# Mechanisms for the Extratropical QBO in Circulation and Ozone

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ABSTRACT

A two-and-a-half-dimensional interactive stratospheric model (i.e., a zonally averaged dynamical-chemical model combined with a truncated spectral dynamical model), whose equatorial zonal wind was relaxed toward the observed Singapore zonal wind, was able to reproduce much of the observed quasi-biennial oscillation (QBO) variability in the column ozone, in its vertical distribution in the low and middle latitudes, and also in the high southern polar latitudes. To reveal the mechanisms responsible for producing the modeled QBO signal over the globe, several control runs were also performed. The authors find that the ozone variability in the lower stratosphere—and hence also in the column—is determined mainly by two dynamical mechanisms. In the low to midlatitudes it is created by a ''direct QBO circulation.'' Unlike the classic picture of a nonseasonal two-cell QBO circulation symmetric about the equator, a more correct picture is a direct QBO circulation that is strongly seasonal, driven by the seasonality in diabatic heating, which is very weak in the summer hemisphere and strong in the winter hemisphere at low and midlatitudes. This anomalous circulation is what is responsible for creating the ozone anomaly at low and midlatitudes. Transport by the climatological circulation and diffusion is found to be ineffective. At high latitudes, there is again a circulation anomaly, but here it is induced by the modulation of the planetary wave potential vorticity flux by the QBO. This so-called Holton–Tan mechanism is responsible for most of the QBO ozone signal poleward of 60°. During spring in the modeled northern polar region, chaotic behavior is another important source of interannual variability, in addition to the interannual variability of planetary wave sources in the troposphere previously studied by the authors.

## 1. Introduction

The equatorial quasi-biennial oscillation (QBO) in zonal winds in the lower stratosphere has been known for a long time (Veryand and Ebdon 1961; Reed et al. 1961; Reed and Rogers 1962; Reed 1965; Wallace 1973; Coy 1979). The phenomenon manefests itself as a descent of easterly wind over westerly wind, followed by westerlies over easterlies, with a variable period of about 30 months. Early theoretical studies focused mostly on the vertical structure of the phenomenon over the equator (Lindzen and Holton 1968; Holton and Lindzen 1972; Ling and London 1986). Since the 1970s, satellite observations of ozone have suggested a QBO phenomenon of global extent (Hasebe 1983; 1984; Lait et al. 1989; Bowman 1989). Recently, Randel and Cobb (1994), Tung and Yang (1994a), and Yang and Tung (1994, 1995) established that the QBO signal in column ozone is strong and statistically significant in the extratropics. Also, it extends to the midlatitudes in both hemispheres during the winter and spring seasons, the midlatitude signal actually being stronger than that in the equatorial region. During these seasons in the Southern Hemisphere, the QBO is strong and coherent all the way to the South Pole (see also Garcia and Solomon 1987). Over the North Pole region, however, the year-to-year variability appears to be dominated by the variability of planetary waves propagating up from the lower atmosphere (Kinnersley and Tung 1998).

Although some two-dimensional models have managed to produce a QBO signal in column ozone outside the Tropics, there has been considerable confusion and debate over how the equatorial QBO signal is ''transmitted'' to the higher latitudes in the real stratosphere. At the heart of the debate there are two questions. 1) How far poleward does the circulation associated with the QBO in equatorial zonal wind extend? (We shall call this meridional circulation the ''direct QBO circulation,'' although it has sometimes been referred to as the ''secondary meridional circulation induced by the equatorial QBO.'') 2) What additional dynamical mechanism is responsible for generating the QBO signal poleward of this direct circulation?

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Using a beta-plane model Plumb and Bell (1982) studied the direct circulation associated with the QBO in zonal winds produced by the easterly and westerly momentum sources of the equatorial waves and found that it is equatorially confined (from 30°N to 30°S). Plumb (1982, 1984) argued that the influence of spherical geometry is unlikely to alter this result. The classic picture of QBO circulation consists of two cells symmetrically straddling the equator, with rising (descending) motion over the equator during an easterly (westerly) phase of the QBO and descending (rising) branches over the subtropics. It appears to be consistent with the observed distribution of column ozone in the Tropics, which shows a negative (positive) anomaly over the equator during the easterly (westerly) QBO phase, with the anomaly changing sign near both 11°–12°N and 11°–12°S (see Randel and Cobb 1994; Yang and Tung 1994). Such a picture, however, does not by itself explain the robust seasonal synchronization of the QBO signal found in observations in the subtropics by Hamilton (1989) and by Gray and Dunkerton (1990).

Recently, Jones et al. (1998) and Kinnersley (1999) considered the seasonality of the QBO direct circulation and found that, similar to the Hadley circulation in the troposphere studied by Lindzen and Hou (1988), the nonlinear circulation during solstice seasons may have a much stronger winter direct cell than the classic, equatorially symmetric two-cell circulation usually assumed for the QBO circulation. The latter appears to be appropriate only during equinoxes. During solstices in a easterly QBO phase, the rising branch of the direct circulation occurs on the summer side of the equator. The summer cell is almost negligible. The winter cell connects this rising branch across the equator to the winter hemisphere. Tracers transported by such a circulation should show the seasonal synchronization and so the finding of Hamilton (1989) and Gray and Dunkerton (1990) mentioned above, regarding the preference for the maximum column ozone anomaly to occur during the winter season in the subtropics, is thus explained. Furthermore, if the winter cell of this direct circulation can extend farther beyond the subtropics it can possibly also explain at least part of the observed QBO signal in ozone over the midlatitudes. Using an idealized model Kinnersley (1999) found that in the absence of damping the direct circulation is confined to within about 30° of the equator. However, when Rayleigh friction with a relaxation time of 20 days (representing planetary wave drag) was applied to the zonal wind the winter cell of the direct circulation extended to the midlatitudes.

Beyond the poleward edge of the direct circulation (which may extend to midlatitudes), another mechanism is needed to explain the QBO signal observed there, especially in the Southern Hemisphere, where the QBO signal extends all the way to the polar region during winter and spring. One possibility is that the Brewer–Dobson circulation can advect the QBO ozone anomaly from the subtropics or midlatitudes to the higher latitudes (Holton 1989). A second is that diffusion due to breaking planetary waves can extend the anomaly poleward (Gray and Pyle 1989). Another mechanism was proposed by Holton and Tan (1982) and later studied in a simple model by Tung and Yang (1994b) and in a more realistic model by Kinnersley and Tung (1998). This mechanism involves the interaction of planetary waves in the extratropical waveguide with the tropical zonal wind, which determines the width of the westerly waveguide. In an easterly phase of the QBO, the easterlies intrude more poleward and therefore the westerly waveguide is narrowed in the extratropics. The planetary waves in such a waveguide tend to be directed more poleward and attain larger amplitudes in the stratosphere over the mid- and high latitudes. The dissipation of these waves induce subsidence, which acts to create a positive anomaly in the column density of ozone. In the simple linear model of Tung and Yang (1994b), where only this mechanism (together with a classic two-cell equatorial circulation) is incorporated, there is a deficiency of QBO signal over the subtropics, but the QBO signal over mid- and high latitudes appears to be consistent with observation. Kinnersley and Tung (1998) incorporated both mechanisms in a more sophisticated nonlinear two-and-a-half-dimensional model and obtained a better simulation over the whole globe, including the subtropics. Much earlier, using a nonlinear Eulerian mean two-dimensional model with fixed diffusion coefficients, Gray and Dunkerton (1990) produced the seasonal synchronization of the subtropical column ozone of the right magnitude. In that model [and those of Gray and Pyle (1989) and Gray and Ruth (1993)] the subtropical anomaly is then transported poleward by the parameterized planetary wave diffusion. However, their diffusion coefficients were calculated using a method that did not take into account the fact that adiabatic reversible wave motions do not produce a net transport of trace gases, and, hence, they may have overestimated the importance of planetary wave mixing in transporting the ozone anomaly poleward. Indeed, the actual effectiveness of such diffusion in transporting the ozone anomaly was questioned by Tung and Yang (1994b) using a transformed Eulerian mean formulation. The results of our model indicate that poleward transport by planetary wave diffusion is not as effective as in the model of Gray and Ruth (1993), although the mechanism by which their model produced the lower-latitude ozone column anomaly was probably the same as that of this model. The main cause of the high-latitude ozone anomaly in our model is via the Holton and Tan modulation of the planetary wave potential vorticity flux, and hence a modulation of the meridional circulation, as studied by Tung and Yang (1994).

It will be shown here that, although planetary wave diffusion of a low-latitude ozone anomaly may contribute to the midlatitude ozone anomaly if there is no other source of a midlatitude ozone anomaly, in fact the midlatitude ozone anomaly is created by other mechanisms—the direct circulation and, to a lesser extent, the Holton–Tan mechanism referred to above—and diffusion by planetary waves actually serves to reduce the midlatitude ozone anomaly by spreading it to lower and higher latitudes.

It should be noted that although the QBO signal appears to represent a large fraction of the interannual variability of ozone over the globe, the large year-to-year variability during winter over the North Pole region appears to be influenced mainly by the variability of planetary waves from propagating below the stratosphere. Such a factor appears to be less important in the Southern Hemisphere. Kinnersley and Tung (1998) produced a realistic simulation of the interannual variability of ozone using the Two-and-a-Half-Dimensional Interactive Isentropic Research model (THIN AIR) of Kinnersley (1996), modified so that its zonal wind over the equator is relaxed to the observed QBO wind. This model includes an interactive calculation of the propagation and dissipation of the three longest planetary waves, which are forced near the tropopause using observed wave heights. They showed that with the exception of the North Pole region, results of a model incorporating the QBO as its *only* interannual variability can be favorably compared with the observed interannual variability. Although Kinnersley and Tung (1998) delineated the relative importance of these contributions to interannual variability, the mechanisms through which the QBO in equatorial zonal wind caused the variability in the extratropical ozone were not analyzed in detail. It is the aim of this paper to discuss these mechanisms by analyzing a similar but slightly longer run. These mechanisms will be listed in section 2, along with a brief discussion of previous studies of some of these mechanisms.

In section 3 the model will be briefly described [since it is the same as in Kinnersley and Tung (1998)]. The treatment of the Total Ozone Mapping Spectrometer (TOMS) and Stratospheric Aerosol and Gas Experiment (SAGE II) data will be outlined in section 4. In section 5, the various versions of the model used to isolate the above mechanisms will be described. The results will be presented in section 6 and the conclusions drawn in section 7.

## 2. Mechanisms

Although ozone in the lower stratosphere is influenced directly by the above dynamical mechanisms, in the upper stratosphere ozone is determined mainly by temperature-dependent photochemical interactions with other trace gases. However, these gases will themselves be influenced by the same dynamical mechanisms described above. Hence, in order to study the ozone anomaly induced by the QBO it is necessary to use a model (such as the one used here) that simulates all the trace gases that interact with ozone, as well as their interaction with the dynamics of the stratosphere.

There are five distinct mechanisms present in the model used here, assumed also to be present in the real stratosphere, which may produce an extratropical QBO signal in ozone. These mechanisms are as follows.

(a) Modulation of extratropical planetary waves (and hence the meridional circulation) by interaction with the equatorial zonal wind QBO. Several types of interaction have been suggested (e.g., reflection or absorbtion at a critical line, restriction of waveguide). Evidence for such a modulation has been obtained from observations (e.g., Holton and Tan 1982; Dunkerton and Baldwin 1991) and it has been shown (Tung and Yang 1994b) that an idealized modulation of planetary wave Eliassen–Palm (EP) flux divergence can produce an extratropical ozone column signal. The importance of this mechanism in the model will be investigated in section 6b.

(b) Poleward advection and/or diffusion of the subtropical ozone anomaly to middle and high latitudes. This mechanism was modeled by Holton (1989) and is the main mechanism by which the model of Gray and Pyle (1989) and Gray and Ruth (1993) produced a high-latitude ozone QBO. The importance of this mechanism in our model will be investigated in sections 6c, 6d, and 6e.

