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Effects of the eruption of Mount Pinatubo on the quasi-biennial oscillation as revealed with MRI chemistry-climate model

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Introduction

The equatorial quasi-biennial oscillation (QBO) is characterized by interesting irregularities in its period of oscillation. One possible perturbation that causes such irregularities is a large increase in aerosol abundance following a large volcanic eruption. The idea is based on the fact that the diabatic heating due to volcanic aerosols drives upward motion that could be strong enough to block the downward phase propagation of the QBO, especially in the easterly shear zone (e.g. Dunkerton, 1983). Several studies have been made on this mechanism with simple mechanistic-models (e.g. Tanji and Hasebe, 2002), but very few experiments with much sophisticated model have been made. In this study, the influence of the eruption of Mount Pinatubo on the middle atmosphere, especially the equatorial QBO, is investigated by using a coupled chemistry-climate model of Meteorological Research Institute (MRI-CCM) that reproduces internally generated QBO and incorporates full interactions between radiation, dynamics and chemistry in the middle atmosphere.

MRI Chemistry-Climate Model (MRI-CCM)

Dynamical module ☞ MRI/JMA98 GCM (Shibata et al., 1999)

Chemistry module ☞ full chemistry including 3 heterogeneous reactions on sulfate aerosols, and transport process (hybrid semi-Lagrangian scheme) (Shibata et al., 2005)

Resolution ☞ T42 (64x128 Gaussian Grids: 2.8 deg)
eta-ordinate (Surface to 0.01hPa)
68 layers (Δz = 500m from 100 to 10hPa)

Non-Orographic Gravity Wave Drag ☞
Hines (1997) parameterization with enhanced perturbation source in the tropics (30S-30N) by superimposing a Gaussian-function source (0.7m/s) on the isentropic source (2.3m/s)

Radiative Feedbacks to the dynamical module ☞ O_3, N_2O, CH_4

Experiments

Using the MRI-CCM, we performed 5-member ensemble run (Figure 1) under CCMVal REF1 scenario from ∼1980 to 2004 (Table 1). The REF1 scenario takes into account two major volcanic eruptions (El Chichon in 1982 and Pinatubo in 1991) by prescribing the observed surface area densities (Figure 2), effective radius and optical thickness of volcanic and background aerosols. The observed GHGs, CFCs, sea surface temperature (SST) and solar variability are also prescribed in the snenario.

Table 1. CCMVal REF1 Scenario (REPRODUCING THE RECENT PAST: 1980-2004)

Scenario	Period	GHG	Halogen (CFCs)	SSTs	Volcanic Aerosol	Solar Flux	QBO
REF1	1980-2004	Based on IPCC (2001)	Used for WMO/UNEP 2002 runs	HadISST1	Jackman et al. (1996)	Lean et al. (1997)	Internally generated

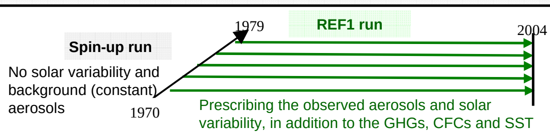

Figure 1. Schematic of the 5-member ensemble run under the REF1 scenario

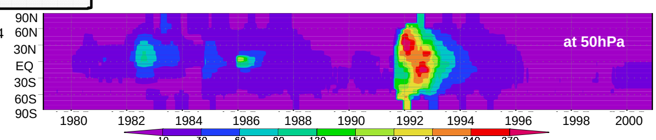

Figure 2. Prescribed zonal-mean surface area densities of sulfate aerosols (10^9 cm^2/cm^3) on theREF1 run

The following three heterogeneous reactions on sulfate aerosols are incorporated in the MRI-CCM.

