The Modeled Latitudinal Distribution of the Ozone Quasi-Biennial Oscillation Using Observed Equatorial Winds

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ABSTRACT

A simulation of precise years of the quasi-biennial oscillation (QBO) is achieved in a two-dimensional model by relaxing the modeled equatorial winds in the lower stratosphere toward radiosonde observations. The model has been run for the period 1971–90. A QBO signal in column ozone is produced in the model that agrees reasonably well with observational data from the BUV, TOMS, and SAGE II satellite datasets. The model results confirm previous indications of the importance of the interaction of the QBO with the annual cycle in the determination of the subtropical ozone anomaly. The low-frequency modulation of the subtropical ozone anomaly is now particularly clear.

The low-frequency modulation of the subtropical ozone anomaly in the model arises as a result of the interaction of the QBO with the annual cycle in the vertical advection by the Hadley circulation. The possibility of a further, similar modulation arising from the interaction of the equatorial wind QBO and the annual cycle in midlatitude eddy activity is discussed, with particular emphasis on the implications for the eddy transfer of ozone to high latitudes and on the ability to predict the severity of the Antarctic ozone hole. A link is proposed between the QBO signal in the severity of the Antarctic ozone hole and the amount of ozone observed in the subtropical/midlatitude springtime maximum in the Southern Hemisphere. On the basis of this relationship, the reliability of the model as a predictor of the severity of the ozone hole is explored. A conclusion of the study is that a reliable predictor of the severity of the ozone hole must take into account the timing of the descent of the equatorial wind QBO at the equator with respect to the annual cycle and that the use, as in previous studies, of a single parameter, such as the sign of the 50-mb equatorial wind, will not be entirely reliable because it cannot do this.

1. Introduction

Recent advances in the modeling of the quasi-biennial oscillation (QBO) in ozone have been made by the inclusion of a parameterization of the dynamical QBO in a 2D model that included a fully interactive treatment of ozone and other photochemical reactions (Gray and Pyle 1989, hereafter referred to as GP89). By successfully parameterizing the QBO in equatorial winds through a specification of the damping of Kelvin and Rossby gravity waves as they propagate vertically through the equatorial stratosphere, a QBO signal in ozone was produced in the model. Various overall characteristics of this signal, such as the timing of the ozone anomalies in relation to the equatorial winds, the phase change in the subtropics, and the timing of the subtropical anomalies relative to the equatorial anomalies, compare well with observations, and the underlying mechanisms of these features have been explored (GP89; Gray and Dunkerton 1990, hereafter referred to as GD90).

The approach taken in GP89, while fairly rigorous, was highly idealized insofar as the period of the modeled QBO was essentially constant throughout the run and there was a strong tendency for the equatorial QBO period to be synchronized with the annual cycle (so that the period was either two years or three). In subsequent runs this situation was improved (by omitting the parameterization of the semiannual oscillation) so the resulting period was just over two years (see, for example, GD90). Nevertheless, the period was still constant throughout the run because the specified amplitude of the Kelvin and Rossby gravity waves at the tropopause was kept constant.

In reality, the observed period of the equatorial QBO in winds, temperature, and ozone is highly variable, with periods between 22 and 34 months in duration, a feature not reproduced in previous modeling studies. In fact, the regularity of the modeled QBO period was turned to an advantage and exploited in previous stud-
ies since it enabled an examination of the QBO mechanisms and relationships (for example, between the QBO period and the annual cycle in GD90) in a relatively simple situation that did not have the added complication of a variable period. Nevertheless, these underlying mechanisms having been studied, it is now desirable to investigate whether the model can mimic the actual evolution of the ozone QBO in the atmosphere in response to the observed wind distribution, rather than to an idealized equatorial wind QBO of constant period.

The purpose of this study is, therefore, to force the modeled winds to mimic the observed winds at the equator and then to compare the resulting modeled ozone QBO with observations from the BUV (Back-scattered Ultraviolet) and TOMS (Total Ozone Mapping Spectrometer) instruments that together provide us with nearly 20 years of data on the QBO signal in ozone amounts. In GD90 it was suggested that the asymmetry in timing and amplitude of the subtropical ozone QBO anomaly was due to the timing of the equatorial QBO relative to the annual cycle that produced a low-frequency modulation of the signal. Further evidence of this low-frequency modulation of the subtropical QBO by the annual cycle is presented in this study.

In the next section a brief summary of the mechanisms of the ozone QBO is provided. In section 3 we describe in detail how the model was forced to emulate the observed QBO in equatorial winds. The resulting ozone QBO in the model is presented and compared with observations in section 4.

The presence of a QBO modulation of the Antarctic ozone hole has been noted and the possible underlying mechanisms discussed (e.g., Bojkov 1986; Garcia and Solomon 1987; Lait et al. 1989). Some significant attention has been paid to the possibility of predicting the severity of the ozone hole based on the phase of the equatorial wind QBO. The majority of such studies have been based on the sign of the wind over the equatorial region at a particular pressure level, for example, the 50-mb level. While these predictions have been successful to a certain degree, there have been notable exceptions: for example, in the spring of 1986 (Lait et al. 1989). In section 5 we explore possible reasons for these failures and examine how well the model performs based on a simple relationship between midlatitude ozone amounts and the severity of the ozone hole. Finally, a summary of the results and conclusions of this study is provided in section 6.