(c) Advection by the direct QBO circulation. In initial studies (e.g., Holton and Lindzen 1972; Plumb and Bell 1982) this was modeled as a seasonally independent circulation, confined to the Tropics. In some subsequent studies this seasonally independent circulation has been either assumed explicitly for performing calculations (e.g., Holton 1989; Tung and Yang 1994b) or assumed conceptually. Recently, however, Kinnersley (1999) and Jones et al. (1998) have shown that an interaction of the equatorial QBO with the seasonal mean circulation may result in a strongly seasonal QBO circulation anomaly extending into subtropical and perhaps middle latitudes in the winter hemisphere. Although this mechanism must have been effective in most previous two-dimensional modeling studies of the QBO (e.g., Gray and Ruth 1993; Kinnersley and Tung 1998) incorporating nonlinear angular momentum advection, its role was not recognized or analyzed. The importance of this mechanism in the model will be investigated in section 6e.

(d) Modulation of the photochemical equilibrium value for ozone above about 25 km due to the anomalous advection of other trace gases, in particular, $NO_2$ (see, e.g., Chipperfield et al. 1994). The importance of this mechanism in the model will be investigated in section 6f.

(e) Chaotic behavior. Even though the planetary waves in this model are forced on the 368 K surface using an annually periodic forcing, their seasonal evolution in the stratosphere may not be the same every year. It is expected that they will be influenced partly by the equatorial zonal wind QBO, but they may also behave chaotically, as shown by Holton and Mass (1976), among others. The importance of this mechanism in the model will be investigated in section 6g.

The importance of these five mechanisms in producing the model's ozone QBO will be investigated by running the model with certain modifications to isolate each mechanism.

## 3. Model

The model used here is the "THIN AIR" (two-and-a-half dimensional interactive isentropic research) model with zonally truncated dynamics and zonally averaged chemical and radiative modules. It is described fully in Kinnersley (1996, 1998) and Kinnersley and Tung (1998).

The two-dimensional model includes interacting modules for chemistry, radiation, and dynamics, and uses a grid of 19 boxes from pole to pole and 29 boxes from the ground to about 100 km. The meridional circulation is calculated by requiring that thermal wind balance be maintained in the presence of diabatic heating (calculated in the radiation module) and zonal body forces (calculated by the planetary wave and gravity wave modules).

The planetary wave module solves the quasigeostrophic system of equations for the three longest zonal wave components [i.e., it integrates the prognostic equations for the wave components of Ertel's potential vorticity (PV) using the geostrophic winds derived by inverting PV at each time step] and includes wave–wave interactions as well as interactions with the modeled zonal-mean state. Its bottom boundary is the 368 K isentropic surface (which lies near 150 mb) and its waves are forced there with the observed daily wave heights expressed in terms of the Montgomery potential. For the control run described in this paper, the model's planetary waves were forced on the 368 K isentropic surface using the observed planetary wave amplitudes from July 1980 to June 1981. This one year's forcing was repeated year after year. The additional damping of planetary waves (with a timescale of 1.5 days) used in the Tropics in some of the experiments of Kinnersley and Tung (1998) is not used in this paper. Omission of this damping results in a slightly smaller (and thus more realistic) midlatitude ozone anomaly and a stronger modulation of the planetary waves by the equatorial QBO (see section 6b) but does not qualitatively affect the conclusions of this paper.

As in Kinnersley and Tung (1998), in the version used here the planetary wave breaking parameterization has been replaced by a constant meridional diffusion of wave potential vorticity that damps two-grid-length-scale anomalies with an *e*-folding time of about 10 days. It was decided to use the simpler scheme here to show that the results do not depend strongly on the kind of wave-breaking parameterization used. Note that this diffusion does not act on the trace gases but represents in a very crude way the breaking of planetary waves and allows the planetary waves to produce an irreversible flux of Ertel's PV and hence a body force on the zonal wind (see, e.g., Tung 1986). This body force then induces a meridional circulation that transports the model's trace gases.

The direct effect of breaking planetary waves on the trace gases is parameterized as a meridional diffusion of the gases with a coefficient $K_{yy}$. This diffusion coefficient is determined using the simple flux-gradient method used by Yang et al. (1990) among others, which depends on the ratio of Ertel's PV flux to the meridional gradient of the zonal-mean PV.

A simple gravity wave parameterization helps to produce realistic upper-stratospheric and mesospheric winds and also determines the vertical diffusion of trace gases in the stratosphere using Lindzen's (1981) technique. Near the tropopause a value of 1 $m^2 s^{-1}$ is used to represent cross-tropopause diffusion. This diffusion affects mainly the climatological mean ozone column [reducing it on average by about 20 Dobson units (DU)] but has a very small effect on the size or phase of the modeled ozone anomaly.

The only interannually varying forcing applied to the model is the specification of its equatorial zonal winds for the period from December 1977 to April 1993 between 10 and 70 mb. The zonal winds in the model equatorward of 9°N and 9°S were relaxed toward the observed Singapore wind over this time period, with time constants of 1 day and 10 days at the equator and 9°, respectively, similar to Gray and Ruth (1993). The forcing at 9° is thus weaker than that used in Kinnersley and Tung (1998), and this leads to a slightly weaker (and more realistic) QBO signal in ozone column at low latitudes. Again, this is only a small difference and does not affect the main conclusions of this paper.

In some of the other runs described here, the planetary wave model was not used interactively. The wave PV flux calculated by the planetary wave model during the control run was saved and used in these runs. This was done in order to remove the wave–mean flow interaction so that the effect of other interactions could be isolated.

## 4. Data

The version 7 TOMS dataset was used for values of the ozone column from November 1978 to April 1993. The data were detrended using a least squares fit to determine the trend. In addition the solar cycle component was removed by linear regression against the 10.7-cm solar flux smoothed with a 12-month running mean. Removal of the trend and the solar component allowed a better comparison with the model data to be made since the model used here does not simulate either the trend or the solar cycle.

SAGE II data were also used but these data span the shorter period from November 1984 to June 1991 (pre-Pinatubo). The data do, however, allow a comparison with the vertical profile of the modeled ozone anomaly. The SAGE data were not interpolated across regions where no data were available, and the values below 17 km were not used since they were too noisy. Sunrise and sunset values were averaged where both were available at the same latitude; otherwise the value used here was taken from whichever one was available. Since the SAGE data were provided on a 1-km vertical spacing, while the model's vertical-level spacing was about 3.5 km, the three SAGE levels closest to each model level were averaged together before a correlation with the model data was calculated. As with the TOMS data, the SAGE data were also detrended and the solar cycle removed before analysis and comparison with the model.

After both sets of data were detrended and the solar cycle removed, the anomaly for each month was calculated. We defined the anomaly in a certain quantity (e.g., ozone) for a certain month to mean the departure of that month's quantity from the time-averaged value for that month.

## 5. Model runs

A series of runs were made with the model in order to isolate the various mechanisms that were producing the model's ozone anomaly. The control run was a 14-yr run from December 1977 to April 1993 and was started from the end of a previous model run that had no interannually variable forcing and which had reached an annually periodic state (within the limits of its chaotic behavior, which will be discussed in section 6g). The control run is the same as the run described in Kinnersley and Tung (1998) except that it covers a slightly longer time interval and does not have the tropical damping of planetary waves (which allows the slightly chaotic behavior present in this run; see section 6g). The model's zonal wind between 10 and 70 mb was relaxed to the observed Singapore zonal wind as described above. The model's planetary waves were forced at the 368 K surface using the observed wave heights from July 1980 to June 1981 and were allowed to interact in the stratosphere with the zonal wind there. The eddy PV flux (which is the sole wave-drag term and the isentropic equivalent of the EP flux divergence) produced by the planetary waves over the entire model domain was averaged in 2-day blocks and saved to be used by further runs.

We would like to estimate the fraction of the control run's total ozone anomaly, which can be attributed to each of the mechanisms described in section 2, in order to understand their relative importance at various latitudes and seasons. Therefore, in order to isolate the effect of these mechanisms, a series of model runs was performed in which only a limited number (preferably one, but sometimes more than one) of these mechanisms were present. These model runs will be described in the following.

(I) In the above-described control run, the model's planetary waves (and hence their PV flux) were modulated by an interaction with the equatorial zonal wind, which in turn induced a modulation of the circulation and, hence, of the ozone [as investigated in a simple model by Tung and Yang (1994b)]. In order to isolate the effect of this interannually varying PV flux the model was run with no forcing of the equatorial QBO in zonal wind but with the 14 years of PV flux from the control run being read in from storage and used in the model. The interannual variability in this run (run I) is therefore due solely to that of the extratropical planetary wave forcing calculated by the control run.

Since the variability in this specified PV flux arose solely from the interaction (in the control run) of planetary waves with the equatorial QBO (since the planetary waves on the 368 K surface are annually periodic) this run is a test of the importance of mechanism a referred to in section 2: the impact of planetary were variability, due to the Holton and Tan (1982) mechanism, on the mean circulation and the ozone column.

There is, however, a problem with specifying the PV flux throughout the whole model domain if the intention is to isolate the influence that the modulation of planetary wave PV flux had in the control run on the meridional circulation (and hence the ozone). The problem is that the meridional circulation induced by a zonal body force $F$ (in our case, the PV flux) depends strongly on the meridional gradient of angular momentum, $\tau_y$. (This is clear in the steady-state case and where vertical advection can be neglected, so that the meridional velocity is given by $V = F/\tau_y$.) The angular momentum gradient is smallest close to the equator, which is where it is, in addition, strongly modulated by the equatorial QBO. The effect that a modulation of $F$ will have on the mean circulation will therefore be most dependent on $\tau_y$ near the equator. If we wish to estimate the effect that the modulation of the PV flux alone had on the circulation in the control run we would therefore have to ensure that $\tau_y$ was the same as in the control run. Away from the equator, the anomaly in the PV flux is the main cause of the anomaly in $\tau_y$, so this should result in an accurate estimate of the effect of the PV flux on $V$. However, near the equator, $\tau_y$ is determined mainly by the relaxation of the modeled winds toward the Singapore winds, so that in order to reproduce the $\tau_y$ of the control run we would need to force the equatorial winds as in the control run. However, specifying the equatorial QBO would affect the mean circulation itself, and the result would be effectively the same as the control run, which is not the desired result.

It would be preferable, for the purposes of estimating the amount of interannual variability due to a certain process, to have only that source of interannual variability present in the model, such as in run I. However, because of the problem described above the simplest and most accurate way to evaluate the effect of the planetary wave interannual variability is to compare the control run to a run identical to the control run but with annually periodic planetary wave PV flux (which is described below as run IIIb). The difference between these two runs will therefore be due to the interannual variability of the PV flux, prescribed in the control run but not in run IIIb.

We will describe the results of both estimates of the effect of the planetary wave PV flux anomaly in section 6b.

(II) Previous models of the circulation induced directly by forcing of the equatorial zonal wind QBO were of a two-celled seasonally symmetric circulation extending about 20° into both hemispheres. It was suggested that the low-latitude ozone anomaly produced by such a circulation could be advected (Holton 1989) by the climatological (Brewer–Dobson) mean circulation or transported by climatological (non-QBO related) breaking planetary waves (e.g., Gray and Ruth 1993) to higher latitudes during winter, thus giving rise to an extra-tropical seasonal ozone column anomaly. Although our model circulation over the equator is not symmetric (see section 6e) it is nevertheless interesting to see, using our model, whether climatological advection and/or planetary wave transport (parameterized as $K_{yy}$) of a model produced tropical ozone anomaly could give rise to the midlatitude ozone anomaly.

Therefore the model was run twice, once (run IIa) with $K_{yy}$ (the horizontal diffusion of trace gases) set to zero and a second time (run IIb) with the annually periodic $K_{yy}$ saved from the fourth year of the control run. In both runs there was no forcing of the equatorial wind toward the Singapore wind. Also, the planetary wave PV flux was not calculated interactively but was annually periodic and specified from the fourth year of the control run. The only source of interannual variability in both runs was through the specification of all the trace gases within 27° of the equator using the data from the 14 years of the control run. The specification of gases was carried out in isobaric coordinates and not in isentropic coordinates so that the column amounts of ozone and the other gases would not be affected by the height of the isentropic surfaces. This specification of the tropical ozone anomaly is supposed to represent the ozone anomaly that would be produced by a narrow QBO circulation such as described by Plumb and Bell (1982) (although there is already a seasonality in the ozone anomaly we prescribe, which is not present in the Plumb and Bell model).

