Ozone feedback stabilizes the quasi-biennial oscillation against volcanic perturbations

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Received 23 August 2001; revised 17 January 2002; accepted 18 January 2002; published 10 April 2002.

[1] Possible interference by volcanic aerosols with downward propagating quasi-biennial oscillation (QBO) in the equatorial stratosphere has been studied by using a mechanistic model that incorporates the feedback of ozone through short wave absorption. The ascending motion driven by the radiative heating due to volcanic aerosols could be combined with the QBO-induced upward motion to block the descent of the easterly shear zone of the QBO when the ozone feedback is not taken into account. However, as the ozone concentration in the cold easterly shear zone is relatively low and the aerosol-driven vertical ozone advection makes its concentration still lower, the negative anomalies of solar heating due to perturbed ozone compensate for the aerosol-induced diabatic heating. Thus the interactions between dynamics and radiation intermediated by the ozone feedback play an important role in stabilizing the time evolution of the QBO against perturbations by volcanic aerosols. *INDEX TERMS:* 3332 Meteorology and Atmospheric Dynamics: Mesospheric dynamics; 3359 Meteorology and Atmospheric Dynamics: Radiative processes; 0370 Atmospheric Composition and Structure: Volcanic effects (8409)

1. Introduction

[2] The quasi-biennial oscillation (QBO) in the equatorial stratosphere has prompted much scientific interest due to its peculiar periodicity and long-lasting super rotation over the equator since its discovery in the early 1960s [*Reed et al.*, 1961; *Veryard and Ebdon*, 1961]. The zonal wind in the middle and lower stratosphere alternates its direction with the period of about two years exhibiting a gradual descent of wind regimes [e.g., *Wallace*, 1973; *Baldwin et al.*, 2001]. It is understood as driven by the interaction between the vertically propagating waves and the mean flow as originally proposed by *Lindzen and Holton* [1968] and *Holton and Lindzen* [1972] (hereafter referred to as HL72). The thermal wind relationship, that still holds quite close to the equator due to the long time scale and equatorial symmetry of the QBO, requires temperature oscillation together with the wind oscillation. That is, there should be warm (cold) anomalies associated with westerly (easterly) shear of the zonal wind. Such temperature anomalies suffer from radiative damping, which further requires compensating adiabatic heating by mean vertical motion to maintain the QBO [*Reed*, 1964; *Plumb and Bell*, 1982]. The secondary mean meridional circulation thus predicted is visualized by the modification of aerosol distributions [*Trepte and Hitchman*, 1992].

[3] Stratospheric minor constituents such as ozone are also affected by the dynamical QBO. Since the ozone mixing ratio exhibits a strong vertical gradient, the QBO-induced vertical motion drives the ozone QBO due to vertical advection in the lower stratosphere where ozone is controlled by dynamical motion [*Dunkerton*, 1983; *Hasebe*, 1984; *Ling and London*, 1986]. However, the observed phase relationship between wind and ozone QBOs disproves this interpretation [*Hasebe*, 1994]. The discrepancy is hypothetically resolved by introducing an ozone feedback, in which short wave diabatic heating due to QBO-perturbed ozone modifies the secondary mean meridional circulation to realize an in-phase relationship between temperature and ozone [*Hasebe*, 1994]. Although the validity of this hypothesis is still under debate [*Li et al.*, 1995; *Huang*, 1996], some additional mechanism must be sought to understand the equatorial ozone QBO.

[4] The QBO is characterized by interesting irregularities in its period of oscillation. It is known that the phase propagation is occasionally suspended to result in a "ledge" in the time-height section of the zonal wind. One of the mechanisms that cause such suspension could be an anomalous heating due to aerosols injected by large volcanic eruptions [*Dunkerton*, 1983]. This idea is based on the fact that the diabatic heating due to aerosols drives upward motion that could be strong enough to block the downward phase propagation of the QBO. Based on HL72-type mechanistic model calculations, *C. Marquardt, private communication* [1992] (hereafter referred to as M92) and *Marquardt* [1997] showed that the downward phase propagation of the QBO is blocked by forced diabatic heating when it is introduced in the easterly shear zone as in the case of Mt. Pinatubo eruptions while there is scarcely no change in the westerly shear case corresponding to El Chichón. These results are consistent with the observed wind QBO. On the other hand, *Kinne et al.* [1992] pointed out that the volcanically forced upward motion should reduce ozone mixing ratio due to vertical advection, and that this could "buffer" the upward motion due to reduced ozone heating in the lower stratosphere.

