The role of ozone-induced diabatic heating anomalies in the quasi-biennial oscillation

By DINGMIN LI1*, K. P. SHINE1 and L. J. GRAY2

1University of Reading, UK
2Rutherford Appleton Laboratory, UK

(Received 1 March 1994; revised 8 November 1994)

SUMMARY

The diabatic effects of the quasi-biennial oscillation (QBO) in ozone on the oscillation of temperature and zonal mean winds are investigated using a 2-dimensional model with full interaction between dynamics, radiation and photochemistry. It is found that the temperature anomaly caused by the ozone QBO makes a significant (25%) contribution to the total temperature anomaly of the QBO although the corresponding change in wind is smaller (about 10%). It is shown that the diabatic effects of the ozone QBO should not be neglected in attempts to simulate the QBO in other parameters.

KEYWORDS: Diabatic heating Ozone Photochemistry QBO Stratosphere

1. INTRODUCTION

Following the discovery of the quasi-biennial oscillation (QBO) in zonal winds in the equatorial lower stratosphere (Veryard and Ebdon 1961; Reed 1962), attempts were made to explain the QBO in terms of some radiative mechanism—see, for example, the discussion by Wallace and Holton (1968) and Lindzen (1987). Later it was discovered that the features of the QBO could be explained by the transfer of momentum to the zonal flow by the dissipation of vertically propagating waves (Lindzen and Holton 1968; Holton and Lindzen 1972; Lindzen 1987).

The motivation for the present note started with the development of an ozone climatology for general-circulation model use. If the model’s ozone climatology was specified as 12 monthly-mean fields then the QBO in ozone (e.g. Hasebe 1983, 1994; Ling and London 1986; Zawodny and McCormick 1991) would not be included; depending on the length of the averaging period, the ozone climatology might be biased towards one or other phase of the QBO which may then result in a temperature bias. It was, therefore, necessary to investigate the influence of the QBO in ozone on the stratospheric temperature field. The QBO in ozone is believed to be primarily due to the variation of the meridional circulation during the oscillation (at equatorial and subtropical latitudes) (e.g. Gray and Pyle 1989; Gray and Dunkerton 1990) and to a modulation of ozone transport due to planetary waves (at mid and higher latitudes) (see Tung and Yang (1993) and references therein). However, the diabatic influence of the ozone changes themselves on the QBO have not been investigated using an interactive dynamical—radiative model. To some extent this was revisiting the earlier ‘diabatic’ theories of the QBO which may have a bearing on general-circulation-model or mechanistic-model experiments (e.g. Takahashi and Boville 1992; Boville and Randel 1992; see also Pawson 1992) which ignore any changes in ozone associated with the QBO and their subsequent diabatic effects. Recently, Hasebe (1994) has also drawn attention to the possible role of anomalies in diabatic heating in determining features of the QBO.

It is well known that ozone is important for determining diabatic heating in the stratosphere. Once its distribution is changed, it will inevitably affect the dynamical field via diabatic heating or cooling; for long-period phenomena such as the QBO, this feedback may be significant. Figure 1 shows a simple calculation of the ozone-induced temperature anomaly in equatorial latitudes using a radiatively determined model (Shine 1987) and observed SAGE (Stratospheric Aerosol and Gas Experiment) II (Zawodny and McCormick 1991) ozone data. The radiatively determined temperature anomaly is caused solely by the observed ozone anomaly in the absence of dynamical processes. (It is recognized that this is grossly unrealistic as diabatic heating anomalies in the tropical lower stratosphere are restricted in their effect on temperature anomalies (Andrews et al. 1987 p. 314); it nevertheless illustrates the potential importance of the ozone anomalies.) The observed zonal-mean zonal wind in the same region is also shown in Fig. 1. Figure 1 shows that ozone and temperature are almost in phase and slightly ahead of the wind phase, in agreement with the prediction made by theory (Plumb and Bell 1982; Plumb 1984). Figure 1 also indicates that the temperature change caused by the oscillation in ozone can contribute more than 1 K in amplitude, which is about 30% of the observed equatorial temperature anomaly associated with the QBO (Angell and Korshover 1964). This confirms that the ozone QBO is potentially important for the other features of the QBO.

* Corresponding author: Department of Meteorology, University of Reading, 2 Earley Gate, Whiteknights, Reading, Berkshire RG6 2AU, UK.
Figure 1. Temperature anomaly due to the ozone quasi-biennial oscillation calculated using a radiatively determined model. Solid line: modelled temperature anomaly in K for January 1985 to December 1989. Dashed line: observed SAGE II ozone anomaly in parts per million by volume for the same period. Dash-dot line: observed monthly-mean zonal-mean zonal winds above the equator in units of 10 m s⁻¹ (updated from Naujokat (1986)). Temperature and ozone are averages horizontally from 7.5°S–7.5°N and vertically from about 22 to 28 km, while the wind is vertically averaged from 21 to 31 km.