Run IIa therefore demonstrates the poleward advection of the tropical ozone anomaly by the mean circulation (Holton 1989). This will be shown to be small and, hence, run IIb demonstrates mainly the poleward diffusion of the tropical ozone anomaly.

(III) To see how strongly the direct QBO circulation in the low and middle latitudes affects the ozone column, the model was run with an annually periodic PV flux and with $K_{yy}$ set to zero, as in run IIa. Hence the Holton–Tan mechanism is inoperative in this run. The model's zonal wind was, however, forced toward the Singapore wind equatorward of 9° as in the control run. The year-to-year variability in the modeled ozone column is therefore due mainly to mechanism c (since poleward advection of the anomaly is small, as will be shown in section 6b). This is run IIIa. In order to demonstrate the effect that diffusion by $K_{yy}$ has on the ozone anomaly produced by this direct circulation, a further run was performed, run IIIb, in which $K_{yy}$ was not set to zero but was annually periodic and specified from the values calculated in the third year of the control run.

As mentioned in (I), run IIIb will also be used to estimate the effect of interannual variability in the planetary wave PV flux, since it is identical to the control run except that it has no interannual variability in its planetary wave PV flux.

(IV) Since ozone is photochemically controlled in the middle and upper stratosphere, run IV was performed to show the effect of QBO-induced changes in the other trace gases on the ozone distribution (mechanism d). In this run there was no forcing of an equatorial QBO in zonal wind, the PV flux was annually periodic as before, but all the trace gases except ozone were specified from the control run.

(V) To see whether the interaction of the planetary waves with the zonal mean state is chaotic or whether it is determined mainly by the equatorial QBO, the model was run again (run V) with everything the same as the control run, but with the equatorial QBO specified starting with December 1976 (rather than December 1977 as in the control run). This run is therefore one year longer than the control run. If the planetary waves (and everything else in the model) are determined mainly by the equatorial QBO, then month $n$ from the control run should be very similar to month $n + 12$ from run V. If this is not the case it is possible that the model is chaotic or that it has a significant memory of previous years (e.g., Scott and Haynes 1998, manuscript submitted to *Quart. J. Roy. Meteor. Soc.*).

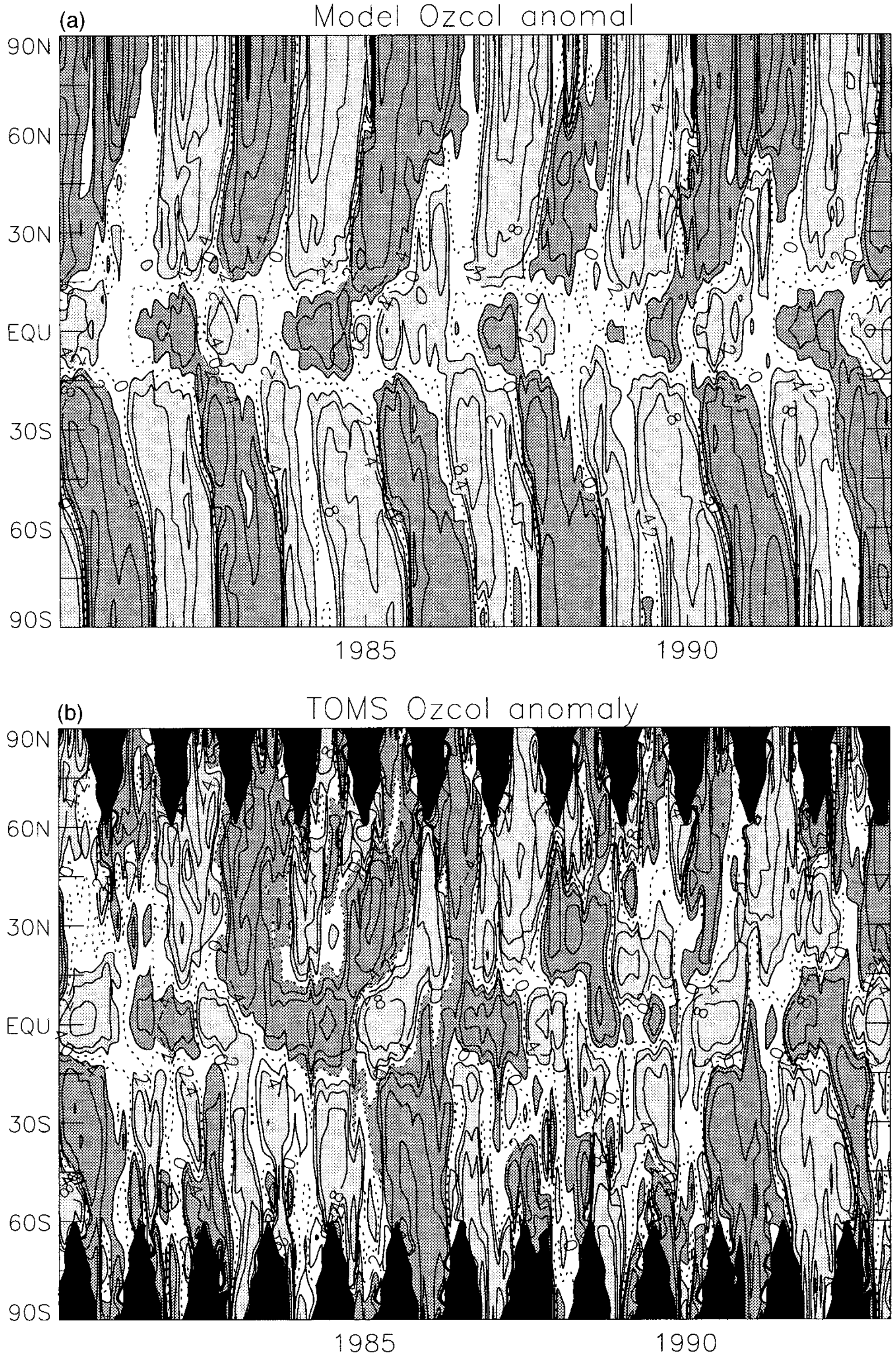


FIG. 1. (a) Modeled ozone anomaly and (b) TOMS ozone anomaly with the trend and solar cycle removed, from Nov 1978 to Apr 1993; contours at 0, ±2, ±4, ±6, ±8, ±10, ±15, ±20, and ±30 DU. (b) Black area is where no observations could be made.

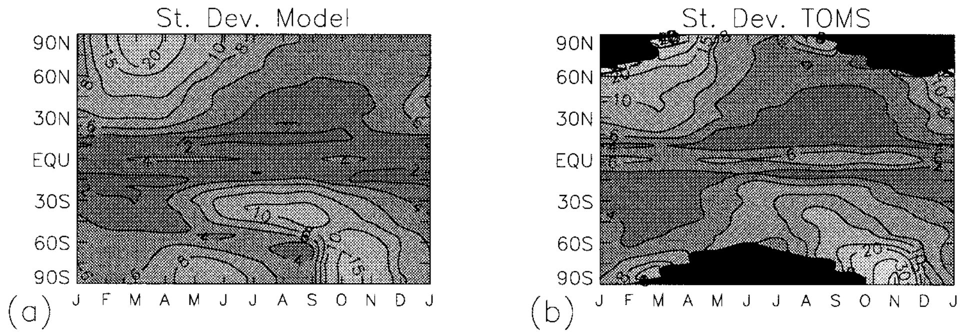


FIG. 2. Standard deviations of monthly mean ozone column anomaly from (a) model data and (b) TOMS data (with trend and solar cycle removed), using data from Nov 1978 to Apr 1993. Contours at 2, 4, 6, 8, 10, 15, 20, 30, and 40 DU. (b) Black area is where no observations could be made.

## 6. Results of model runs

### *a. Control run*

A direct comparison between the modeled and observed ozone anomalies is shown in Figs. 1a and 1b. Shown are the ''raw'' anomalies in the model and in the TOMS data without further filtering or analysis to extract a ''QBO signal.'' As defined previously, an anomaly in the data (or model result) at a particular month is the deviation from the climatological mean for that month in the time series in the data (or in the model result). Thus the observed anomaly shown in Fig. 1b presumably contains all forms of interannual variability, with the exception of the solar cycle and a linear trend, which have been removed. In general, the model results appear very realistic as compared to the TOMS data (a more quantitative comparison will be made shortly). This is remarkable especially in light of the fact that in the model the lower-boundary planetary wave forcing is annually periodic and there are no other forms of interannual variability other than the QBO in the zonal winds in the equatorial region. By and large, the pattern as well as the amplitude of the anomaly are well simulated, although there appears to be some underestimate of the equatorial QBO amplitude in the ozone column (by about 2–3 DU) and the polar values, as will be discussed in a moment. The model successfully reproduced the observed node at 12°N and 12°S, with the extratropical ozone anomalies 180° out of phase with the equatorial anomalies. The amplitude of the anomaly on the poleward side of this node is about 8 DU, as in the TOMS data. The subtropical deficiency of the modeled ozone anomaly in Tung and Yang (1994b) is no longer present in this model. The improvement can be attributed to the nonlinear QBO direct circulation, which also produces a more robust seasonal sychronization. Poleward of 50° one can see a gradual increase in amplitude toward the poles, due possibly to the Holton–Tan mechanism, reaching amplitudes greater than 15 DU. TOMS data show a similar increase but reach a higher amplitude in the Northern Hemisphere polar region, possibly due to other forms of planetary wave variability not included in this model.

There is a slight hint of poleward propagation or advection of ozone in the model from 12° to the midlatitudes, which is not apparent in the TOMS data.

Figure 2 provides a quantitative comparision of the amplitudes (but not the phase) of the anomaly, as measured by the standard deviation in the model ozone column (Fig. 2a) and TOMS (Fig. 2b). The seasonal and latitudinal variations of the modeled and observed anomalies are remarkably similar. As mentioned above, the discrepancies in amplitudes are confined to very low and very high latitudes. At high northern latitudes in March the model underpredicts the very high variability (of over 30 DU) observed poleward of 80°. This, however, is to be expected, since the Northern Hemisphere high-latitude variability was shown by Kinnersley and Tung (1998) to be simulated well only after including the observed variability in the lower-boundary planetary wave forcing, which is held constant in these experiments.

The modeled ozone column anomaly is well correlated in phase and pattern with that derived from the TOMS data (see Fig. 3) equatorward of about 50°N and 50°S during winter and spring, when amplitudes of the anomalies are significant. Correlation coefficients less than 0.5 are not shown. The low correlations generally occur where the amplitudes of the anomalies are low, with the notable exception of the northern polar regions in winter and spring. Here a low correlation in the presence of large amplitudes indicates that the fluctuations are not related in a statistically significant manner. In the Southern Hemisphere's polar region there is also a fairly good correlation between the modeled and observed ozone columns in November when the observed variability is large, although the amplitude of the modeled anomaly near the Antarctic ozone hole is smaller than observed, as remarked upon and discussed in Kinnersley and Tung (1998). This may be due to the fact that the observed increase in stratospheric chlorine is

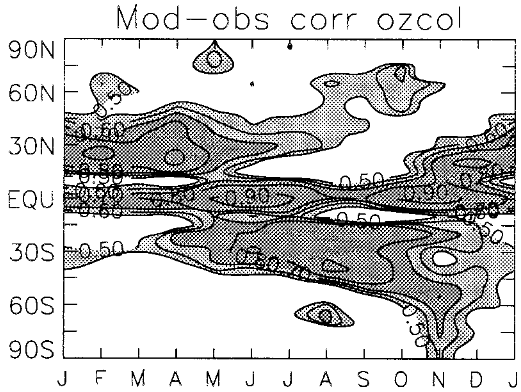


FIG. 3. Correlation of monthly mean modeled ozone column with the TOMS data (with trend and solar cycle removed) over the period from Nov 1978 to Apr 1993. Contours start at 0.5, with values over 0.7 shaded more heavily.

not included in these model runs, nor is any other source of chemically forced interannual variability.