$ClONO_2 + (H_2O)_l \rightarrow HOCl + HNO_3$

$N_2O_5 + (H_2O)_l \rightarrow 2\,HNO_3$

$BrONO_2 + (H_2O)_l \rightarrow HOBr + HNO_3$

Results

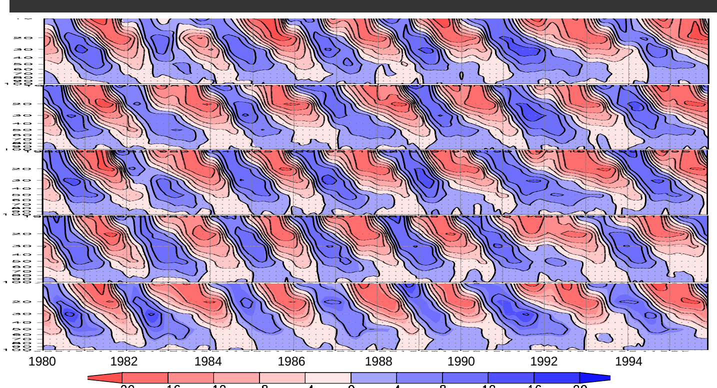

Figure 3. Modeled time series of the zonal-mean zonal wind for each 5-ensemble run averaged between 15S-15N from 100 to 10 hPa. Linear trend, annual cycle, solar and ENSO terms are removed with a linear multiple regression.

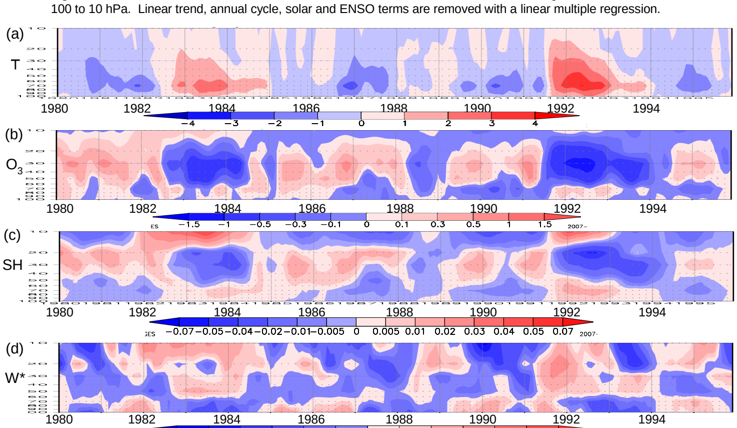

Figure 4. Modeled ensemble-mean time series of the zonal-mean temperature [T] (K) (a), ozone [O_3] (mPa) (b), short wave heating rate [SH] (K/day) (c), and residual vertical velocity [W*] (m/s) (d) averaged between 15S-15N from 100 to 10 hPa. Linear trend, annual cycle, solar and QBO terms are removed with a linear multiple regression.

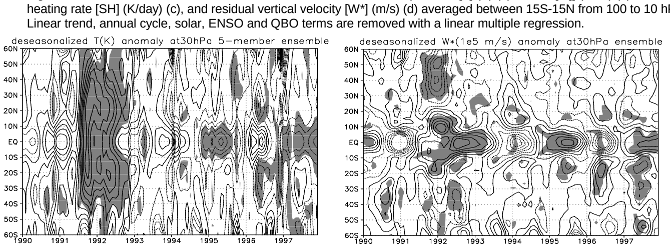

Figure 5. Modeled ensemble-mean time series (1990.01-1997.12) of the zonal-mean temperature anomaly (K) (left) and residual vertical velocity (W*) anomaly (×10^5 m/s) (right) at 30hPa. Shading denotes regions where the anomalies are larger than the 2σ levels of the standard deviations of the 5-member ensemble run.

