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A Two Dimensional Model of the Quasi Biennial Oscillation of Ozone

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ABSTRACT. The largest amplitudes of the observed Quasi Biennial Oscillation (QBO) in column ozone are found in high latitudes and this must be taken into account in any explanation of the increased depletion of ozone in the southern polar spring during the 1980's. A QBO in zonal wind, temperature and column ozone has been successfully modelled in a two dimensional dynamical/chemical model by the introduction of a parametrization scheme to model the transfer of momentum to the zonal flow associated with the damping of vertically propagating Kelvin and Rossby-Gravity waves. The largest anomalies in column ozone of approximately 20 DU are present at high latitudes. The equatorial ozone QBO is out of phase with the mid- and high latitude ozone QBO, in good agreement with observations.

1 Introduction

The presence of a quasi-biennial oscillation (QBO) in zonal winds, temperature and column ozone in the equatorial stratosphere is well known (Reed 1960, Veryand and Ebdon 1961, Wallace 1973, Angell and Korshover 1978, Coy 1979, Tolson 1981, Hasebe 1983, Naujokat 1986). The largest amplitudes of the ozone QBO, however, are found in high latitudes and this must be allowed for in any explanation of the increasing depletion of ozone in the southern polar spring during the 1980's (Bojkov 1986, Garcia and Solomon 1987). We describe a simulation of the QBO in a two-dimensional model which extends from pole to pole and includes a comprehensive photochemical scheme. We are therefore able to investigate the effects of the equatorial QBO on the extra-tropical dynamics of the model and the relationship between the dynamical QBO and the distribution of ozone.

2 The Model

The two-dimensional model of Harwood and Pyle (1975,1977,1980) was employed in the study. The model configuration is essentially the same as that employed by Gray and Pyle (1987a), hereafter referred to as GP, except that the improved 'wide-band' radiation scheme developed by Haigh (1984) has been used. This has resulted in a much deeper and stronger Hadley circulation in the equatorial lower stratosphere. (Note that, in this respect the present model differs from that described by Gray and Pyle 1987b). The parametrization scheme to model the Semi-Annual Oscillation (SAO) developed in GP was retained in the present runs but the gravity wave breaking parametrization was omitted.

The zonal wind QBO has been modelled by including the momentum deposition associated with thermally dissipating Kelvin and Rossby-Gravity waves. A WKB approximation is used to derive an expression for the mean flow acceleration: $\frac{d\bar{u}}{dt} = Aexp(\frac{z-z_0}{H})R(z)exp(-P(z))$ where $R(z) = \frac{\alpha(z)N}{k(\bar{u}-c)^2}$ and $P(z) = \int_{z_0}^{z} R(z')dz'$ (Lindzen and Holton 1968). A is the vertical momentum flux at z_0 (=16 km), $\alpha(z)$ is the thermal damping rate, N is the Brunt-Vaisala frequency and k is the zonal wavenumber. The equation was solved with parameter values appropriate to the Kelvin and Rossby-Gravity waves shown in the table below. Note that two Kelvin waves were forced which were identical apart from their phase speeds. The mean flow acceleration associated with the faster phase speed c=60 ms^{-1} occurs at higher levels in the modelled atmosphere and gives rise to the westerly phase of the SAO. The damping of the waves has been restricted to thermal damping, as in the SAO parametrization of GP; above 30 km the damping rate $\alpha(z)$ was chosen to be the 'slow' damping rate of Dunkerton (1979) which peaks at approximately $2x10^{-6}$ s^{-1} at 50 km; below this level a constant value of $0.35x10^{-6}$ s^{-1} was specified. Although no mechanical damping was explicitly employed in the QBO parametrization scheme, the model includes a vertical diffusion operating on the model wind fields with a constant value of k_{zz} = 1.0

m^2s^{-1} at all latitudes and heights. A gaussian distribution about the equator was applied to the forcing associated with the two types of waves, with an e-folding width $Y_L = (\frac{2\nu}{k\beta})^{\frac{1}{2}}$ for the Kelvin waves and $Y_L = (\frac{2\nu}{\beta(\frac{\beta}{\nu}-k)})^{\frac{1}{2}}$ for the Rossby-Gravity waves where $\frac{\beta}{\nu} = c$ (Holton 1975). All other symbols have their usual meaning and an overbar denotes a zonal average. The parametrized forcing associated with the Kelvin and the Rossy-Gravity waves were both present at all times of the modelled year.