2. The ozone QBO

The quasi-biennial oscillation in equatorial winds consists of alternating easterly and westerly winds that oscillate with a variable period of between 22 and 34 months (Fig. 1). The oscillation is a maximum over the equator at 25–30 km and dies out rapidly away from the equator. The zonal wind reversals occur at higher levels initially and this vertical shear gradually descends with time at a rate of approximately 1 km per month (although this rate of descent can also be highly variable). A corresponding QBO in temperature is also observed in the lower stratosphere; warm temperature is in thermal wind balance with westerly vertical shear (i.e., westerly above easterly) and vice versa. Subsidence is required over the equator to maintain a warm anomaly against radiative damping; mass continuity then requires upwelling in the subtropics to form the return arm of the circulation. In the presence of an easterly wind shear a secondary QBO circulation of a similar nature but in the opposite direction is induced. These QBO circulations allow an explanation of many of the gross features of the observed QBO in ozone shown in Figs. 2 and 3 (Reed 1964; Ling and London 1986; GP89). Below about 25 km at these latitudes, ozone may be considered a passive tracer of the flow and hence of the induced QBO circulation.
The reversal from an easterly (westerly) zonal flow to a westerly (easterly) zonal flow is accompanied by a downwelling (upwelling) at the equator relative to the time-averaged circulation and a reversal from a negative (positive) to a positive (negative) anomaly in the column amounts of ozone at the equator. The sign of the ozone anomaly in each phase of the wind QBO is determined by the vertical distribution of ozone at the equator, which increases with height in this region of the atmosphere. The reversal in the direction of the QBO-induced circulation in the subtropics additionally explains the change in phase of the ozone QBO in the subtropics. A rationale for some of the more detailed features of the pattern of the observed ozone QBO, such as the asymmetry between the two hemispheres at subtropical and higher latitudes, requires the interaction of the QBO circulation with the annual cycle (GP89; Hamilton 1989; Holton 1989; GD90; see also the discussion following).

The mechanism for the high-latitude QBO signal in the zonal wind, temperature, and ozone distributions is not well understood. It is thought likely to be due to variations in eddy transfer, the strength of which is affected by the position (i.e., latitude and height) of the zero wind surface, and hence the QBO, in subtropical latitudes (Holton and Tan 1982; Hamilton 1989; O’Sullivan and Salby 1990; Dunkerton and Baldwin 1991) with a possible secondary effect due to the radiative response to the extra tropical ozone anomaly (GP89). The role of the QBO in the observed interannual variability of the “depth” (i.e., the severity) of the Antarctic ozone hole is also not well understood. A further discussion of this latter topic is delayed until section 5.

The interaction of the QBO-induced equatorial circulation with the seasonal cycle of the mean meridional circulation is of particular importance to the present study. It was shown in GD90 that in the summer hemisphere of the model, the subtropical ozone QBO anomaly is disrupted due to the presence of vertical advection (upwards), while at similar latitudes in the winter hemisphere the anomaly is enhanced by downward vertical advection. This leads to a north–south asymmetry in the amplitude of the modeled subtropical anomaly that depends crucially on the timing of the induced QBO circulation in relation to the seasonally cycling mean circulation. As explained in more detail in section 4 (and GD90), this effect causes one hemisphere (the winter one at the time of phase change at the equator) to display a strong, regular QBO signal while in the other hemisphere the signal is disrupted. The asymmetry between the hemispheres is not necessarily always in the same sense: because the equatorial QBO period is not exactly two years the phase relationship between the QBO and the annual cycle changes with time. For example, suppose that the QBO period is 26 months. If one cycle begins in December, the next will begin in February, the next in April, and so on. It will take six cycles, or 13 years, for the QBO to come back to its initial point in the annual cycle. At the beginning of this 13-year cycle the Northern Hemisphere is in winter and the subtropics of that hemisphere will display a strong, regular QBO pattern due to reinforcement by the Hadley circulation, while the Southern Hemisphere subtropical anomaly will be disrupted and hence weak. In some instances, the summer hemisphere anomaly is disrupted to such an extent that the anomaly may not change sign, resulting in an abnormally long anomaly in that hemisphere and also producing a pattern in which the equatorial anomaly is connected to the subtropical anomaly due to the lack of a phase change between equator and subtropics. Toward the middle of the 13-year cycle the situation is reversed: the QBO period has fallen behind the annual cycle to the extent that the QBO cycle now begins in June, the Southern (i.e., winter) Hemisphere now
displays a strong coherent QBO pattern at subtropical latitudes, and the Northern Hemisphere pattern is disrupted. For a clear example of this pattern, see Fig. 16 of GD90. This low-frequency modulation of the QBO by the annual cycle was put forward in GD90 as the explanation for the difference in period of the QBO at subtropical latitudes; while the equatorial QBO is truly "quasi," with periods that vary between 22 and 34 months, at subtropical and higher latitudes the QBO tends to be closer to a two-year signal interspersed with an occasional phase of the anomaly that extends for much longer than average.