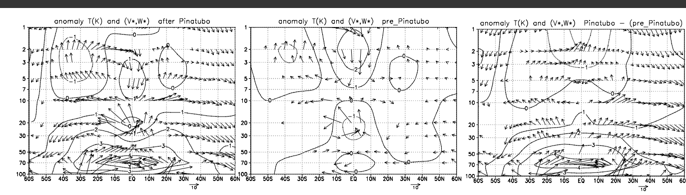

Figure 6. Latitude–height cross section of 5-member composites of temperature anomaly (contour) and residual mean meridional velocity anomaly (arrow) averaged for 3 months (left), wherein the central day is the first transition day from westerly to easterly zonal-wind in the tropics at 30hPa after the Pinatubo volcanic eruption in June, 1991 ("Pinatubo" composites). The composites of the "pre-Pinatubo" eruption (1985.01-1990.12) (middle) and the differences between the "Pinatubo" and "pre-Pinatubo" composites (right) are also shown.

Momentum Budgets

$$\partial U/\partial t + v^*[(a\cos\phi)^{-1}(u\cos\phi)_\phi - f] - X = +(\rho_0 a\cos\phi)^{-1}(\nabla\cdot F) + \text{(unresolved) GWD} - w^*\partial U/\partial z$$

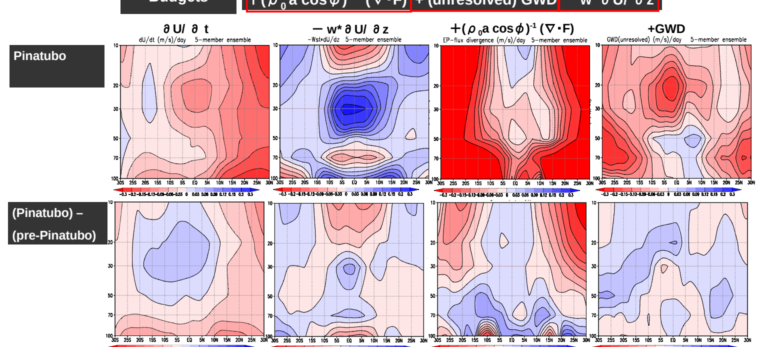

Figure 7. Same as Figure 6, but for the dU/dt, −W* dŪ/dz, (ρa cos ϕ)$^{-1}$∇・F, and unresolved gravity wave drag (GWD). The upper panels show their "Pinatubo" composites, while the lower panels show the differences between the "Pinatubo" and "pre-Pinatubo" composites. The unit is in ms^{-2}.

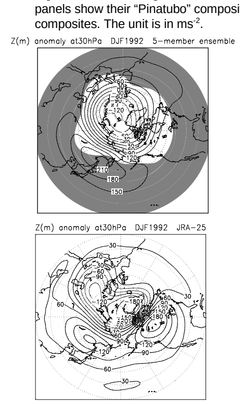

Figure 8. Modeled ensemble-mean geopotential height anomaly (m) at 30 hPa in the NH (20N-90N) averaged for DJF 1991/1992 (upper) and that of JRA-25 reanalysis (lower). Shading in the upper panel denotes regions where the anomalies are larger than the 2σ levels of the standard deviations of the 5-member ensemble run.

Summary

- The possible influence of major volcanic eruptions on the stratospheric QBO is investigated. Ensemble scenario run for reproducing the recent past is performed by using the full coupled chemistry-climate model of MRI (MRI-CCM) which reproduces internally generated QBO.
- The simulated ensemble run shows that after the Pinatubo eruption the modeled downward propagation of the phase of zonal-wind is slower and frequently suspended in the easterly shear zone with the elongation of the period of its oscillation by several∼10 months.
- Multiple regression and composite analyses show that the anomalous net diabatic heating after the Pinatubo eruption in the tropical stratosphere significantly enhances W*, with the increase of westerly momentum upward advection to result in westerly zonal wind acceleration in the easterly shear zone. On the other hand, gravity wave drag have slightly reversal effect to this.
- The enhanced W* in the tropical stratosphere by the Pinatubo eruption promotes the compensating downward residual circulation for the first winter after the Pinatubo eruption, especially in the northern mid-latitudes.