	Kelvin Wave		Rossby-Gravity Wave
Zonal wavenumber	1		4
phase speed (ms^{-1})	+25	+60	-25
A, amplitude of vertical momentum flux at z_0 (m^2s^{-1})	12.5×10^{-3}	3.5×10^{-3}	15.0×10^{-3}

3 The QBO in Zonal Wind

The time-height section of the zonal wind at the equator from a model run that included both the QBO and SAO parametrizations is shown in figure 1. Four periods of the QBO are evident. The semi-annual oscillation is dominant above 35 km and the QBO is the dominant signal between 10 and 30 km, in good agreement with observational data. Both phases of the QBO exhibit a gradual descent with time (at an average rate of just over 1 km per month); the amplitude of the modelled QBO is a maximum at approximately 25 km where the winds vary between 20 ms^{-1} and -18 ms^{-1}. Thermal wind balance is maintained against thermal dissipation in the model by the development of a meridional circulation with adiabatic heating (cooling) in the cold (warm) region associated with upward (downward) motion (Reed 1964, Plumb and Bell 1982). Therefore, the direction of the induced circulation depends upon the phase of the QBO. During a westerly (easterly) phase descending (ascending) motion is present at the equator, just below the level of maximum wind shear, with rising (sinking) motion at mid-latitudes. The direct forcing of the zonal wind in the model due to the damping of vertically propagating equatorial waves is restricted to latitudes less than about 20 degrees from the equator; however, changes to the modelled atmosphere, particularly in the amount of the ozone column, occur further poleward of this as a result of the induced meridional circulation.

4 The QBO in Ozone

Observations of large ozone reductions in high southern latitudes during Spring (Farman et al., 1985) make the understanding of the latitudinal variation of the ozone QBO particularly important. Garcia and Solomon (1987), for example, have speculated that the QBO is relevant to the understanding of the temporal variation of the springtime column ozone in southern polar latitudes during the 1980's.

The photochemical time constant of ozone decreases with increasing altitude and generally, at any given height, with decreasing latitude. With a lifetime of hours in the upper stratosphere ozone is expected to be close to its steady state value. On the other hand, the ozone concentration in the polar lower stratosphere can be far from its equilibrium value since the photochemical time scale is long in that region and dynamics exerts a major influence. Between these two regions is a portion of the atmosphere where dynamical and photochemical time scales are roughly comparable. It is the morphology of this transition region that defines the ozone budget and distribution. The strength of the lower stratosphere circulation is a crucial parameter in a successful model simulation of the ozone distribution.

Figure 2 shows the time-series of ozone anomaly from the model run (the monthly mean has been subtracted from each point). A prominent QBO signal is present at all latitudes. The largest anomaly is in high latitudes, reaching 20 Dobson Units in some cases. A phase reversal is present at approximately 20 degrees latitude so that high latitude anomalies are out of phase with the equatorial anomalies. There is no evidence for in-situ photochemical control of the high latitude ozone anomaly. This is not suprising given that the photochemical constant of ozone is long there. None of the radicals involved in ozone photochemistry, including OH, HO_2, NO and NO_2, show significant biennial variations in high latitudes.

The overall behaviour of the modelled ozone QBO compares favourably with the zonally averaged observations of the QBO derived by Hasebe (1983) using SBUV data. In agreement with observations the positive ozone anomalies occur at approximately the same time as the westerly phase of the equatorial zonal wind QBO at 50 mb (see figure 2).