[5] The purpose of the present study is to explore the influence of the ozone feedback in stabilizing the time evolution of the QBO against volcanic perturbations by using a simple mechanistic model.

2. Model Description

[6] Following *Dunkerton* [1983] and M92, the HL72 model has been modified to include the vertical advection of zonal momentum in addition to the originally incorporated wave driving due to Eliassen-Palm flux divergence and vertical diffusion:

$$\frac{\partial u_B}{\partial t} + w_B \frac{\partial u_B}{\partial z} = -\frac{1}{\rho_0}\frac{\partial}{\partial z}(F_K + F_R) + K\frac{\partial^2 u_B}{\partial z^2}, \tag{1}$$

where u and w are the zonal and vertical velocity components, respectively, $\rho_0(z)$ basic state density, F_K and F_R the vertical component of EP flux due to Kelvin and mixed Rossby-gravity waves, respectively, K the diffusion constant, and the suffix B denotes the QBO component.

[7] The temperature QBO is derived from the thermal wind relationship formulated on the equatorial β-plane. With an additional assumption that the meridional structure of the wind and temperature QBO is modeled in Gaussian form, the thermal wind relationship reduces to the following formula [*Hasebe*, 1994]:

$$\theta_B = -\frac{k^2\Omega}{a}\frac{\partial u_B}{\partial z}, \tag{2}$$

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where k is the meridional scale of the QBO, Ω the earth rotation, a the earth radius, and θ the buoyancy acceleration defined by RT/H, where R is the gas constant for dry air, T temperature, and H the scale height.

[8] The ozone feedback is modeled in the same manner as in *Hasebe* [1994]. The vertical motion is described by the thermodynamic equation that states the balance between adiabatic and diabatic heating. The latter is set to include those by QBO-perturbed ozone and volcanically injected aerosols in a linearized form in addition to the IR Newtonian cooling:

$$w_B N^2 = -h\theta_B + S\chi_B + \varepsilon\chi_V, \tag{3}$$

where N is the Brunt-Väisälä frequency, h the Newtonian cooling coefficient, χ the ozone mixing ratio, χ_V the non-dimensional aerosol perturbation, and S and ε the heating coefficients.

[9] The continuity equation of ozone includes photochemistry, linearized with respect to ozone and temperature, in addition to the dominating vertical advection of the basic state ozone:

$$\frac{\partial\chi_B}{\partial t} + w_B\chi_{0z} = \Gamma\chi_B + \alpha\theta_B, \tag{4}$$

where $\chi_{0z}(z)$ is the vertical gradient of the basic state ozone mixing ratio, and Γ and α the photochemical coefficients.

[10] The time evolution of aerosols represented in non-dimensional form is described by the continuity equation expressed as follows:

$$\frac{\partial\chi_V}{\partial t} + \left(w_A + w_B + w_f\right)\frac{\partial\chi_V}{\partial z} = K_V\frac{\partial^2\chi_V}{\partial z^2} - \frac{1}{\tau}\chi_V, \tag{5}$$

where w_A and w_f are the aerosol's annual and fall-out velocity components, respectively, K_V the vertical diffusion coefficient for aerosols, and τ denotes chemical e-folding time.

[11] The lower and upper boundaries are taken to be 17 and 45 km, respectively, with the condition $u_B \equiv 0$ at the boundaries. The following formulae are used:

$$h = \begin{cases} \left(1 + \frac{2(z-18\ \mathrm{km})}{18\ \mathrm{km}}\right) \times 4.67\times10^{-2}\ \mathrm{day}^{-1} (17\ \mathrm{km} \le z \le 35\ \mathrm{km}), \\ \left(1 + \frac{2(35-18\ \mathrm{km})}{18\ \mathrm{km}}\right) \times 4.67\times10^{-2}\ \mathrm{day}^{-1} (35\ \mathrm{km} \le z \le 45\ \mathrm{km}), \end{cases} \tag{6}$$

$$w_A = \left(3 + \sin\frac{2\pi t}{1\ \mathrm{year}}\right) \times 10^{-4}\ \mathrm{m\ s^{-1}}. \tag{7}$$

The analytical forms of F_K and F_R are taken from HL72. Vertical profiles of S, χ_{0z}, Γ, and α are taken from *Ling and London* [1986] with extrapolations. The numerical values of other parameters are listed with the sources of reference in Table 1.