3. Modeling the equatorial wind QBO

The model employed in this study is the two-dimensional Eulerian model developed by Harwood and Pyle (1975, 1977, 1980) and used in recent studies of the QBO by GP89, GD90, Gray and Chipperfield (1990), and Chipperfield and Gray (1992). Zonal-mean values of temperature, wind components, and chemical constituent mixing ratios are calculated with a resolution of $\pi/40$ in latitude, $0.5 \ln(p_0/p)$ in the vertical (where $p$ is the pressure and $p_0$ is the surface value), and a 4-hour time step. The model extends from pole to pole and from the ground to approximately 100 km. A detailed radiation scheme is included (Haigh 1984). The gas kinetic data are those outlined in GD90 and previous studies.

In contrast to the studies of GP89 and GD90, the version of the model employed in this study did not include a parameterization of the damping of Kelvin and Rossby gravity waves that are believed to give rise to the semiannual and quasi-biennial oscillations. Instead, a QBO in the equatorial winds was introduced into the model by relaxing the modeled winds toward the monthly mean winds obtained from daily radiosonde measurements above Singapore (1°22'N, 103°55'E), at heights 70 mb, 40 mb, 20 mb, and 15 mb (Naujokat 1986). A simple Newtonian relaxation method was employed at the appropriate (four) levels of the model in the equatorial lower stratosphere. The modeled winds were calculated in the usual manner but with an added forcing term that relaxed toward the observed winds on an $e$-folding time scale of 24 hours. (This relaxation time was found to be the most appropriate in order for the modeled winds to be constrained as close to the observed winds as possible while avoiding unrealistic effects that occur if the relaxation rate is too fast compared with the model time step.) A linear interpolation between the monthly averaged observations was performed to obtain the "target" velocities toward which the model was relaxed on each individual day of the model run. In order to avoid sharp discontinuities, the forcing was spread over five model grid boxes centered on the equator (a range of approximately 20 degrees either side of the equator) with the strongest forcing at the equator. The model run was commenced in February 1971 and continued until 1990. This period was chosen as overlapping with the period of available ozone data from the BUV, TOMS, and SAGE II instruments.

The time series of equatorial winds from this run is shown in Fig. 4; a comparison with Fig. 1 indicates that the winds in the model follow the observations to a reasonable degree of precision, as intended.

4. The modeled ozone QBO

The modeled QBO in column ozone is shown in Fig. 5 for the period 1971–1978, which overlaps with the time period of the BUV data in Fig. 2. In all model plots presented here the data have been Fourier analyzed at each latitude and the harmonics with periods less than 500 days (approximately 17 months) have been subtracted. This differs from many other studies in which the data have been filtered using a window of only a few months either side of some representative QBO period. We suggest that it is important not to restrict the results to a small preselected range of pe-

![Fig. 4. Height time series of the modeled equatorial winds (m s$^{-1}$) for the period 1971-90. Dashed contours indicate easterly winds.](image-url)
periods. The BUV data in Fig. 2 (derived by Hasebe 1983, 1984) have been strongly filtered, and show only those periods falling within a window centered on 26 months and with half-widths at 19.3 and 34.9 months; it is zero near 48 months.

A comparison of Figs. 2 and 5 shows that the two QBO patterns are broadly similar, particularly in the later years. However, note the strong filtering of the BUV data in Fig. 2, while Fig. 5 contains a much broader spectrum of periods. This leads to some substantial variations, particularly in the timing of the phase changes. Hasebe (1983) also examined an oscillation of approximately four-year period (which was not negligible) that has been filtered from Fig. 2 but remains in Fig. 5. Differences of detail between the two figures are therefore not surprising. There are occasions when the modeled equatorial anomaly changes sign rather earlier in the year than in the data, for example, in 1974 and 1975. This results in the Northern Hemisphere anomaly in early 1974 having the wrong sign. Despite this, the overall pattern of anomalies has been captured by the model. For example, the broken lines in Fig. 5 group together midlatitude anomalies that have a fairly regular period and a well-defined phase change in the subtropics. In general, one hemisphere or the other shows this coherent pattern, while in the other hemisphere the anomaly is weaker and has a less regular pattern. In Fig. 5 the Southern Hemisphere “dominates” first and then the Northern Hemisphere, in broad agreement with Fig. 2 in the time period of overlap of the two plots.

The alternating disruption of the subtropical anomaly in one hemisphere and then the other produces a pattern in which the equatorial anomaly appears to merge with the subtropical anomaly of one or other of the hemispheres. This is particularly apparent in the BUV data, where the Northern Hemisphere subtropical anomaly (at around 25°N) appears to merge with the equatorial anomaly so that it is equal to or even greater than the equatorial anomaly. Hamilton (1989) has suggested that this is due to mixing associated with midlatitude planetary waves, such that the transport of high ozone values from midlatitudes to the subtropics is greatest during the westerly QBO phase and serves to enhance the subtropical anomaly. Holton (1989), on the other hand, showed that much of the hemispheric asymmetry in the magnitude of the subtropical anomaly could be reproduced by horizontal advection of the equatorial anomaly by the mean Hadley circulation. In this model, as described in GD90, a similar pattern is produced due to vertical advection by the Hadley circulation, which results in the downward transport of the ozone anomaly at higher altitudes in winter/spring (which serves to reinforce the anomaly at lower levels) and upward transport of the anomaly during summer/autumn (which serves to reduce the magnitude of the anomaly and hence disrupts the signal). The hemispheric asymmetry of the timing of the
anomaly is therefore a result of the timing of the equatorial ozone anomalies relative to the seasonal cycle: because the phase relationship between the QBO and the annual cycle is constantly changing, the asymmetry about the equator of the subtropical ozone anomaly also changes with time. The effect of the interaction is to produce a nearly biennial oscillation in the subtropics with low-frequency modulation (see section 2).