The shape of the modeled density-weighted ozone anomalies on height–latitude plots is shown in Fig. 4 for the midseason months. There is a large equatorial anomaly near 24 km that is slightly stronger in January and July than in the equinox months. The strong seasonality of the extratropical anomaly in the solstice months is apparent, with a large anomaly in the winter lower stratosphere between about 15° and 50°. By spring, the winter anomaly has been apparently transferred to higher latitudes (though it will be shown that this high-latitude anomaly is due mainly to the Holton–Tan mechanism and not to advection or diffusion from lower latitudes), while the autumn anomaly is growing at low latitudes. A weaker anomaly near 30 km is also apparent (concurrent with the lower-stratospheric anomaly), both over the equator and at low to middle latitudes.

Comparison with the anomalies derived from the SAGE data (Fig. 5) shows general agreement both in the size and the seasonality of the lower-stratospheric equatorial and extratropical anomalies. Interestingly, the equatorial SAGE anomaly near 24 km is slightly stronger in January and July, as in the model. However, near 30 km both the equatorial and low-latitude winter/spring anomalies are much stronger in the SAGE data. The correlation between modeled and observed anomalies over the six years when the SAGE data was available (Fig. 6) shows large values coinciding approximately with the equatorial and winter/spring anomalies in the lower stratosphere. There are also large values coinciding with the 30-km anomalies, so it appears that even if the simulated anomaly is too small at that altitude, it is at least approximately in the correct position with the correct phase.

The cause of the lower-stratospheric ozone anomaly from 30° to 60° in the winter hemisphere was conjectured by Randel and Wu (1996) to be due to an anomaly

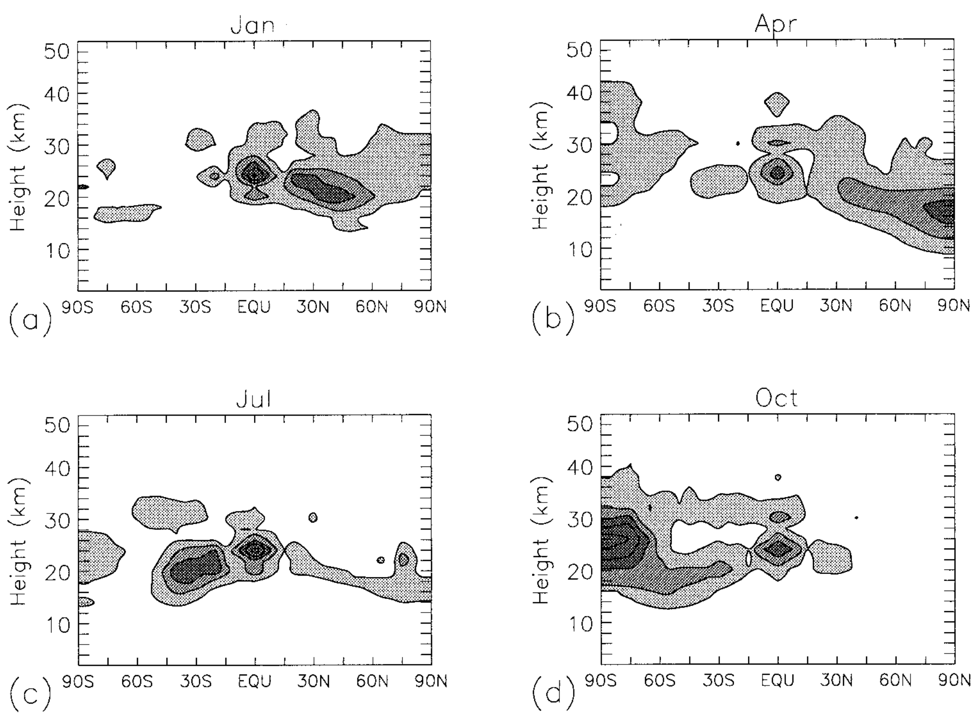


FIG. 4. Density-weighted modeled ozone anomalies {in ppmv multiplied by exp[(20 - $z$)/7]} for (a) Jan, (b) Apr, (c) Jul, and (d) Oct. Data from the simulated months from Nov 1984 to June 1991, for comparison with the SAGE II data. Contours in intervals of 0.05; values above 0.05 are shaded.

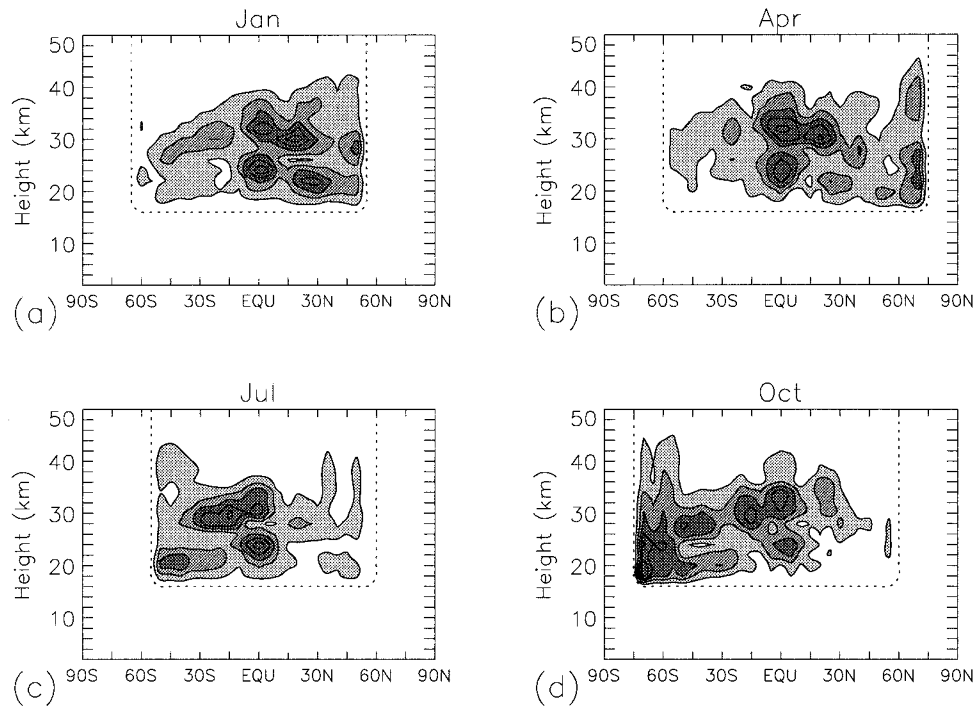


FIG. 5. As in Fig. 4 but using SAGE II data. The dotted contour defines the limits of observation.

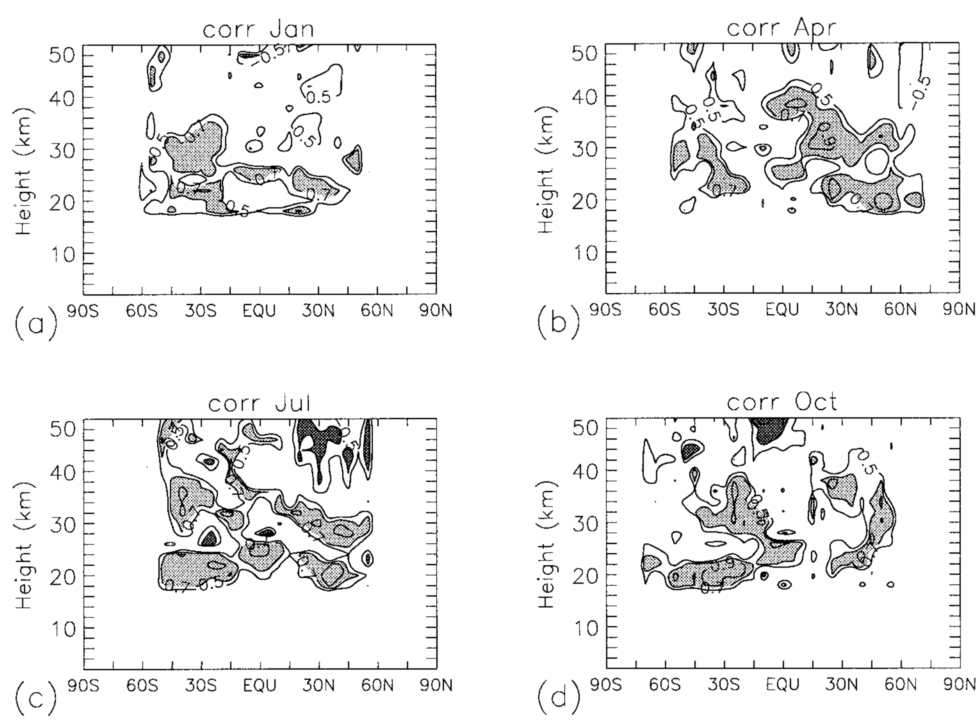


FIG. 6. Correlation of SAGE II ozone anomalies with modeled ozone anomalies for (a) Jan, (b) Apr, (c) Jul, and (d) Oct. Contours at ±0.5, ±0.7, and ±0.9, with values above 0.7 shaded lightly and values below −0.7 shaded darkly. Correlations of 0.7 and 0.9 correspond approximately to the 95% and 99% significance levels.

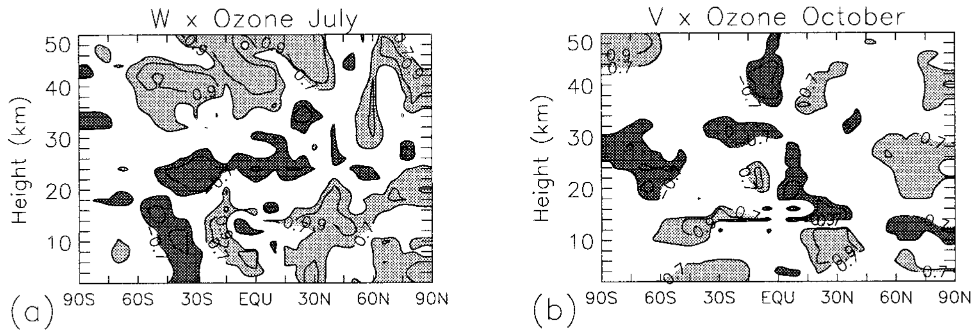


FIG. 7. Correlation between modeled ozone and modeled (a) vertical and (b) horizontal velocity for Jul (for the six Julys used in the calculations shown in Fig. 6). Contours at ±0.7 and ±0.9, with values above 0.7 shaded lightly and values below −0.7 shaded darkly.

in the vertical velocity, because of its collocation with a region of large vertical gradient and small horizontal gradient in the ozone mixing ratio. This process seems to be important also in the model. The correlation between the modeled vertical velocity and the modeled ozone over the six years of the SAGE data period is strong and negative near 22 km between 20° and 50°S in July (Fig. 7a), implying a connection between ascent and a lower ozone column.

As noted by Randel and Wu (1996), the upper-stratospheric anomaly near 30° in the winter hemisphere is unlikely to be due to vertical motion since it occurs in a region of almost vertical ozone isopleths. Consistent with this, it seems that horizontal motion is at least partly responsible for this anomaly in the model, with a fairly strong negative correlation between the modeled ozone anomaly and the horizontal velocity near 30 km in October (Fig. 7b) consistent with poleward motion leading to an increased ozone column.

Figure 8 shows the amplitude of the modeled vertical velocity anomaly and its relationship to the 15-mb Singapore wind for a solstice and equinox month. Note that the anomaly in the vertical velocity is much smaller in the summer hemisphere than in the winter one (Fig. 8a).