Table 1. Numerical Values of the Model Specific Parameters

c_K	25 m s^{-1}	*Wallace-Kousky* [1968]
c_R	-23 m s^{-1}	*Yanai-Maruyama* [1966]
K	5×10^{-1} m^2 s^{-1}	modified from HL72
A_R	$-5 \times 10^{-3}\ \rho_0(17)$ m^2 s^{-2}	modified from HL72
H	6.7 km	*Ling-London* [1986]
ε	1×10^{-7} m s^{-3}	modified from M92
w_f	-2.8×10^{-4} m s^{-1}	*Mote et al.* [1996]
K_V	3×10^{-2} m^2 s^{-1}	*Mote et al.* [1996]
τ	2000 days	modified from M92

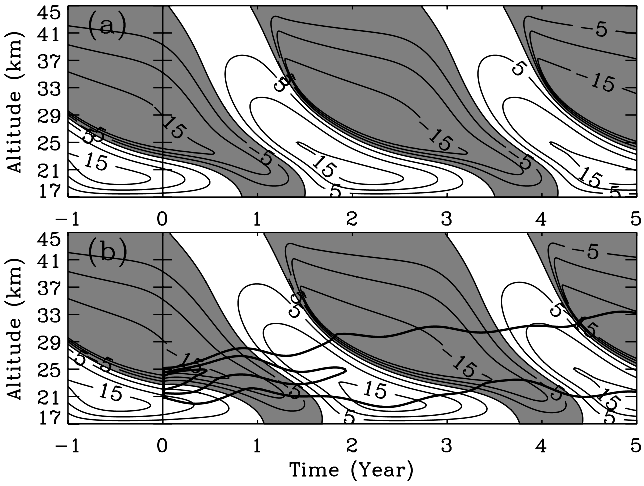

Figure 1. Time-height sections of the simulated zonal wind in case the ozone feedback is not taken into account. Easterlies are shaded. The contour interval is 5 m s^{-1}. Top: control run without aerosol injection, bottom: perturbation run with aerosol injection in the easterly shear zone at 23 km. Thick contours are the non-dimensional aerosol amount with values 1/e, 1/10, and 1/100 from the center of injection.

3. Results

[12] Figure 1 illustrates the time-height sections of zonal wind for the cases where the ozone feedback is switched off by setting $S = 0$ in Equation (3). The contour interval is 5 m s^{-1} with shades for easterlies. As seen from Figure 1a, the model without aerosols simulates the QBO reasonably well. The aerosols are injected at time 0 with the Gaussian shape in the vertical direction centered at 23 km (Figure 1b). The seasonal march is set to coincide with Northern summer at the time of aerosol injection while the altitude profile is chosen to mimic the one observed just after the Mt. Pinatubo eruptions [*Winker and Osborn*, 1992]. The thick lines are the contours of non-dimensional aerosols specifying the values 1/e, 1/10, and 1/100 from the center of injection to outwards. When the injection layer overlies the easterly shear zone as in Figure 1b, the

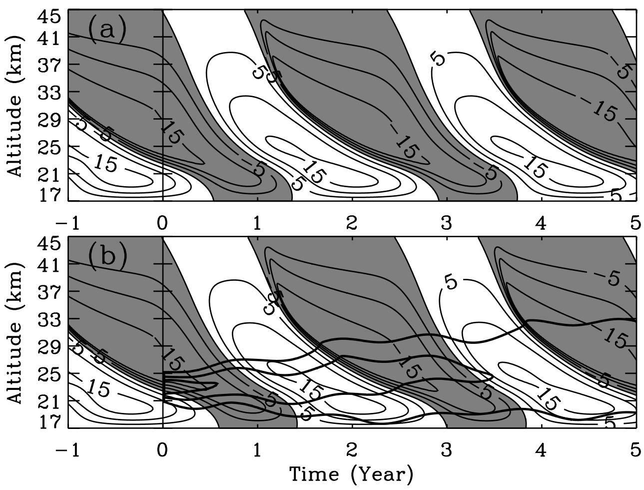

Figure 2. The same as Figure 1 but for the cases where the ozone feedback is functioning.