During the period observed by the BUV instrument, the QBO anomaly in the Southern Hemisphere was regular and relatively strong, while the Northern Hemisphere anomaly was disrupted and displayed a pattern in which the subtropical anomaly appeared to be an extension of the equatorial anomaly (see Fig. 2). However, note that toward the end of the observing period and also during the period of the TOMS measurements (see the following), this pattern changes: from 1976 onward the pattern switches so that the Northern Hemisphere subtropical anomaly is more regular and the equatorial anomaly appears to connect to the Southern Hemisphere subtropical anomaly. During the TOMS period this pattern of (a) regularity in one hemisphere and (b) the equatorial anomaly connecting to the other hemisphere is less apparent; the equatorial anomaly is more confined to equatorial latitudes and the connection of the equatorial anomaly to the subtropical anomaly flips from one hemisphere to the other and back again (see discussion of Fig. 6). The availability of the TOMS data to form a longer time series shows, therefore, that the asymmetry between the two hemispheres is not constant with time (i.e., the equatorial anomaly does not always extend into the Northern Hemisphere, as the BUV data suggests). Consequently, we suggest that it is probably not explained by the presence of greater planetary wave activity in the Northern Hemisphere than in the Southern Hemisphere (Hamilton 1989). It is more likely explained, as suggested in GD90 and outlined earlier, by the interaction of two frequencies, namely, the annual cycle of 12 months with the QBO cycle of approximately 28 months, to produce a longer-period modulation. We suggest that the period of the QBO during the BUV period was approximately constant so that this low-frequency modulation was more obvious than during the TOMS period in which the QBO period was variable (the latter variability would serve to complicate the resulting pattern of low-frequency modulation). The fact that the model described in this paper has been able to reproduce the switching from one hemisphere to the other by accurately modeling the duration of each phase of the QBO signal at the equator and hence its phase relation to the annual cycle supports this hypothesis.

The modeled ozone QBO may also be compared with the QBO anomaly in the column ozone measurements from the Total Ozone Mapping Spectrometer, which provides column ozone data from November 1978 to the present. Figure 3 shows the latitude time series of the QBO anomaly in the TOMS data from Lait et al. (1989), in which a broadband filter has been applied to the data (for details of their filtering techniques, see Lait et al. 1989). Figure 6 shows the same data (with the addition of a further year) in which, to enable a more rigorous comparison with the model results, the TOMS data have been sampled and treated in the same manner as the model output. Hence, daily, zonally averaged TOMS values were employed at 10-day intervals and at approximate intervals of $9^\circ$ latitude to coincide with the model grid and the fact that fields from the model are saved at 10-day intervals. At the time of the study, the only available TOMS data were those from Version 5, in which no compensation is made for various known instrument features, primarily the degradation of the diffuser plate (these data are the same as those employed by Lait et al. 1989). The TOMS data display a sizable downward trend over the 11-year period, partly resulting from instrument effects and partly due to the decrease in global column ozone observed elsewhere (Stolarski et al. 1991). A quadratic trend was removed from the TOMS data independently at each latitude using a least-squares fit method. In common with other studies it was found that the subtracted trend was greatest at the poles and least in equatorial regions. The data were then Fourier analyzed and, following the treatment of the model results, the mean and harmonics with periods shorter than 500 days removed. A comparison of Figs. 3 (from Lait et al.) and 6 (our filtering) indicates an overall similarity in the pattern of the QBO. Some of the details are different (especially when compared with the unfiltered data in Figure 7 of Lait et al.), which highlights the extreme caution that is necessary when interpreting data that has been filtered.

Figure 7 shows the corresponding time series of the ozone QBO signal from the model run. A comparison of Figs. 6 and 7 indicates that the broad patterns of the anomalies are very similar (although the amplitude of the anomalies in the model is rather larger than observed); the model appears to have captured the timing of the change in phase of the equatorial ozone anomalies. For example, positive anomalies are present in equatorial latitudes for most of 1980, mid 1982–mid 1983, mid 1984–end of 1985, and mid 1987–mid 1988, in both model and observations. Additionally, and importantly, the model has also captured the hemispheric asymmetry in the timing of the subtropical anomalies. Notice, for example, a general pattern in which the middle to high latitude QBO signal in the Southern Hemisphere is a fairly regular two-year pattern between 1985–1987 and the long positive anomaly in 1983/84, which agrees well with Fig. 6. Similarly, in the Northern Hemisphere, a fairly regular two-year signal is present in the period 1982–85 in both model and observations (at approximately the same time period as the disrupted signal in the Southern Hemisphere) but a rather less regular signal in other years. This tendency for one or
Fig. 6. Latitude time series of the zonally averaged column ozone anomalies (DU) from the TOMS satellite instrument in which the data sampling and filtering is similar to that applied to the model data. Dashed contours indicate negative anomalies.

Fig. 7. Latitude time series of the modeled column ozone anomalies (DU) for the period 1979–90. Dashed contours indicate negative anomalies.
other of the hemispheres to "dominate" at any one time was noted in GD90 and results (in the model) from the interaction of the QBO period with the annual cycle. The hemispheric asymmetry of the column ozone QBO and the ability of the model to simulate them were noted in GP89 and GD90. The main improvement in this study is the ability of the model to simulate the subtropical anomalies of particular years, based on the observed timing and nature of the equatorial wind QBO.

