in column ozone amount is present at all latitudes in the model. The largest anomalies of approximately 20 DU occur at high latitudes. A phase change is evident at approximately 20° lat so that the equatorial QBO is, in general, out of phase with the mid- and high latitude QBO, in good agreement with observations (Hasebe 1983, 1984). Additionally, the modeled QBO reproduces the observed phase relationship between the QBO signals in equatorial zonal wind and column ozone. A mechanism for the modeled QBO in equatorial column ozone is described involving the modulation of the strength of the vertical velocities at the equator in the lower stratosphere and hence a modulation of the transport of ozone across the so-called transition region, which separates those regions in which ozone is in photochemical equilibrium from those in which the distribution of ozone is primarily determined by dynamics. The high latitude ozone anomaly in the model results from a combination of mean and eddy transport of ozone. The general pattern of the modeled QBO in ozone displays a strong interaction with the annual cycle, so that the maximum anomaly at high latitudes in the two hemispheres are displaced by several months, in good agreement with observations. This is essentially due to the relative timing of the change in phase of the equatorial ozone anomaly compared with the direction of the net circulation.

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