The modelled QBO in column ozone arises as a result of the interaction of dynamics and photochemistry in the following sequence of events. The equatorial zonal wind QBO give rise to a rising and sinking motion at the equator as already described. Hence, during a westerly phase the strength of the equatorial ascent of the Hadley cell is reduced and during an easterly phase it is enhanced. During an easterly phase the enhanced upward motion lowers the ozone column by reducing the lower stratosphere mixing ratios, since the mixing ratio profile increases with altitude; conversely, during a westerly phase downward motion increases the ozone column by advecting higher mixing ratios into a region where the photochemical lifetime is long. Thus during a westerly (easterly) phase a positive (negative) equatorial ozone anomaly will result.

The induced circulation is also responsible for the high latitude QBO in ozone. During a westerly phase of the QBO the induced downward motion at the equator implies an upward motion in the subtropics which opposes the Hadley circulation. The latitudinal extent of the induced circulation is restricted to the subtropics, however (Plumb 1982), so that it cannot directly transfer an ozone anomaly to high latitudes. Nevertheless, the descending arm of the Hadley cell extends to mid-latitudes and crosses the transition region from photochemical to dynamical control of the ozone distribution. Hence, for example, a suppression of the strength of the Hadley circulation during a westerly phase of the QBO results in a negative anomaly in mid-latitudes (not just in the subtropics). The ozone anomaly is then transferred further poleward by eddy motions (this is opposed by the mean motion and hence the distribution of ozone at high latitudes is determined by the balance between eddy and mean motion - see for example, Harwood and Pyle (1977) and Haigh (1984)).

The high latitude column ozone anomaly maxima in the two hemispheres of the run are displaced by several months; they tend to occur in spring/early summer and coincide with the column ozone maxima. This compares well with observations and arises in the model because the phase of the modelled QBO in column ozone tends to reverse during April/May of each year. Because of the direction of the mean circulation in the following months the ozone anomaly is immediately evident in the southern hemisphere mid-latitudes and this is then transferred to higher latitudes via eddy transfer (which is strongest in winter months). The corresponding anomaly maximum does not occur in the northern hemisphere until six months later when the direction of the mean circulation has reversed in direction.

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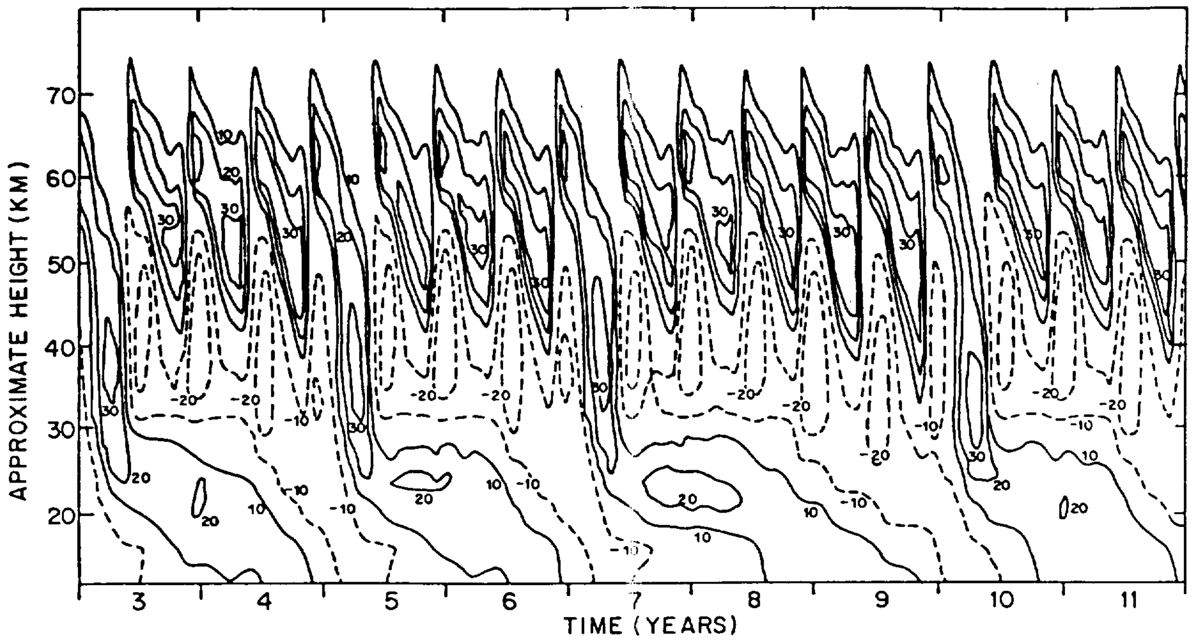