Further evidence that the model captures the important interaction of the QBO circulation with the annual cycle in the mean meridional circulation is provided by the fact that one phase of the modeled ozone QBO at subtropical latitudes is occasionally much longer than one would expect from the duration of the equatorial anomaly; this behavior is also present in the observations. For example, the model has captured, to a reasonable degree, the pattern displayed in 1983 and 1984 when the ozone amounts in the Southern Hemisphere were anomalously high in two consecutive years. [Notice, however, that the narrowband filter of Lait et al. (see Fig. 7c of their paper) distorts this signal, displaying a prolonged negative anomaly during 1982–83 instead of a prolonged positive anomaly in 1983–84, which is present in the unfiltered TOMS data, the broadband filter of Lait et al. (Figs. 7a and 7b of Lait et al. 1989), and also in Fig. 6 (our filtering).] The prolonged Southern Hemisphere positive anomaly in 1983 and 1984 can be traced back (in Figs. 6 and 7) to the timing of the reversal of the ozone anomaly at the equator. In 1983 the equatorial ozone anomaly switched from positive to negative at around March. This was in plenty of time for a positive subtropical anomaly to be set up in the Southern Hemisphere (as a result of the QBO-induced secondary circulation) and for it to be reinforced by the downwelling associated with the mean Hadley circulation during winter. The anomaly is also transferred to high southern latitudes almost immediately via the increased eddy transport that occurs in winter/spring. In the following year (1984) the equatorial anomaly did not reverse from negative back to positive until rather later in the year (around August/September), that is, in the Southern Hemisphere springtime. By this time there was insufficient time for a substantial negative subtropical anomaly to develop in the subtropics—by September the direction of the mean circulation has begun to reverse and the Southern Hemisphere subtropics has progressed toward the summer conditions in which the mean circulation is upwards, resulting in the disruption of the anomaly. Hence, the development of a negative subtropic ozone anomaly in the Southern Hemisphere has to wait until the more favorable conditions in the following winter (June 1983). This results in an anomalously long positive high-latitude anomaly of approximately two years in the Southern Hemisphere from June 1983 to March 1985. This is in reasonably good agreement with the TOMS observations shown in Figs. 3 and 6, although the negative Southern Hemisphere anomaly in 1982–83 is rather longer and more pronounced in the model than in the observations. (As we have already mentioned, it is unwise to compare any too much detail data that have been filtered differently; while we have endeavored to filter the two datasets as closely as possible there still remains the differing amounts of linear trend subtraction that has been removed from the two datasets; discrepancies arising from this will be greatest at high latitudes.) Despite some discrepancies between Figs. 6 and 7 we suggest that the model has captured the gross characteristics of the observed ozone QBO during the two periods in which data is available.

Column ozone data was also available from the SAGE II instrument aboard the Earth Radiation Budget satellite from 1984. The QBO signal in this data has been analyzed and reported by Zawodny and McCormick (1991; see their Fig. 2). The time evolution and amplitudes of the modeled QBO in the period 1984–90 also compare well with the SAGE II QBO signal.

5. The high-latitude ozone QBO

a. Review of previous studies

A QBO signal in high-latitude ozone amounts was first noted by Angell and Korshover (1964, 1967, 1973, 1978) and later confirmed by Oltmans and London (1982), Hasebe (1983), and Lait et al. (1989). Additionally, Bojkov (1986) and Garcia and Solomon (1987) noted an apparent QBO modulation of the minimum ozone amounts observed in the Antarctic ozone hole that forms in springtime in the Southern Hemisphere. Garcia and Solomon noted that years in which the 50-mb equatorial zonal winds over Singapore were westerly (easterly), the severity of the ozone depletion within the hole was greater (less) than average. This association is in general agreement with the distributions of the ozone QBO shown in the previous section: a positive (negative) equatorial ozone anomaly is associated with a westerly (easterly) phase of the equatorial wind QBO, and the phase change in the ozone QBO with latitude in the subtropics accounts for the observed opposite association between the polar ozone and the 50-mb tropical wind direction.

In a recent paper, however, Lait et al. (1989) have further examined the proposed relationship of the ozone hole with the 50-mb equatorial wind QBO phase. They showed that the simple correlation of ozone-hole depth with the equatorial winds at 50 mb became seriously degraded in 1986. Figure 8 summarizes their Fig. 1: the phase of the average equatorial winds in August–September at the 50-mb level over Singapore is indicated. Note the breakdown of the simple correlation in 1986, in which a relatively shallow hole is associated with a westerly equatorial phase. Equatorial wind values at different pressure levels and months
greater poleward eddy transfer of heat and ozone than in westerly phase years. Various explanations for the observed QBO in the severity of the Antarctic ozone hole have been suggested. A straightforward modulation of the depth of the hole by the previously observed QBO in ozone amounts cannot account for the large amplitude of the ozone hole variability. An additional mechanism that serves to amplify the signal appears to be required (Lait et al. 1989). A strong candidate is the QBO in high-latitude temperature that is thought to be responsible for a QBO in the abundance of polar stratospheric clouds (PSCs). This QBO signal in PSCs, in turn, may result in a QBO in the efficiency of destruction of ozone, as the presence of PSCs is believed to be crucial to the chemistry responsible for destruction of ozone within the cold, isolated polar vortex (see, for example, Solomon 1988 and references therein). This hypothesis is strengthened by the presence of a strong QBO signal in the sightings of PSCs by the SAGE instrument, which is highly correlated with both temperatures and the severity of the ozone hole (McCormick, personal communication). It should be borne in mind, however, that the QBO in temperature is itself likely brought about by variations in wave activity; dynamically active years tend to be warmer, while dynamically quiet years are colder. Thus, temperature variations and variations in transport are not independent (and their effects are additive); the basic mechanism of both is the variability of wave activity.