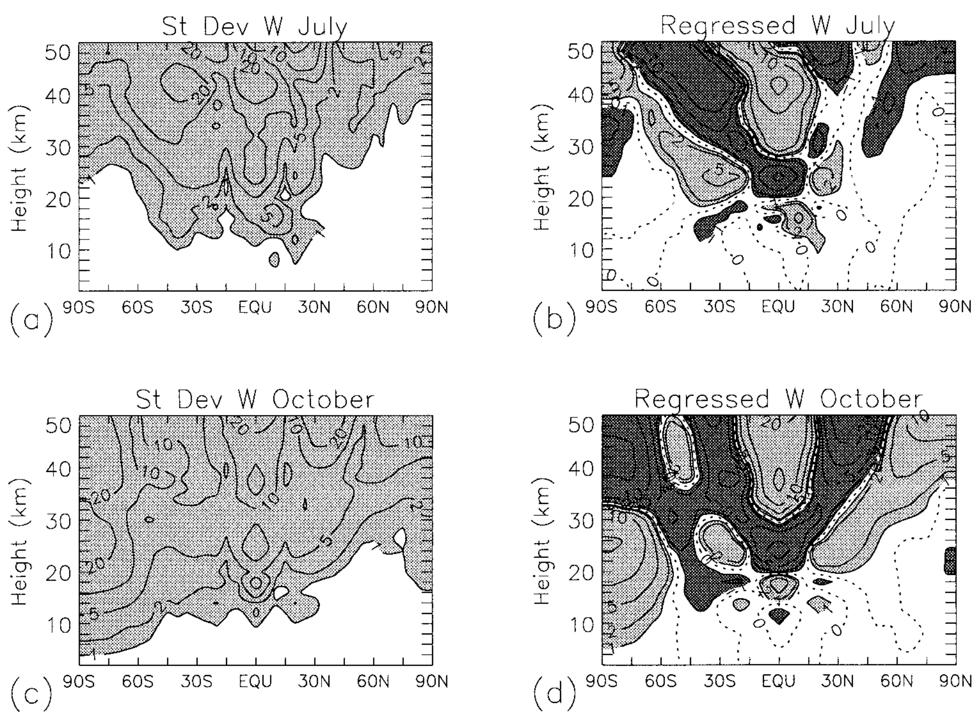


FIG. 8. (a) Standard deviation of modeled Jul-mean vertical velocity about its time-mean (contours at 1, 2, 5, 10, and 20 m day$^{-1}$, light shading for values greater than 1 m day$^{-1}$) and (b) standard deviation of modeled Jul-mean vertical velocity multiplied by its correlation with 15-mb Singapore wind. Contours and light shading as for (a); dark shading for values less than −1 m day$^{-1}$. (c), (d) As in (a) and (b) but for Oct. The time period used is the full 14 years of the model run.

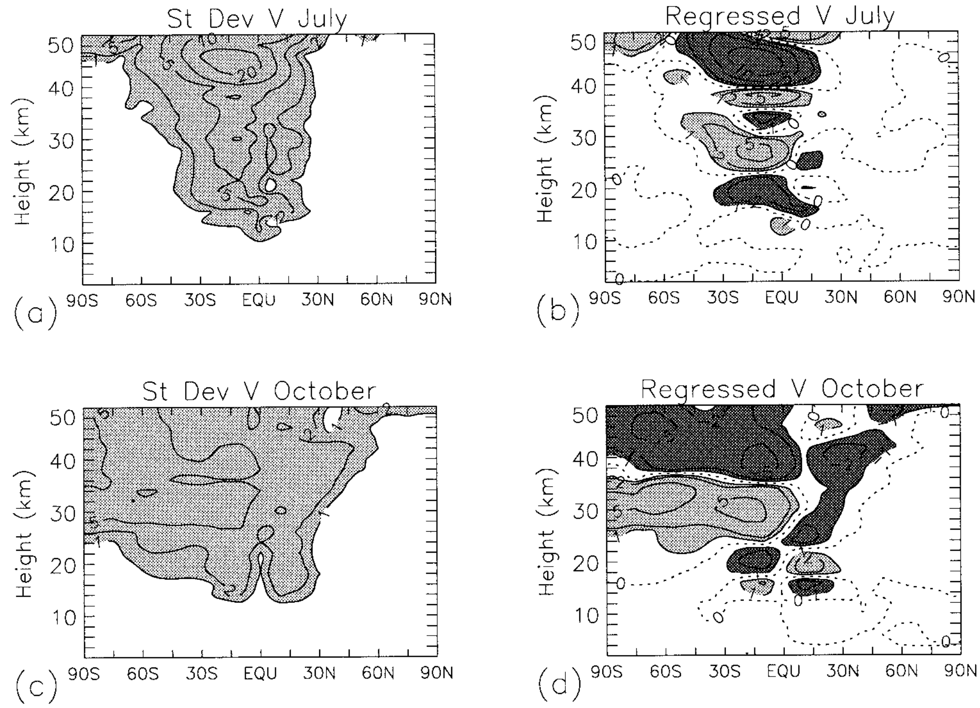


FIG. 9. As in Fig. 8 but for modeled horizontal velocity (contours at 1, 2, 5, 10, and 20 km $day^{-1}$).

Thus it seems that the small value of the ozone column anomaly in the summer hemisphere is not due to upward advection of it by the mean circulation, as proposed by Gray and Ruth (1993), but in fact because there is no anomalous circulation large enough to create a summer anomaly in the first place. This seasonal asymmetry in the QBO-induced circulation anomaly was further investigated in Kinnersley (1998). In order to gain some idea of how the anomaly in the vertical velocities is related to the equatorial QBO, and also of its spatial autocorrelation, we calculated its correlation with the 15-mb Singapore wind. (Although the 30-mb Singapore wind is generally used for correlations with the ozone column, because we were analyzing height–latitude data we used the 15-mb Singapore wind, which resulted in larger correlation coefficients.) What is shown in Fig. 8b is the standard deviation of the vertical velocity (Fig. 8a) multiplied by its correlation with the 15-mb Singapore wind. It can be viewed as the part of the anomaly that can be ''explained'' by the 15-mb Singapore wind, while its sign determines whether it is in phase or out of phase with the 15-mb wind. This is explained in more detail in the appendix. Near 24 km, a two-celled structure is evident, with a strong winter cell and a much weaker summer cell, while above 30 km there is a similar seasonally biased structure with the opposite phase to that at 24 km. This is similar to the circulation anomaly investigated by Jones et al. (1998) and Kinnersley (1999).

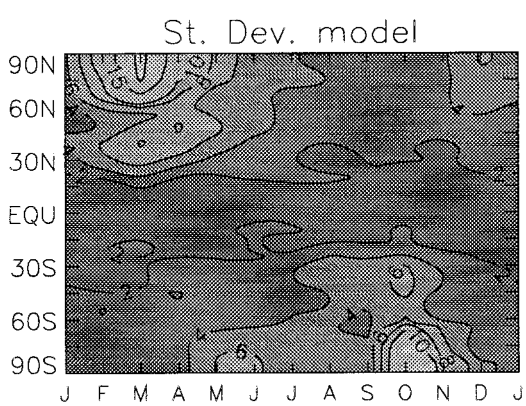


FIG. 10. As in Fig. 2a but for run Ia (planetary wave PV flux modulation only).

In contrast to July, the vertical velocity anomaly in October (Figs. 8c and 8d) is large at southern high latitudes and yet is more symmetric about the equator at low latitudes (equatorward of about 40°). Figure 8d shows that a large part of the southern high-latitude anomaly is related to the 15-mb Singapore wind and it will be shown in section 6b that it is due mainly to the QBO-modulated variability in planetary wave fluxes.

The anomaly in the horizontal velocity (Fig. 9a) is also very dependent on season, with a large winter anomaly that extends across the equator (Fig. 9b) and a very small summer anomaly. Figure 9b also shows the clear phase change above and below about 24 km. The low-latitude spring and autumn anomalies (Fig. 9c) are about equal in size, but both smaller than the winter

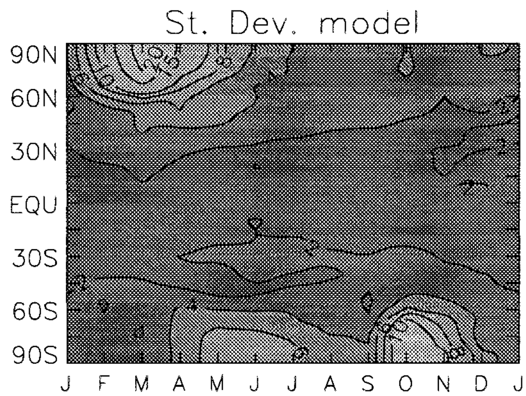


FIG. 11. As in Fig. 2a but for the difference between the control run and run IIIb (showing the true effect of the modulation of the planetary wave PV flux).

one (below about 25 km). Above about 25 km there is a large anomaly in the Southern Hemisphere in October (consistent with the anomaly in vertical velocity), which is also strongly related to the 15-mb Singapore wind (Fig. 9d).

*b. Effect of QBO-modulated planetary waves (run I)*

The standard deviation of the ozone anomaly produced by run I is shown in Fig. 10 for comparison with the control run (Fig. 2a). Without an equatorial QBO in this run, the ozone anomaly in the equatorial region is very small. There is a large variability at high latitudes, which is almost the same as that of the control run, but also a significant variability at middle latitudes and the subtropics.

However, as discussed in section 5, the specification of an annually varying PV flux in the near-equatorial region without the accompanying modulation of the angular momentum gradient present in the control run may lead to a false estimate of the role of the PV flux anomaly at low latitudes. It was explained in section 5 why the difference between the control run and run IIIb (the same as the control run but with an annually periodic planetary wave PV flux) should give a more accurate estimate of the importance of the PV flux anomaly. The difference between these two runs was therefore taken and the rest of this section uses this difference to calculate the anomalies in ozone, PV flux, and meridional velocity due to the interannual variability of PV flux. The ozone anomaly thus calculated is shown in Fig. 11. The low-and middle-latitude standard deviation is much smaller than in Fig. 10, whereas the high-latitude value is about the same.

The total anomaly corresponding to Fig. 11 is shown in Fig. 12. In certain years it is very clear that the middle and high-latitude anomalies have the opposite sign to each other. This is understandable, since an anomaly in the circulation produced by an anomalous body force at middle latitudes will induce a global circulation

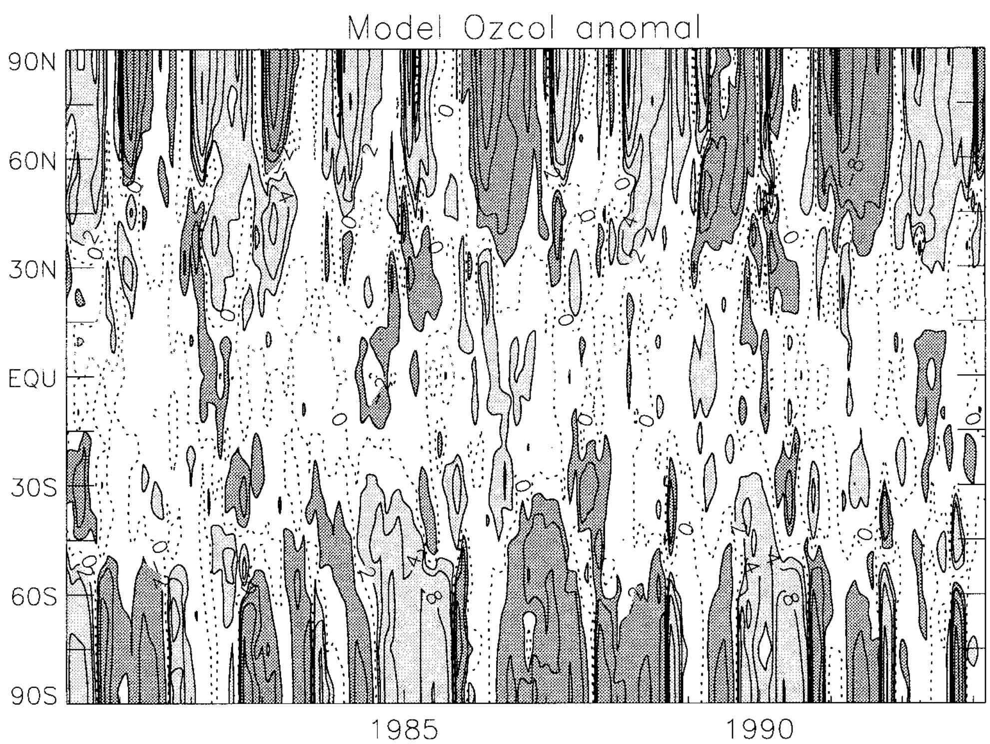


FIG. 12. As in Fig. 1a but for the difference between the control run and run IIIb (showing the true effect of the modulation of the planetary wave PV flux).