By using a recently developed 2-dimensional (2-D), dynamical–radiative–photochemical interactive model (Kinnersley and Harwood 1993) with isentropic surfaces as vertical coordinate, the present study investigates how important the ozone feedback is on the dynamical fields. The next section will describe the model used and experiments performed. The third section will present the results.

2. MODEL AND EXPERIMENTS

The 2-D (latitude–height) model used in the present study is that described by Kinnersley and Harwood (1993). Taking advantage of the fact that the cross-isentropic movement of air is proportional only to diabatic heating, and that adiabatic planetary waves, even if large and non-steady, can only result in transport along isentropic surfaces, the model uses isentropic levels as its vertical coordinate (except below the tropopause where pressure coordinates are used to avoid the intersection of isentropes with the ground). The model extends from pole to pole, with horizontal resolution of \(\pi/19\), and from the ground to about 100 km, with a vertical resolution of about 3.5 km. It calculates winds, temperature and chemical constituent mixing ratios with a time step of 4 hours; winds and temperatures are calculated up to 100 km, while the chemistry is considered only below 60 km. The model parametrizes the eddy flux of chemicals and Ertel potential vorticity from the three longest Rossby waves; chemical and dynamical eddy fluxes are therefore consistent with each other and with the zonal mean state at each time step. The model runs here used model-parametrized potential vorticity fluxes. The radiative heating is calculated using the scheme of Haigh (1984) below 60 km. Thus the model ozone field is fully interactive, allowing important feedbacks between radiation, dynamics and chemistry, and is therefore suitable for the present study.

By forcing a relaxation of model zonal wind towards observed equatorial winds in a similar 2-D isobaric model, Gray and Ruth (1993) simulated a QBO in total ozone similar to that seen in the Total Ozone Mapping Spectrometer (TOMS) satellite observations. The same relaxation scheme has been incorporated into the isentropic model by Chipperfield et al. (1994) and is used in the present study to investigate the feedbacks of the ozone QBO on the dynamical fields.

Three model experiments were carried out. In the first experiment (referred to as Run 1) the model zonal winds were forced to relax toward the observed equatorial winds (updated from Naujokat (1986)).
As discussed later and by Gray and Ruth (1993), this leads to a simulated ozone field with a QBO signal similar to the observed ozone field. In the second experiment (Run 2) this modelled ozone field was then input into the model at every time step but the wind relaxation was switched off. This experiment should indicate the impact of the inserted ozone, which includes a near-realistic QBO signal, on the dynamical field. In the third experiment (Run 3) both the forced relaxation of winds and input of ozone field were switched off; this allows the model to evolve by itself and can show to what extent the signals resulting from the second experiment are caused by ozone feedback.

It would be more realistic to perform an experiment using observed ozone data directly. Such an experiment requires an observed ozone data set that includes the QBO signal with good vertical resolution and extends from pole to pole and is continuous for about 10 years. The SAGE II and Solar Backscattered Ultra Violet data sets could be used, but neither can provide both globally resolved data at a good vertical
Figure 3. Time–height cross-section of temperature anomaly in K from model experiments: (a) from Run 1 and (b) from Run 2. The fields are filtered (see text). Contour interval is 1 K for (a) and 0.25 K for (b). Negative anomalies are dotted.

resolution for a sufficient period of time; it is simpler to use the model ozone fields provided it is established that they reproduce the main features of the observations.

3. RESULTS AND DISCUSSION

The model was integrated for 10 years from 1983 for each of the three experiments described earlier. Figure 2 shows the SAGE II observed QBO anomaly in equatorial ozone mixing ratios from 1985 to 1989 and the corresponding modelled anomaly of ozone mixing ratio from Run 1. The SAGE II field is smoothed and the modelled anomaly is filtered as described by Gray and Ruth (1993) as are all other fields presented in this note; the data are Fourier analysed and the harmonics with periods less than 500 days have been removed. It is shown that the model successfully simulates the observed phase of the ozone QBO between 20 and 30 km; the modelled amplitude is about 0.2 parts per million by volume (p.p.m.v.)
larger than the observed except in 1985 where it is 0.4 p.p.m.v. larger. The disagreement below 20 km has also been noted by Chipperfield et al. (1994). Comparison with TOMS observations also shows that between 20°S and 20°N the modelled column-ozone QBO is very similar to the observation both in phase and amplitude. Therefore, it is possible to use this modelled ozone field as input to simulate a near-realistic feedback of ozone QBO on the dynamical fields.