A prediction of the severity of the ozone hole, however, appears to be out of reach until the relationship between the equatorial wind QBO and the high-latitude QBO in temperature and ozone is resolved. The QBO modulation of the eddy mixing is not properly taken into account in the present Eulerian mean model. Eddy transport of heat and ozone is carried out by a diffusion mechanism that acts to smooth out horizontal gradients in temperature and ozone. Because of the QBO in subtropical amounts of ozone, there is therefore a QBO signal in the gradient of ozone and temperature between midlatitudes and the subtropics; hence, there will also be a QBO signal in transport of heat and ozone to high latitudes in the model [contrary to a statement in the recent WMO assessment (WMO 1990)]. Therefore, if a QBO anomaly in ozone is present in the subtropics it will be automatically transferred to high latitudes; the greater part of this transfer will occur in winter/spring when eddy activity (and hence the model diffusion coefficients) is highest. This mechanism is evident in Fig. 7. In reality, a QBO modulation of the eddy transport term $O_3$ will also exist due to a QBO in the position of the zero wind surface affecting the level of planetary wave activity. Although the model diffusion coefficients vary during the year to represent the greater wave activity during winter and spring, this variation is the same in each modeled year so the model does not allow for a QBO in wave activity. The relative magnitude of these two contributions (i.e., the diffusive

**Fig. 8.** Minimum monthly mean total ozone south of 30°S for the nine Octobers between 1979 and 1987 from the TOMS satellite instrument (adapted from Fig. 1, Lait et al. 1989). Also shown are the October minimum monthly mean temperatures (thick lines) in the 70–100-mb region (dotted line). The direction of the August–September average 50-mb zonal winds over Singapore is indicated by W (west) or E (east).

have been employed in the search for a correlation that holds well in all years. For example, Garcia and Solomon used 50-mb October winds, while Lait et al. used 50-mb August–September averages. Angell (1990), on the other hand, employed the average of 50-mb and 30-mb June–July–August values of temperature. Lait et al. further noted that the rate of decline of polar ozone during September was better correlated with the 30-mb equatorial winds than the 50-mb winds. Additionally, various parameters have been employed to characterize the variability of the ozone hole; Garcia and Solomon used the minimum value of ozone south of 30°S, while in a recent WMO assessment study (WMO 1989) the October mean total ozone over the South Pole was used. The use of the minimum value south of 30 degrees south seems to be the more logical parameter to employ, since the minimum values of ozone are not necessarily to be found directly over the South Pole.

We suggest, in the following section, that there may not be a single parameter (such as the 50-mb equatorial winds) that can be identified to accurately predict the high-latitude ozone or temperature QBO, since the relationship between the equatorial QBO and the high-latitude QBO depends on the combination of a number of factors, such as the rate of descent of the phase of the QBO and the time of year in which the phase change occurs.

*b. The Antarctic ozone hole QBO*

As discussed in section 2, the mechanism for the observed QBO signal in high-latitude ozone and temperature is not well understood. A likely mechanism is the modulation of extratropical planetary wave activity by the position of the zero wind surface in the subtropics (Holton and Tan 1982; Hamilton 1989; O'Sullivan and Salby 1990; Dunkerton and Baldwin 1991). During an easterly phase of the QBO, wave activity is expected to be more confined, resulting in
mechanism and the wave variability mechanism) in influencing the latitudinal distribution of the ozone QBO remains to be determined. The disagreement in the high-latitude ozone anomalies between Figs. 6 and 7 (particularly, for example, the fact that in some years the TOMS high-latitude anomalies are out of phase with the subtropical anomalies; e.g., in 1980–82 in the Southern Hemisphere and in 1984–86 in the Northern Hemisphere) and in the magnitude of the midlatitude anomalies are possible indications of the absence of the latter mechanism, which is expected to be important (and probably dominant). Despite these acknowledged drawbacks of the model, we suggest that results of the present study are useful in drawing attention to (a) the diffusive aspects of the transfer of the ozone QBO signal to high latitudes and (b) the apparent importance of the interaction of the QBO with the annual cycle, even at high latitudes; the detailed arguments of this latter point are set out later but, in brief, we propose the following. 1) The model has captured the interaction between the QBO in equatorial winds and the annual cycle of vertical advection by the Hadley cell, resulting in a low-frequency modulation of the subtropical ozone anomaly. Because of the diffusive nature of the ozone transport in the model (which simply acts to smooth out horizontal gradients in mixing ratio), this low-frequency modulation is transmitted to mid- and high latitudes of the model, since the gradient of ozone across the sub-tropics has a QBO signal. 2) We note that a relationship appears to be present in the real atmosphere between the value of ozone in the middle to high latitude ozone maximum in spring (the ozone “crescent”) and the severity of the ozone hole (see below). When this simple relationship is used as a predictive tool for the depth of the ozone hole, the model performs better than previous studies in which the sign of the wind over the equator at one particular level (e.g., 50 mb) is employed. We suggest that this is because of the presence of the low-frequency modulation in the model, which results from an interaction of the QBO with the annual cycle over a range of heights in the modeled atmosphere and over a range of latitudes spanning the equator and the sub-tropics. 3) One inference to be made from this unexpected ability of the model (given the previously outlined inability to realistically represent all aspects of the transport to high latitudes) is that a low-frequency modulation is also present in the real atmosphere, not only in the sub-tropics but also at high latitudes. The obvious candidate for this is the interaction of the equatorial wind QBO with the annual cycle in wave activity, as suggested by Hamilton (1989), since the position of the zero wind surface in the sub-tropics is known to influence the propagation of midlatitude waves. Therefore, we highlight the fact that it is important to take into account the time of year and rate of descent of the equatorial wind QBO in relation to the annual cycle of eddy activity at mid-latitudes. The use of a single parameter (e.g., 50-mb winds) cannot do this and in some years predictions based on this parameter will fail. Attempts to find a suitable combination of various heights, for example, 30–50-mb average, and at different times of the year are a reflection of previous authors’ awareness of this problem.