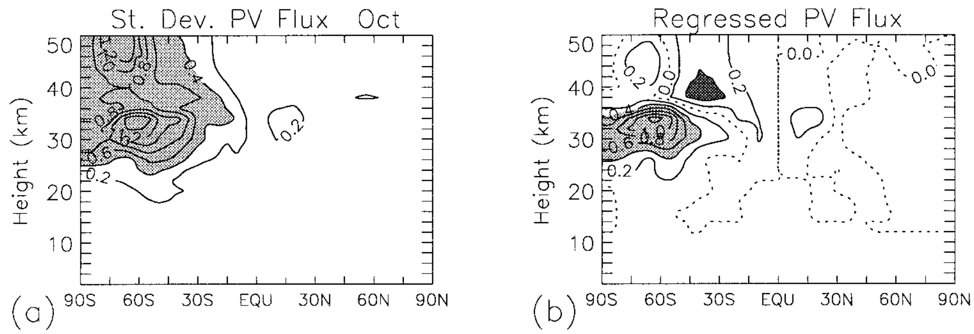


FIG. 13. As in Fig. 8 but for modeled (control run minus run IIIb) Oct-mean planetary wave flux of Ertel's potential vorticity (units are m $s^{-1}$ $day^{-1}$). This is the PV flux anomaly that led to the ozone anomaly of Figs. 11 and 12.

anomaly whose vertical velocity changes from upwelling to subsidence near 40° of latitude [see Fig. 1 of Tung and Yang (1994b)]. This then leads to low- and high-latitude ozone anomalies that are out of phase with each other. What is also apparent is the lack of any distinct poleward propagation of the ozone anomaly, as this mechanism creates the ozone anomaly in situ through an induced circulation anomaly, as discussed in Tung and Yang (1994b).

In this two-and-half-dimensional model the PV flux is produced self consistently by the dissipation of planetary waves also calculated by the model. This is unlike the case of Tung and Yang (1994b), where it is prescribed to be consistent with the observed EP flux divergence of Dunkerton and Baldwin (1991). Note that the amplitude of the PV flux calculated here by the model is about the same order of magnitude as in Dunkerton and Baldwin (1991), although perhaps slightly smaller, but this is quite uncertain because of the poor data quality for the EP flux divergence.

In the Southern Hemisphere, the PV flux anomaly in October (Fig. 13a) is well correlated with the 15-mb Singapore wind (Fig. 13b) south of about 45°S. It will be shown in section 6g that this is a robust correlation, while the planetary wave variability in the Northern Hemisphere in March is not determined by the equatorial QBO but is in fact chaotic. The horizontal velocity anomaly induced by this PV flux anomaly (Fig. 14) in the high-latitude Southern Hemisphere is similar in both magnitude and phase to that of the control run (Figs. 9c and 9d). Note, however, that the regressed velocity anomaly (Fig. 14b) extends closer to the equator than the PV flux anomaly (Fig. 13b) due to the well-known nonlocal nature of the circulation induced by a forcing of the zonal wind.

### *c. Poleward advection of tropical anomaly (run IIa)*

As discussed in section 5, runs IIa and IIb demonstrate how effective advection and diffusion would be in transporting to higher latitudes an ozone anomaly produced at low latitudes by a narrow QBO circulation such as described by Plumb and Bell (1982). If, in reality, the direct QBO circulation is narrow, then these experiments demonstrate how much of the middle latitude ozone anomaly we could expect as a result of transport from low latitudes. [As will be shown soon, the ozone anomaly produced by the direct QBO circulation in the model is large even at middle latitudes and closely resembles the observations, suggesting that the direct QBO circulation in the real atmosphere is more likely to be the wider and seasonally dependent circulation described by Jones et al. (1998) and Kinnersley (1999) than the narrow one of Plumb and Bell (1982).]

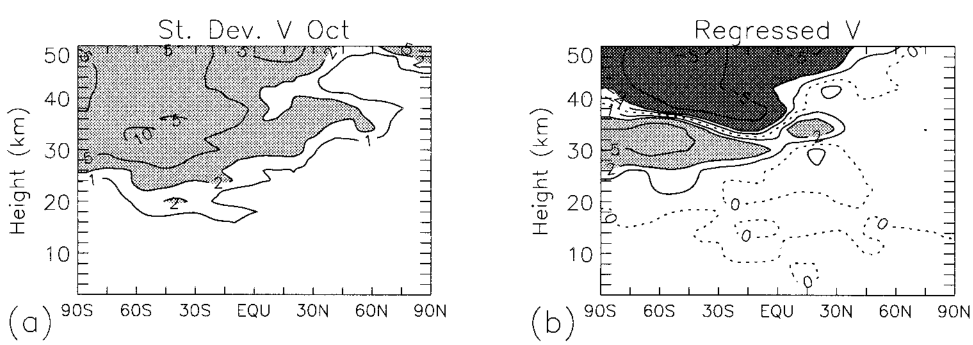


FIG. 14. As in Fig. 8 but for the modeled Oct-mean anomaly in horizontal velocity corresponding to the PV flux anomaly shown in Fig. 13. (Contours at 1, 2, 5, and 10 km $day^{-1}$.)

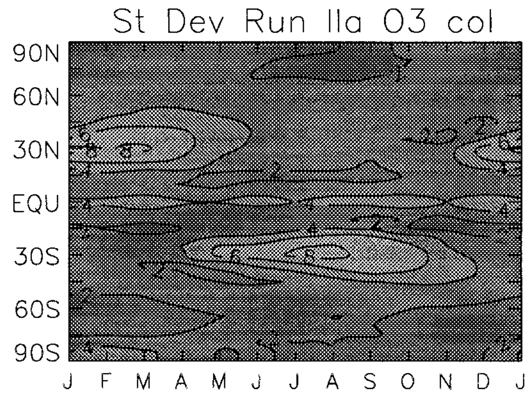


FIG. 15. As in Fig. 2a but for run IIa (advection of tropical ozone anomaly).

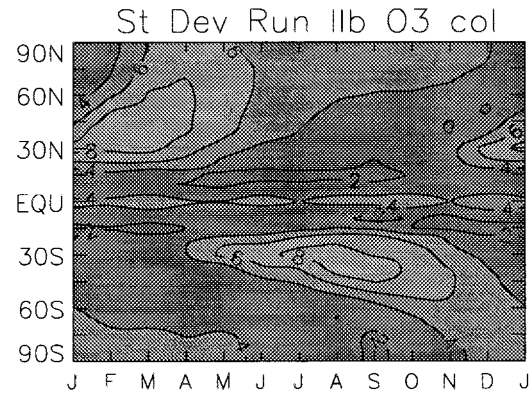


FIG. 16. As in Fig. 2a but for run IIb (advection and diffusion of tropical ozone anomaly).

In this run, the ozone anomaly is specified equatorward of 27° and allowed to be advected poleward by the mean winter circulation. It is seen that the anomaly is only weakly transported to higher latitudes (Fig. 15). This appears to be in conflict with the work of Holton (1989), but his model was very simple and ignored such factors as transport into the troposphere by cross-tropopause diffusion or by mean downwelling, as well as the sharp decline with height in the strength of the poleward circulation near the tropopause.

*d. Poleward diffusion of tropical anomaly (run IIb)*

When diffusion by $K_{yy}$ is added to the previous run, so that now the tropical ozone anomaly is both advected and diffused poleward, we see a large increase in the size of the anomaly poleward of about 40° (cf. Figs. 16 and 15). One may be led by this result to conclude that a significant part of the middle-latitude ozone anomaly may be due to the poleward diffusion of a subtropical anomaly created by the equatorial QBO. However, in both the observed data and in the control run the midlatitude anomaly is actually higher than the subtropical values. Such a higher anomaly cannot be the result of diffusion. Some other mechanism, such as advection by the direct QBO circulation, is needed to produce the midlatitude anomaly. The net effect of diffusion in such a situation is to reduce the midlatitude ozone anomaly while increasing the high-latitude anomaly (see the following section).

*e. Effect of direct QBO circulation (run III)*

Run IIIa, which has no parameterized diffusion of trace gases and no modulation of planetary waves, is able to produce a strongly seasonal ozone column anomaly (Fig. 17), with large values of about 8–10 DU between about 30° and 60° in both hemispheres during winter and spring. The seasonality is due to a seasonality in the circulation induced by the QBO.

Figure 18 shows the vertical velocity anomaly at 20 km and in the part explained by the 15-mb Singapore wind (see appendix), from which it is clear that there is a large low- and middle-latitude circulation anomaly in the winter and spring of both hemispheres and that it is very well correlated with the equatorial QBO. Moreover, the pattern of the vertical velocity anomaly is very similar to that of the ozone column anomaly (Fig. 17). This is not to say that the ozone anomaly is produced entirely by an anomaly in the vertical velocity (since the horizontal velocity must also play a part) but rather that the ozone anomaly appears to be induced in situ by a circulation anomaly. This seasonality is in conflict with the traditional picture of a seasonally independent QBO circulation. Recent work (Kinnersley 1999; Jones et al. 1998) has suggested that the nonlinear advection of the QBO zonal wind anomaly into the winter hemisphere by the mean circulation can result in a strong seasonality of the QBO-induced circulation, with a strengthened and expanded winter cell. Kinnersley (1999) demonstrated that advection of the equatorial zonal wind QBO anomaly into the winter hemisphere would give rise to a large temperature anomaly (due to the strong latitude dependency in the thermal wind equation). This seasonal temperature anomaly will then give

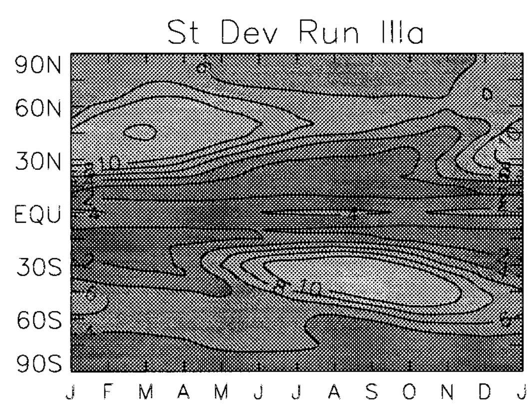


FIG. 17. As in Fig. 2a but for run IIIa (direct QBO-induced circulation with zero $K_{yy}$).

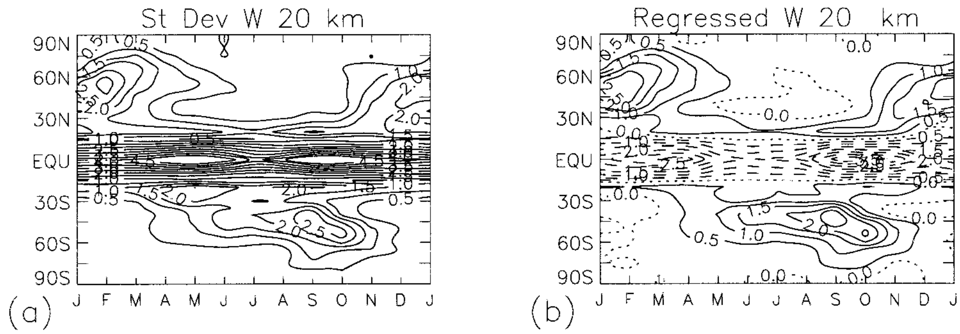


FIG. 18. (a) Vertical velocity anomaly and (b) its regression with the 15-mb Singapore wind, both at 20 km for run IIIa.

rise to a seasonal circulation anomaly in the presence of Newtonian cooling to an equilibrium temperature. Such a seasonality exists in this model and results in the seasonality of the ozone column at low and middle latitudes. This ozone anomaly is then spread over low, middle, and high latitudes, mainly by the parameterized planetary wave $K_{yy}$ in the model (see section 6d).