Figure 1: Time-height section of zonal wi.ds (ms^{-1}) at the equator

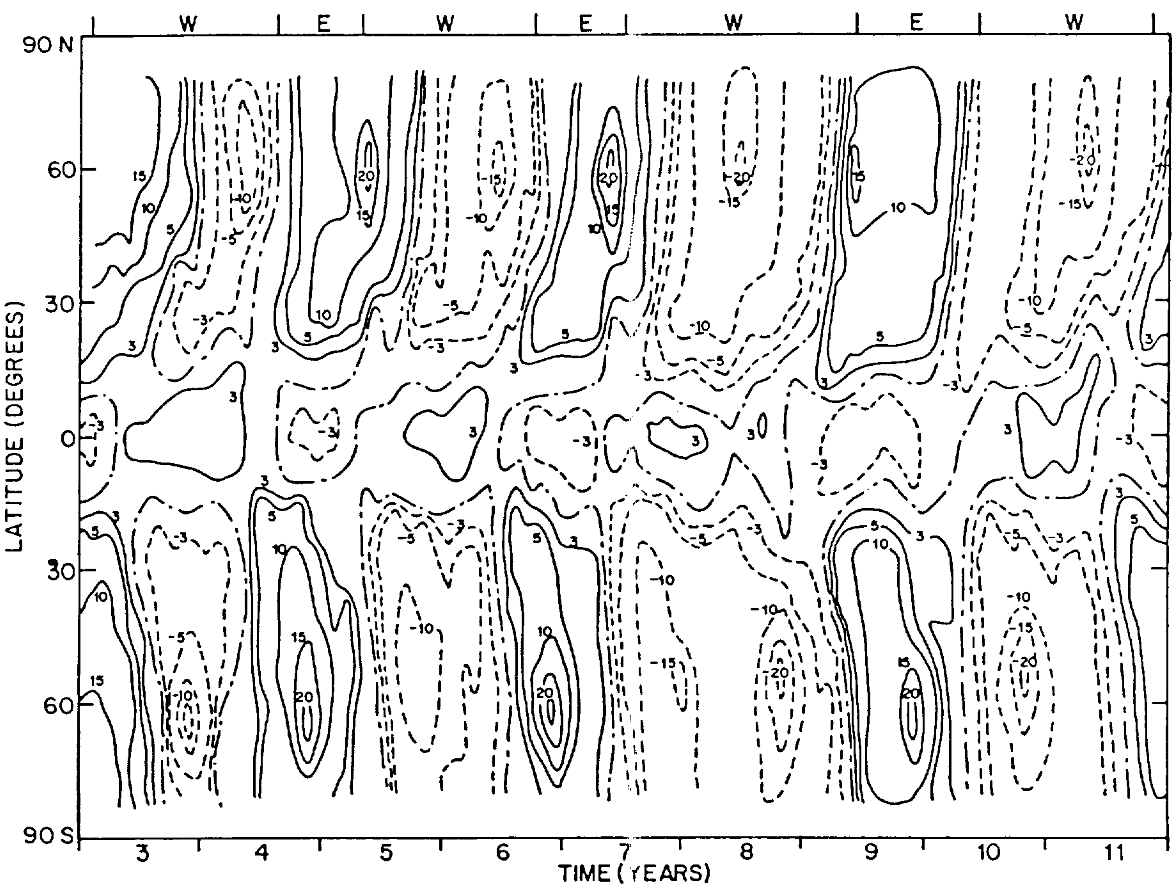

Figure 2: Latitude-time section of column ozone anomaly (Dobson Units). The monthly mean has been subtracted from each point. The direction of the equatorial wind at 50mb is also indicated.