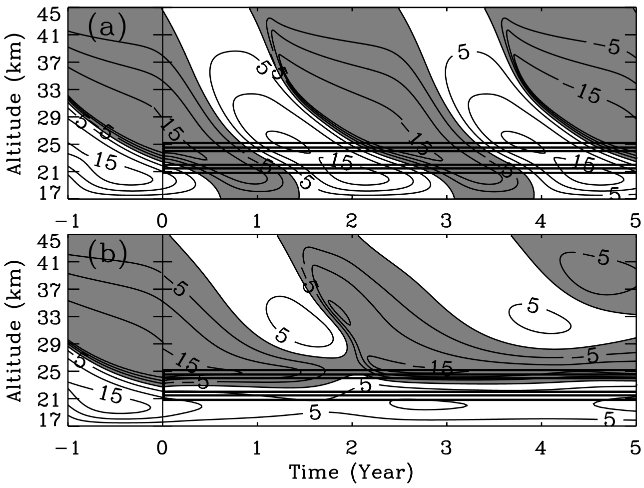

Figure 3. The same as Figure 1b (bottom) and Figure 2b (top) but for the cases where the aerosol amount is fixed with respect to time.

downward phase propagation shows a pause while the aerosols are lifted by self-induced and QBO-driven upward motion. The elongation of the lower-stratospheric westerly resume is consistent with those obtained by M92.

[13] Figure 2 shows the similar results but for the cases with the ozone feedback turned on. As this feedback systematically reduces the magnitude of westerly acceleration due to mean flow, the westerly (easterly) regime propagates slightly slower (faster) in case of Figure 2a as compared to that of Figure 1a. The simulated amplitude of w_B, roughly 0.1 mm s^{-1}, and a slight uplift of χ_V agree reasonably well with observations [*Niwano and Shiotani*, 2001; *Kinne et al.*, 1992]. In contrast to the cases of no ozone feedback, the downward phase propagation continues without interrupted. This result remains unchanged when vertical aerosol advection is not modeled as in M92 (not shown). Thus the ozone feedback has an important role in stabilizing the phase propagation of the QBO under the conditions perturbed by volcanic aerosols.

[14] When the aerosols are injected into the westerly shear zone, however, both simulations with and without ozone feedback do not show significant modification of the QBO. To overcome some ambiguity that could arise from possible oversimplification in our parametrization, model runs are extended to extreme cases in which the aerosol amount does not show any decay but remains fixed with respect to time. The results are shown in Figure 3, where the top and bottom are the cases with and without ozone feedback, respectively. When the ozone feedback is taken into account (top), the effect of aerosol injection is almost negligible. However, in case it is cut, the easterly regime of the QBO no longer reaches the bottom boundary causing the failure of the QBO simulation in the lower stratosphere.

4. Concluding Remarks

[15] One dimensional QBO model by *Holton and Lindzen* [1972], extended to include vertical advection of mean zonal momentum, has been used to explore the role of the ozone feedback [*Kinne et al.*, 1992; *Hasebe*, 1994] in acquiring the robustness for the QBO against perturbations by volcanic aerosols. A series of model runs indicates that the diabatic heating by aerosols in the easterly shear zone could interrupt the downward phase propagation of the QBO if the ozone feedback is not taken into account. However, the ozone feedback nearly eliminates the heating effect of volcanic aerosols, demonstrating the importance of the interactions between dynamics and minor constituents. One of the limitations of the present simulations is that the ozone depletion due to heterogeneous reactions on the aerosol surface is not modeled. However, the results are expected to remain nearly the same since such an effect would only strengthen the ozone feedback. Much sophisticated model experiments are under way by using a general circulation model that incorporates full interactions between radiation, dynamics and chemistry. The results will be published when complete.

[16] **Acknowledgments.** The results presented in this article are based on the Bachelor of Science Thesis of RT submitted to Ibaraki University. Discussions with T. Uetake and comments from M. Shiotani, C. Marquardt and M. Takahashi are greatly appreciated.

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