In the following text we describe the relationship between the middle to high latitude ozone maximum (the ozone “crescent”) and the severity of the ozone hole and examine how well the 2D model is able to predict the severity of the hole using this simple relationship. Figure 9 (curve a) shows the time series of the maximum amount of ozone south of 30 degrees S from the zonally and monthly averaged TOMS data (note that data points are plotted for every month in Fig. 9, unlike similar graphs such as Fig. 8 in which only the October or the August/September average are plotted for each year). For comparison we have also plotted (curve b) the minimum amount of ozone in the same latitude range. The two curves show (a) the maximum values observed in the ridge of high ozone formed during winter/spring at midlatitudes and (b) the minimum values observed at high latitudes in springtime, which are indicative of the depth (i.e., severity) of the ozone hole. The two curves show a good correlation in springtime; during a year in which more (less) ozone than average is present within the ridge of high ozone at midlatitudes, there is also more (less) ozone present at high latitudes, leading to an ozone hole that is less (more) severe than average.

The correlation between the ozone amounts in the ridge of mid-latitude ozone and the severity of the ozone hole is further illustrated in Fig. 10 (Grose, personal communication), which shows polar (orthographic) projections of the monthly averaged ozone for October of 1987 and 1988. Notice that in 1987, a year in which the ozone hole was particularly severe (minimum values in the hole were less than 150 DU), the maximum values within the mid-latitude ridge were also lower than the corresponding values in 1988, which had a much less severe ozone hole. If the QBO in the level of eddy transfer (which affects not only the temperature but also ozone) does, indeed, play an important role in the QBO in the ozone hole, a correlation between the two parameters seems reasonable, since the maximum amount of ozone in the ridge of midlatitude ozone is also dependent on the strength of the eddy transport.

The correlation between the springtime ozone maximum in midlatitudes and the severity of the ozone hole has been highlighted in Fig. 9 by indicating (above the springtime peak values of curve a) the severity of the ozone hole that one would predict based on the sign of the observed midlatitude ozone QBO. SH indicates a predicted shallow hole, based on a positive anomaly in the midlatitudes, and DEEP indicates a deep hole, based on the presence of a negative anomaly in the midlatitudes. Hence, for example, the positive QBO anomaly in the midlatitudes in spring of 1979.
Fig. 9. Maximum (curve a) and minimum (curve b) zonally averaged, monthly mean total ozone south of 30°S (DU) from the TOMS satellite instrument for the period 1979–1989. The maximum amount (curve a) is an indication of the amounts of ozone in the ridge of high ozone present in springtime at mid-latitudes. The “sh” (shallow) and “deep” above the springtime maximum in each year indicates the predicted relative depth of the Antarctic ozone hole based on the relative amounts of ozone in this ridge at mid-latitudes: relatively small (large) amounts of ozone at mid-latitude indicate a more (less) severe ozone hole than average. The minimum amount (curve b) is an indication of the depth of the Antarctic ozone hole. The arrows point to the October values for each year and the “sh” (shallow) and “deep” indicate the relative depth of the ozone hole in that year. The direction of the equatorial zonal wind at 50 mb and 70 mb in September and October (courtesy B. Naujokat) is also indicated (see key).

(curve a) would suggest a shallow ozone hole, while the negative midlatitude anomaly in 1980 would suggest a deeper hole, as indeed is the case (see curve b). A comparison for all the years reveals a high success rate of these predictions, particularly in the time periods 1979–81 and 1984–89 (in the intervening period, 1981–84, the QBO in the severity of the ozone hole is less discernible; we believe that during this period, the QBO signal in curve b is masked to a significant degree by the negative trend in high-latitude ozone onto which the QBO signal is superposed—the data in Fig. 9 have not been detrended). Note that in the year 1986 the midlatitude ozone anomaly was positive and hence would predict a shallow hole, as was indeed the case (see curve b). Thus, the sign of the midlatitude ozone anomaly appears to be a more reliable parameter to employ as the predictive quantity than, say, the phase of the 50-mb equatorial zonal wind. This seems a reasonable and not entirely surprising conclusion to draw since the modulation of eddy transfer by the position of the zero wind surface in the subtropics (and hence the high-latitude temperature and ozone amounts) is controlled by a combination of factors, all of which are potentially important; for example, not only the phase of the equatorial winds at a particular level (e.g., 50 mb) but, more important, the time of the year in which the change of phase of the equatorial winds occurred and the rate at which the phase of the QBO descends with time during winter/spring.