Figure 3(a) shows the filtered temperature anomaly simulated by Run 1. The QBO temperature signal can be clearly seen from the figure, with phase propagating downward at a rate similar to that observed for the zonal wind. The amplitude at 24 km (about 30 mb) and 20 km (about 50 mb) is between 3 and 4 K, which is in good agreement with the analysis of observation by Dunkerton and Delisi (1985). Figure 3(b) shows the temperature anomaly from Run 2 caused by using the ozone-field output from Run 1. It can be seen that imposing an ozone QBO on the model generates a QBO signal in the modelled temperature field, with a phase shift with height, and downward propagation very similar to Run 1 except for a few month’s delay. The amplitude is about 25% of that in Run 1. In Run 3 (not shown) there was no QBO signal at all in modelled fields if both relaxation to the observed winds and input of ozone QBO were switched off; the temperature anomalies in Fig. 3(b) are, therefore, solely caused by the diabatic effects of the ozone QBO.

The modelled temperature oscillation at the equator is compared with observations from channel 4 of the Microwave Sounder Unit (MSU) (J. R. Christy and R. W. Spencer, personal communication) in Fig. 4. The QBO signal in this field has been discussed by Randel and Cobb (1994). The channel 4 weighting function (see, for example, Randel and Cobb (1994)) has been applied to the model output to achieve a closer comparison. Also shown is the model’s ozone-mixing-ratio anomaly, obtained by applying the same weighting function to the ozone fields. Comparing the MSU data with Run 1, there is generally reasonable agreement between both the phase and the amplitude of the oscillation. This further supports the case that Run 1 is an adequate simulation of the QBO. A better agreement between model and observations might not be expected as there are other influences on the lower stratospheric temperatures, such as the effect of volcanic aerosols and the El Niño–Southern Oscillation (ENSO) (see, for example, Randel and Cobb (1994); Christy and Drouìlhet (1994)). The effects of these are not included in the model,
except in so far as they impact on the observed equatorial winds used in Run 1. The effect of the aerosols following the 1991 eruption of Mt. Pinatubo is particularly marked—the aerosols caused a heating when the QBO might have been expected to lead to a cooling. In early 1983, and between 1986 and mid-1989, anomalies in the ENSO time series also affected the temperatures in the lower stratosphere.

Figure 4 also emphasises the phase shift in the QBO in temperature between Run 1 and Run 2. In Run 1 the temperature is responding to variations in both meridional circulation and diabatic heating. In Run 2 it is responding only to the direct diabatic influence of the ozone change.

Figure 5 shows the zonal wind at the equator, as a function of time and height, from Run 2. The QBO in ozone is, via its effect on the temperature, also driving a weak QBO in zonal wind speed at heights above 24 km—periods with easterlies of 3 to 4 m s\(^{-1}\) are interspersed by periods with easterlies around 1 m s\(^{-1}\); such an oscillation is about 10% of the observed QBO zonal-mean zonal wind oscillation. Since the model will be close to a state of thermal-wind balance, the smaller QBO response in zonal wind than in temperature indicates a smaller oscillation in the meridional gradient of temperature than in equatorial temperature itself.

![Figure 5. Time–height cross-section of zonal wind (m s\(^{-1}\)) from Run 2. The fields are filtered (see text). The contour interval is 1 m s\(^{-1}\) and easterlies are dotted.](image)

In summary, the three experiments suggest that the diabatic effect of the QBO in ozone has a significant effect on the temperature QBO and a smaller effect on the QBO in the zonal wind. It is important to include the diabatic effects of the ozone QBO in attempts to model the QBO and this could help to improve the simulation of the QBO in general-circulation models.

**ACKNOWLEDGEMENTS**

Dingmin Li was funded by the Natural Environment Research Council under a grant from the UK Universities Global Atmospheric Modelling Programme Special Topic. Martyn Chipperfield, Sarah Ruth and Jonathan Kinnersley are thanked for their help in various aspects of this work. The comments from Steven Pawson and another referee are greatly appreciated.

**REFERENCES**


Dunkerton, T. J. and Delisi, D. P. 1985 Climatology of the equatorial lower stratosphere. J. Atmos. Sci., 42, 376–496


Naujokat, B. 1986 An update of the observed quasi-biennial oscillation of the stratospheric winds over the tropics. J. Atmos. Sci., 43, 1873–1877

Pawson, S. 1992 A note concerning the inability of GCMs to model the QBO. Aer. Geophysicae, 10, 116–118