The mechanism by which this seasonality arises in the model has strong similarities to that described in Kinnersley (1999), since there is a strong seasonality in the temperature anomaly (Fig. 19a) that is strongly related to the 15-mb Singapore wind (Fig. 19b). The zonal wind anomaly (Fig. 20) is also similar to that of Kinnersley (1999), extending farther into the winter hemisphere than the summer, due to advection by the Brewer–Dobson circulation. The zonal wind anomaly is small in the subtropics and hence would be difficult to detect in observations of zonal wind (even when assimilated into a general circulation model). However, the temperature anomaly is large enough to be observable (and should also be more reliable than zonal wind since it is the primary quantity observed by satellite-borne instruments), and comparison with Fig. 20 of Randel et al. (1999) shows remarkable agreement in both the size and positioning of the temperature anomalies. Note that the model used in Kinnersley (1999) was very idealized and was used merely to demonstrate a mechanism, while the model used here has a detailed radiation scheme and a gravity wave parameterization, among other things, and so a lack of complete agreement with the details of Kinnersley (1999) is not surprising.

The vertical and horizontal velocity anomalies (Figs. 21 and 22) are similar to those of the control run at low and middle latitudes, confirming that this is the main mechanism for a low- and middle-latitude circulation anomaly in the model, and that planetary wave variability is important only at higher latitudes (as discussed in section 6b).

In order to show the combined effect of the direct circulation and diffusion by the planetary waves (parameterized as $K_{yy}$), another run was performed (run IIIb) that was identical to run III except that an annually periodic $K_{yy}$ (taken from the third year of the control run) was used to diffuse the trace gases. The ozone anomaly and its standard deviation produced by this run are shown in Figs. 23 and 24. It is seen that the anomaly is very similar to that of the control run at low and middle latitudes but differs at high latitudes since the PV flux in this run is annually periodic. Some poleward transport of the ozone anomaly can be seen, but the maximum amplitude still occurs at middle and not high latitudes. Diffusion has therefore spread poleward the ozone anomaly produced by the direct circulation anomaly, but it cannot account for the majority of the high-latitude anomaly produced by the control run. Note that including diffusion here has resulted in a lower mid-

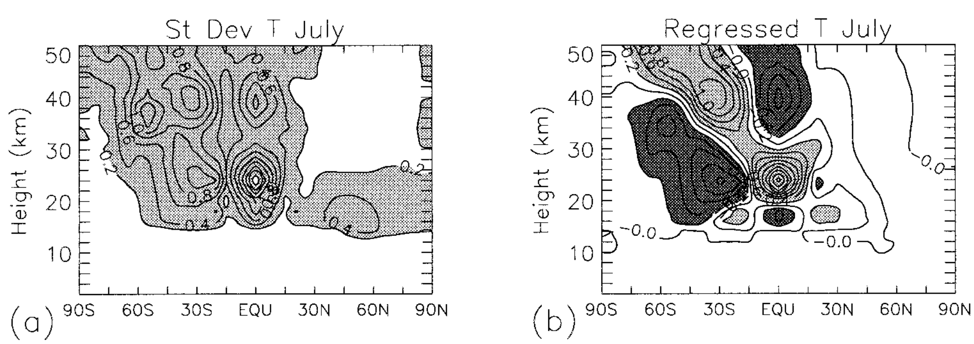


FIG. 19. As in Fig. 8 but for modeled Jul-mean temperature from run IIIa. Contours every 0.2 K; light shading for values greater than 0.2 K; dark shading for values less than −0.2 K.

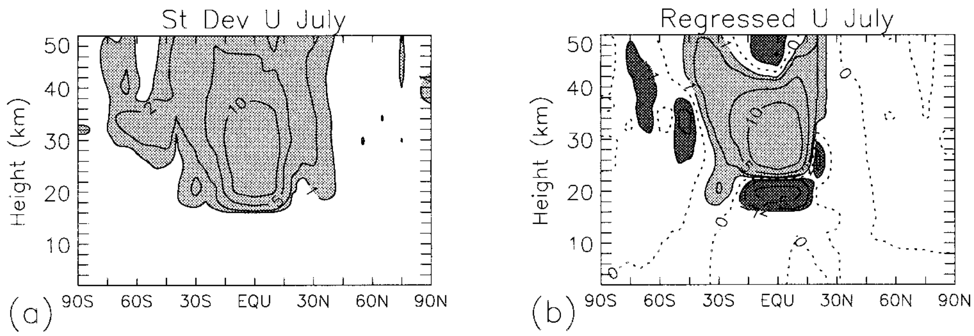


FIG. 20. As in Fig. 8 but for modeled Jul-mean zonal wind from run IIIa. Contours at 1, 2, 5, and 10 m s$^{-1}$; light shading for values greater than 1 m s$^{-1}$; dark shading for values less than $-1$ m s$^{-1}$.

latitude ozone anomaly, in contrast to run IIb where diffusion increased the middle-latitude anomaly.

*f. Effect of other gases on ozone*

The model was next run with all the gases except ozone specified from the control run, with periodic PV flux and no forcing of the zonal wind QBO. This indicates where the ozone anomaly is photochemically controlled. The remaining influence in the upper stratosphere is temperature, so any difference between the ozone anomaly of this run and that of the control run can be attributed to the lack of a dynamically generated temperature anomaly in the middle and upper stratosphere. In order to quantify the importance of photochemical control we have calculated the ratio of the standard deviation of the ozone anomaly of this run to that of the control run, and also the correlation between the two anomalies. Figure 25 shows these two quantities for the months of July and October. The strong correlation and large ratio in the Northern Hemisphere summer, and also in the low latitudes of both hemispheres, between about 30 and 40 km imply that the impact of the other gases on ozone is strong there, as would be expected due to the strong solar radiance. In winter the ratio is small (implying that other processes are more important in producing the ozone anomaly in the control run) and the correlation is poor. In October in the Northern Hemisphere the other gases produce a large ozone anomaly between 20 and 30 km (Fig. 25d), but this

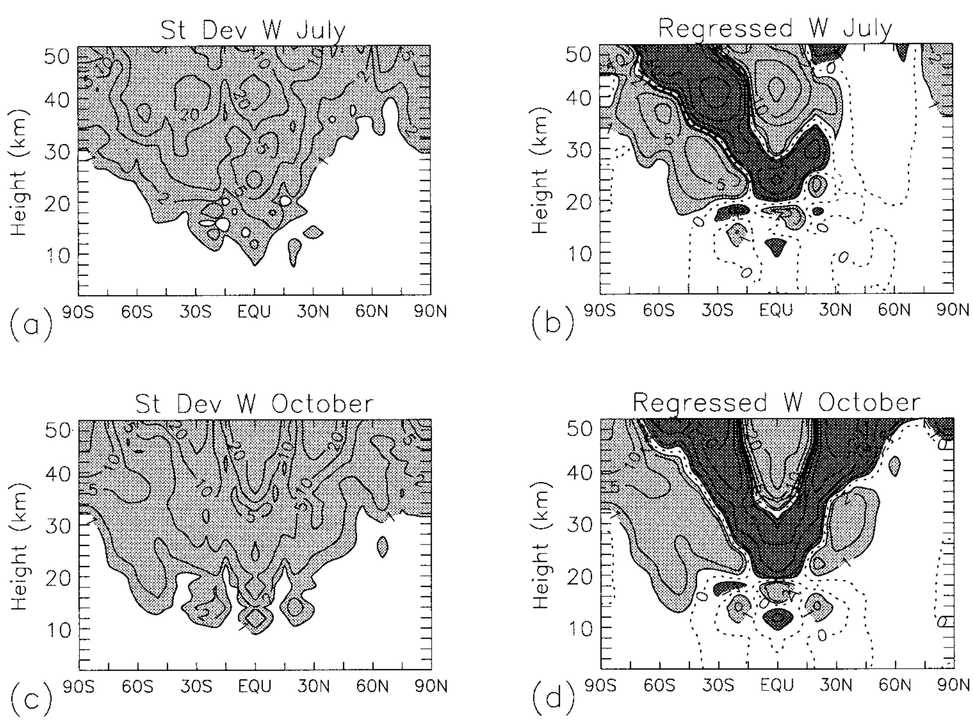


FIG. 21. As in Fig. 8 but for vertical velocity anomaly from run IIIa (direct QBO circulation anomaly with zero $K_{yy}$).

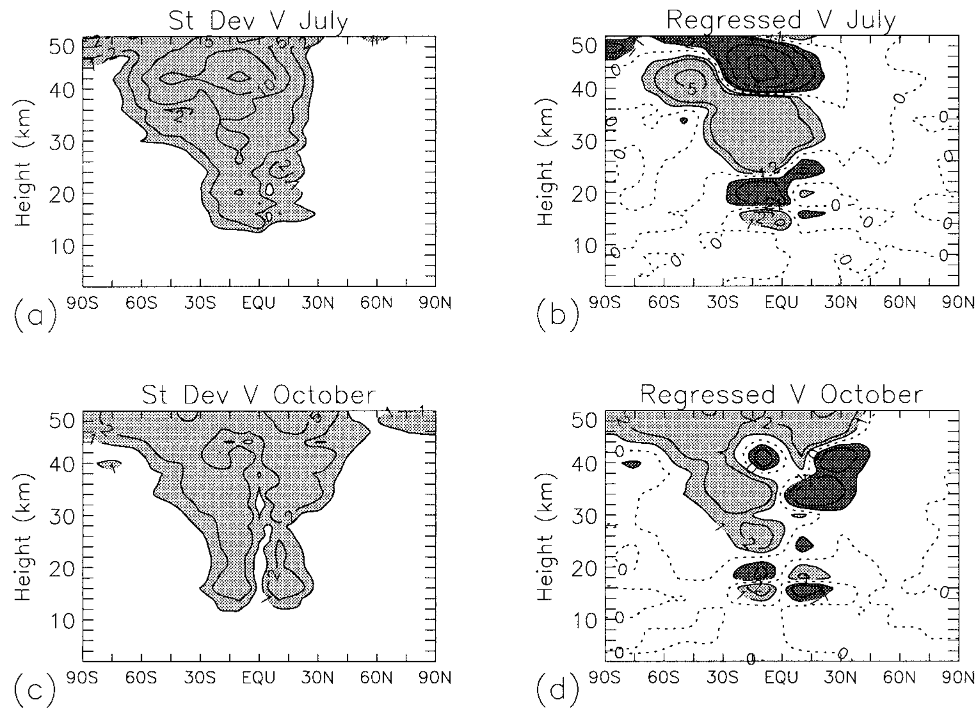


FIG. 22. As in Figs. 9a and 9b (horizontal velocity anomaly) but for run IIIa (direct QBO circulation anomaly with zero $K_{yy}$).