Figure 11 shows a comparison of maximum values of ozone in the latitude band 30°S–90°S from the zonally and monthly averaged TOMS data [i.e., curve (a) of Fig. 10] and the equivalent maximum ozone values from the model run (curve b). As previously suggested, these parameters are representative of the magnitude of the ridge of high ozone values that occurs each spring at middle to high latitudes. An examination of Fig. 11 shows that the model has captured the QBO signal extremely well; not only does the sign of the ozone anomalies agree well but the model has also captured, for example, the pattern displayed in 1983 and 1984 when the ozone amounts were anomalously high in two consecutive years. As discussed in section 4, this behavior can be traced back to the interaction of the QBO with the seasonally cycling meridional circulation and is essentially determined by the timing of the reversal of the zonal wind at the equator.

The only year in which the model does not reproduce the correct QBO signal at mid-latitudes is in 1989 (see Fig. 11). The modeled midlatitude ozone amounts would have suggested a rather shallow ozone hole in that year, instead of the observed hole, which was as
Fig. 10. Monthly averaged polar orthographic plots of the total ozone (DU) over the Southern Hemisphere for (a) October 1987 and (b) October 1988. Shaded areas indicate values greater than 375 DU.
severe as that in 1987. Closer examination of the equatorial winds during this period (Fig. 4) suggests a possible source for this discrepancy. The winds around the 20–40-mb levels were virtually constant throughout the period from mid-1988 until late 1989 (in contrast to the onset of the easterly phase at this level in previous years). In other words, the descent of the easterly phase in this year appears to have “stalled” at around 30 mb for an unusually long time. Thirty millibars (i.e., approximately 24 km) is approximately the height at which the photochemical lifetime of ozone is such that it switches from being temperature controlled (above 24 km) to being more and more influenced by transport (below 24 km). Any inaccuracy in the modeling of the height of this “transition” level is reflected in the modeled column ozone distribution and is likely to be highlighted by such a situation as was present in 1989. In addition, it must be remembered that wind data at only four pressure levels were available with which to constrain the modeled winds, leading to possible inaccuracies in the model and, furthermore, the model grid resolution is approximately 3.5 km in the vertical, leading again to possible inaccuracies in the modeling of the height at which the easterly phase was stalled. All of these sources could lead to inaccuracies in the modeled column ozone as a result of the stalling occurring at around the level of the so-called transition zone.

6. Summary

Observations of the equatorial winds have been used to constrain a 2D model in order to produce a realistic QBO signal in the modeled equatorial winds. The resulting QBO signal in modeled column ozone amounts compares well with observations from the BUV, TOMS, and SAGE II satellite datasets. The model results confirm previous indications of the importance of the interaction of the QBO with the annual cycle in the determination of the subtropical ozone anomaly (GD90). In particular, the low-frequency modulation of the subtropical ozone anomaly, which leads to a hemispheric asymmetry in the pattern of column ozone anomalies, is reproduced. Observations of the depth (i.e., severity) of the Antarctic ozone hole display a QBO signal, the cause of which is not understood. A correlation between the amount of ozone in the ridge of high ozone in midlatitudes and the depth of the Antarctic ozone hole has been demonstrated in the TOMS data (Figs. 9 and 10). We show that the apparent QBO signal in the severity of the ozone hole may be predicted based on the QBO anomaly in ozone at midlatitudes. This appears to be a better tool for the prediction of the severity of the ozone hole than the sign of the equatorial wind at a particular pressure level (e.g., 50 mb) used in previous studies.

Using this simple relationship, we have shown that the 2D model is able to predict the severity of the ozone hole with reasonable accuracy, despite the many drawbacks in the formulation of the model, such as its inability to accurately represent the QBO in wave activity in midlatitudes. We speculate that the success of the model is a result of the low-frequency modulation of the QBO signal in subtropical ozone that is transferred to high latitudes by the diffusive nature of the eddy.
transport parameterization. This suggests that, in the real atmosphere, there may be a further low-frequency modulation of the ozone QBO at high latitudes arising from an interaction between the equatorial wind QBO and the annual cycle in wave activity at midlatitudes.

The 2D model is able to reproduce the observed midlatitude QBO anomalies in column ozone amounts, and we suggest that the 2D model may, therefore, be a more reliable predictor of the severity of the ozone hole than any single factor such as the phase of the equatorial wind at 50 mb. We emphasize that the important factor in the success of the model in reproducing the midlatitude QBO is the ability of the model to capture the combination of factors that influence the nature of the subtropical QBO, such as the timing and the rate of descent of the equatorial wind QBO and the interaction with the annual cycle.

While these model simulations cannot extend our understanding of the precise mechanism for the transmittal of the QBO signal from equator to high latitudes, the model experiments have nevertheless highlighted the importance of taking into account the time evolution of the descent of the equatorial wind QBO and its interaction with the seasonal cycle, which the use of a single parameter (such as the 50-mb winds) does not.

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