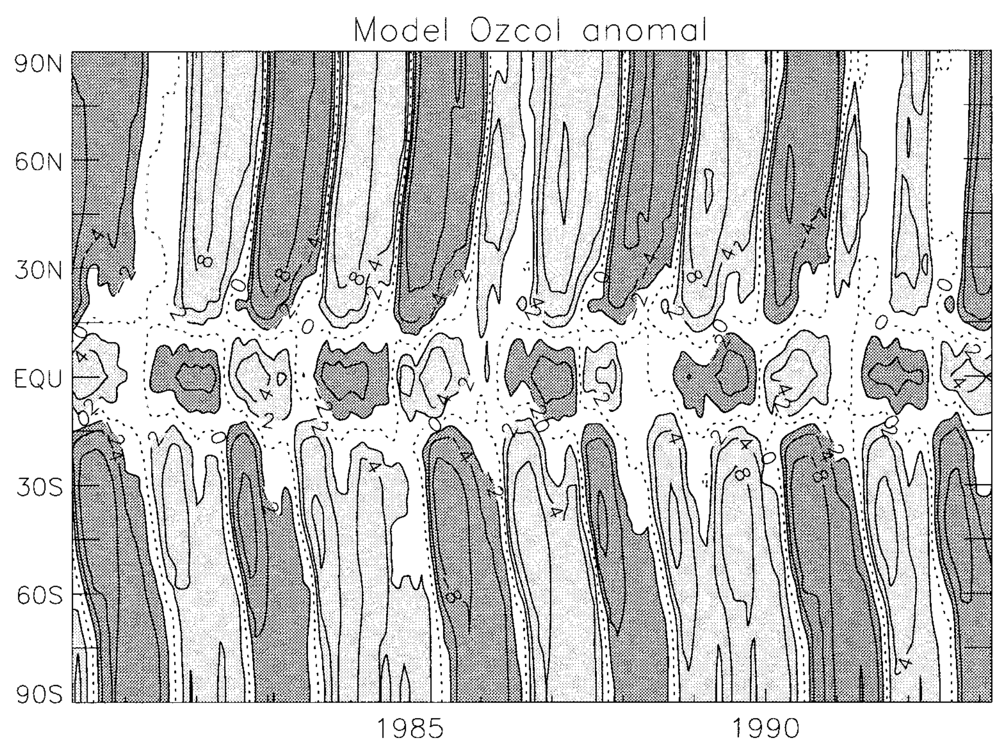


FIG. 23. As in Fig. 1a but for run IIIb (direct QBO circulation anomaly and nonzero $K_{yy}$).

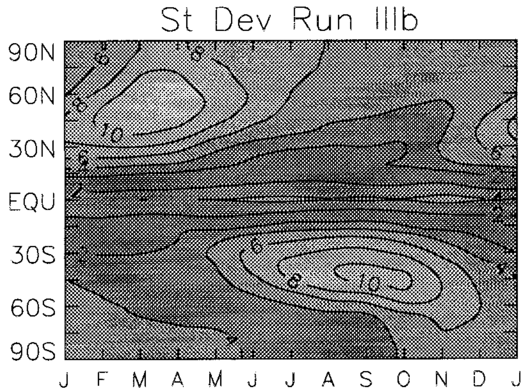


FIG. 24. As in Fig. 2a but for run IIIb (direct QBO circulation anomaly and nonzero $K_{yy}$).

anomaly is not well correlated with the anomaly of the control run (Fig. 25c). It occurs fairly low in the stratosphere, where we might not expect photochemistry to affect the ozone anomaly, and may be due to the downward advection of an ozone anomaly produced higher and earlier by the other gases. In general then, the other gases appear to be important in producing the ozone anomaly in summer at most latitudes between about 30 and 35 km, and in the Tropics near 30 km in all seasons; but above about 40 km and in the winter and spring hemispheres they are much less important.

### *g. Chaotic behavior*

It is possible that the good correlation of the modeled and observed ozone column anomaly in the Southern Hemisphere was due to an interaction with the equatorial QBO, but it is also possible that it was due to internal chaotic variability in the model and hence occurred by chance. Therefore, the model was run again as for the control run but was started with the equatorial QBO forcing for December 1976 instead of December 1977. If the interannual variability in the model is really determined by the equatorial QBO and the initial conditions are forgotten fairly rapidly (which is the case for the dynamical variables in this model), then we should expect the interannual variability to be almost the same as that of the control run. The degree of similarity is revealed in Fig. 26, which shows the correlation from November 1978 to April 1993 between the ozone column anomalies of run V delayed by 12 months and the control run (so that the corresponding simulated months are compared with each other). It is seen that for most months and latitudes the correlation exceeds 0.9, implying that the interannual variability is mainly nonchaotic and well determined by the equatorial QBO. Note that this is a stronger result than merely correlating the ozone column anomaly with the Singapore wind at a certain level or levels, since such a correlation is generally not strong for all months and latitudes (see, e.g.,

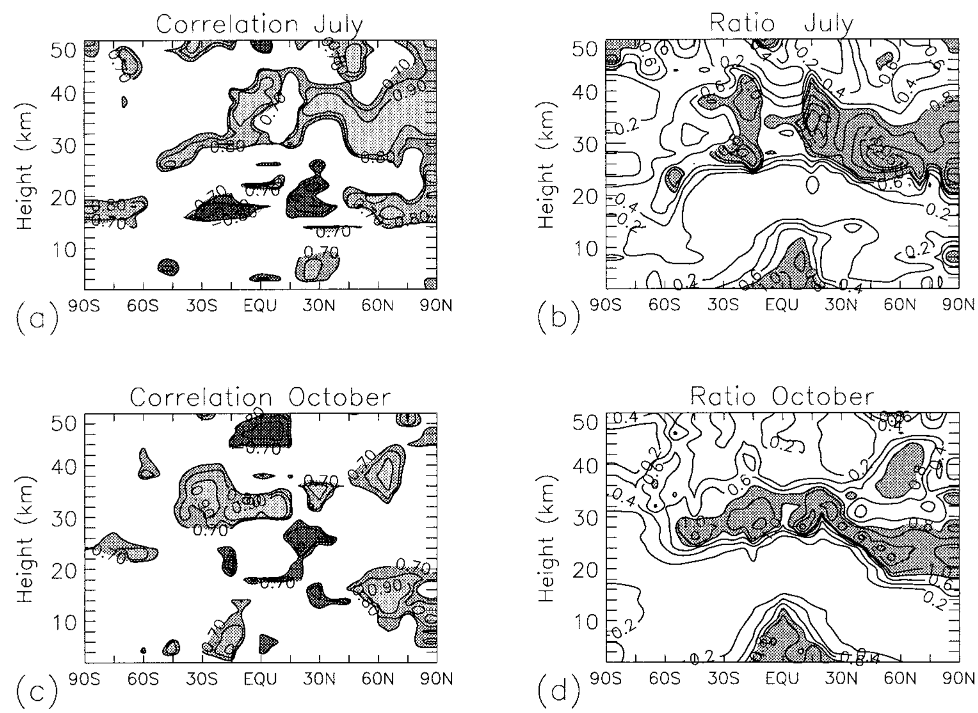


FIG. 25. (a) Correlation between ozone anomaly of run IV (where all gases except ozone were specified from the control run) and that of the control run for Jul. Contours at ±0.7, ±0.8, and ±0.9; light shading of positive values and dark shading of negative values. (b) Ratio of standard deviation of ozone anomaly of run IV to that of the control run in Jul. Contours at 0.2, 0.4, 0.6, 0.8, 1.0, 1.5, 2.0, and 2.5; values above 0.8 are shaded. (c), (d) As in (a) and (b) but for Oct.

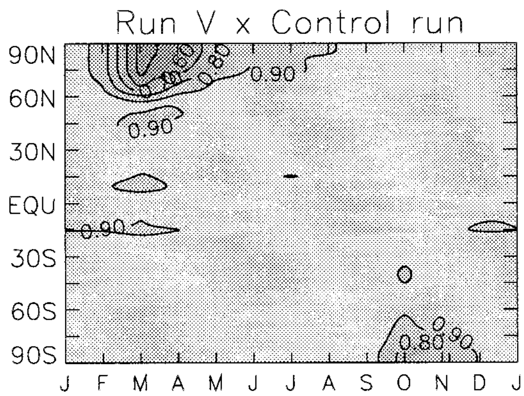


FIG. 26. Correlation between control run and run V (with results from run V shifted by 12 months so that simulated years coincide).

Kinnersley and Tung 1998, Fig. 9). What Fig. 26 implies is that the specification of the equatorial QBO between 10 and 70 mb determines the ozone anomaly at all months and latitudes (with the exceptions discussed below) and that this need not necessarily be revealed by an objective analysis (involving correlations, lagged or otherwise) of the ozone anomaly using the Singapore winds. This conclusion applied to the observations implies that the Singapore winds may be determining more of the interannual variability in the observed ozone column than may be extracted by regression with the Singapore wind at one level or even by a singular value decomposition using the values at all levels (e.g., Randel and Wu 1996). In a sense, the model used here can be seen as a tool for extracting, in a more physically realistic way, the information contained in the Singapore winds than can be obtained by a regression analysis.

The regions of Fig. 26 where the correlations are small are those regions where the modeled ozone column is more chaotic. For most months and latitudes the correlation is over 0.9, implying that the modeled ozone anomaly is very well determined by the equatorial QBO. However, in March north of about 60°N the correlation drops below 0.5, implying at least a disruption of the QBO signal by chaotic behavior. Even if the planetary waves in March behaved chaotically, we would still expect some correlation between run V and the control run because of the persistence of the February ozone anomaly. The chaos in the ozone column in the Northern Hemisphere in March (and to a lesser extent in the Southern Hemisphere spring at high latitudes) may possibly be due to chaos in the timing of the final warming, being some years in February and some years in March.

## 7. Summary and discussion

In the lower stratosphere the model simulates the observed ozone anomaly very well, as shown by comparison with both TOMS and SAGE II data. It reproduces the observed strong seasonality in the ozone anomaly. In the model, this seasonality stems from a seasonality in the vertical velocity of the direct QBO circulation at low and middle latitudes and the seasonality of the planetary wave modulated circulation at high latitudes. This explanation of the seasonality of the ozone column differs from that of Gray and Ruth (1993), which suggests that the climatological mean (Brewer–Dobson) circulation destroys the summer ozone anomaly and advects the winter ozone anomaly poleward (with meridional diffusion by breaking planetary waves possibly adding to this poleward transport of the anomaly). Here, by contrast, it is shown that it is the seasonality of the circulation anomaly (which is large in winter and small in summer) that produces a large ozone anomaly during winter. A similar conclusion was also drawn by Jones et al. (1998), who, however, did not consider the circulation modulation by the planetary waves.

Meridional advection of the ozone anomaly by the Brewer–Dobson circulation is not important in this model, while diffusion by the planetary waves plays only a secondary role, decreasing slightly the low-latitude ozone anomaly while increasing the high-latitude anomaly by at most 4 DU (cf. Figs. 24 and 17).

In our model, the main cause of the high-latitude anomaly is due to the so-called Holton and Tan mechanism (cf. Figs. 2a and 11), whereby the planetary wave PV flux (which is equivalent to the divergence of the Eliassen–Palm flux) is modulated by the equatorial QBO. The modulation of this forcing of the zonal wind causes a circulation anomaly that produces most of the modeled ozone anomaly poleward of about 50°. In the Southern Hemisphere the planetary wave PV flux anomaly, and hence the high-latitude ozone anomaly, is very well determined by the Singapore wind, while in the Northern Hemisphere the planetary wave fluxes in March are much less well determined and the high-latitude ozone column appears to behave chaotically.

A simple experiment suggests that the ozone anomaly simulated by the model is determined by the anomalies in the other modeled gases only in the summer hemisphere and in the Tropics, and between about 30 and 40 km.

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## APPENDIX

### Regression Analysis

The method used to obtain the regressed anomalies used in this paper is given here. The total anomaly in the ozone concentration at a certain latitude–height location, $x$, can be written as $x = \alpha y + R$, where $y$ is the 15-mb Singapore wind and $\alpha$ is determined by minimizing the residual $R$ at each point. Expressing the mean square of the residual as $\langle R^2\rangle = \langle x^2\rangle + \alpha^2\langle y^2\rangle - 2\alpha\langle xy\rangle$, differentiating with respect to $\alpha$ and finding the stationary value give $\alpha = \langle xy\rangle/\langle y^2\rangle$. We could have presented $\alpha$ in this paper, but since we had already chosen to show the standard deviation $\langle x^2\rangle^{1/2}$ of $x$, a more useful quantity for indicating the part of $x$ that is related to $y$ was the standard deviation of $\alpha y$, which is $|\alpha|\langle y^2\rangle^{1/2}$. However, the sign of $\alpha$ tells us whether the regressed anomaly is in phase or out of phase with $x$, so the quantity we have used in this paper to represent the regressed anomaly is $Q \equiv \langle xy\rangle/\langle y^2\rangle^{1/2}$. Note that this is equal to the correlation of $x$ and $y$ multiplied by the standard deviation of $x$.

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