Stratospheric aerosols from major volcanic eruptions: QBO impact on the aerosol cloud dispersal and optical depth

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Abstract

Explosive volcanic eruptions, by injecting considerable amount of particles and sulfur gases above the tropopause, can cause large increases in stratospheric aerosol mass concentration and optical depth. This is particularly true for tropical eruptions, because the efficient confinement of atmospheric tracers in the tropical pipe tends to prolong the aerosol residence time into the stratosphere. The amount of time it takes for the aerosol cloud to disperse in the extra-tropics varies because of several factors, for examples: (a) the modulation of stratospheric dynamics produced by the quasi-biennial oscillation (QBO) of the equatorial winds, (b) time of the year, location and altitude of SO_2 injection, (c) the aerosol radiative feedback on the stratospheric circulation. The latter takes place both directly in solar near-infrared and planetary radiation wavelengths and also indirectly through induced photochemical ozone changes and ozone absorption of aerosol diffused UV radiation. The QBO may strongly influence how effectively the aerosols can be transported out of the tropics, as well as the magnitude of tropical upwelling. All major volcanic eruptions from 1960 to 2000 have been considered in a numerical study conducted with the composition-climate coupled model ULAQ-CCM. This is a chemistry-climate model with on-line a microphysics code for aerosol formation and growth (including SO_x chemistry and explicit gas-particle interactions). Model results are compared between two different simulations: (a) the first including the aerosol radiative effects and the observed phase of the QBO (VE); (b) the second where the nudged QBO has been shifted ahead of one year, thus allowing for all the volcanic eruptions to take place under a different QBO phase (VQS). VQS-VE differences highlight the QBO phase importance in regulating the aerosol confinement in the tropical pipe; this effect is also visible in comparing the aerosol cloud dispersal in the VE case, for eruptions taking place in different QBO regimes. The impact on the aerosol cloud e-folding time and optical depth is discussed for major tropical eruptions (Agung, El Chichón and Pinatubo), and for a smaller one (Ruiz).

Experiment setup

Eruption	Time	Tg-SO_2	QBO E/W shear
Agung (8S,11E)	16 May 1963	12	W
El Chichón (17N,93W)	4 April 1982	7	W
Nevado del Ruiz (5N,75W)	13 Nov 1985	1.2	E
Pinatubo (15N,120E)	16 June 1991	20	E

The model has been run for a total of 30 time-dependent simulations from 1960 to 2000. Of these experiments, 10 (REF) do not include the volcanic aerosols, except in the heterogeneous chemistry code, in order to isolate the radoative effects. 10 (VE), include the aerosol radiative effect and the observed QBO, while the last 10 (VQS) include the aerosol radiative effect, but the QBO is shifted by 1 year in order to change the phase in which the eruption happens.

Lower stratospheric dynamical anomalies

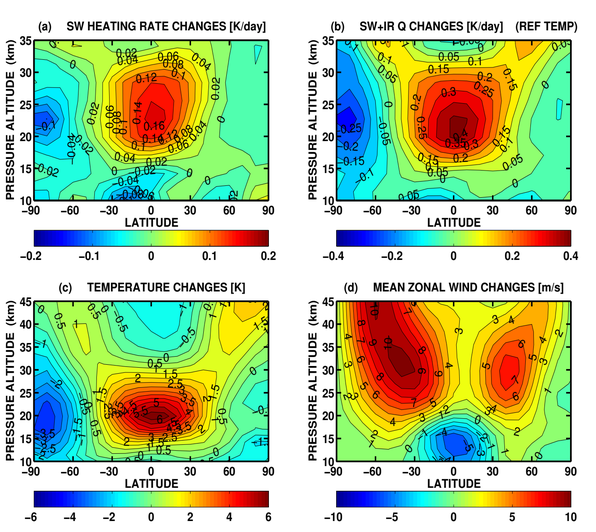

Fig. 1 ULAQ-CCM-calculated mean zonal anomalies due to the Pinatubo aerosols (VE-REF), during September˙October˙November 1991: (**a**) solar heating rates (K/day); (**b**) total heating rates, *i.e.*, solar + longwave ("instantaneous" value with fixed REF temperatures) (K/day); (**c**) temperatures (K); (**d**) zonal winds (m/s).

Fig. 1 summarizes the radiative-dynamical anomalies after the Pinatubo eruption (Sept-Oct-Nov 1991), as calculated in the ULAQ-CCM (VE-REF). The heating rate anomaly is shown in the top two panels: the solar component (**Fig. 1a**) is due to direct aerosol absorption in the NIR wavelengths and O3 absorption of the upward diffused radiation in the UV-VIS wavelengths. It is displaced somewhat above the longwave component, whose maximum is located closer to the temperature minimum in the region above the tropical tropopause layer (TTL). The latter component ("instantaneous" value with fixed REF temperatures) is summed up with the solar one in **Fig. 1b**, to show the total aerosol diabatic perturbation. The maximum heating rate change VE-REF is calculated to be approximately 0.3 K/day, in the 20–25 km altitude layer between 15˚S˙15˚N latitude. While the tropical stratosphere is warmed by the volcanically enhanced stratospheric aerosol, the tropical upper troposphere cools as a result of increased aerosol scattering of incoming solar radiation

The negative south polar anomaly of the diabatic heating rates is due to additional O3 depletion on enhanced surface area density of PSCs, produced by dynamical cooling (decreased horizontal eddy heat fluxes at mid–high latitudes). An average 3–4 K temperature increase (**Fig. 1c**) is predicted during the fall months of 1991 in the 30–50 hPa layer over the tropics. Observations collected in Labitzke and McCormick, 1992 have shown a ~30% smaller warming, with respect to June–July 1991 mean values. The temperature anomaly in **Fig. 1c** induces a significant increase of westerly winds from the thermal wind equation, with peaks at mid-latitudes in the mid-stratosphere (**Fig. 1d**).

QBO oscillations and aerosol transport

During years with dominant E shear, the streamlines of the circulation anomaly caused by the QBO show definite upwelling motion extended everywhere in the tropical stratosphere. During years with dominant W shear, descent relative to the mean stratospheric circulation occurs over the equator and lower stratospheric air masses can be transported within a few kilometers above the tropopause, where poleward isentropic transport is relatively fast. **Fig. 2** shows the different latitude/altitude patterns of aerosol extinction for the considered tropical eruptions, correlated with the equatorial wind QBO phase. During years with dominant QBO E shear, as in the months following the Ruiz and Pinatubo eruptions aerosols are lofted over the equator with less poleward transport. Vertical profiles of the tropical aerosol extinction four months after each eruption are shown in **Fig. 3** and compared with satellite and lidar observations for the Ruiz and Pinatubo volcanic perturbations. The reference volcanically clean vertical profile of the background aerosol extinction at the Equator is also shown and compared with SAGE-II data.

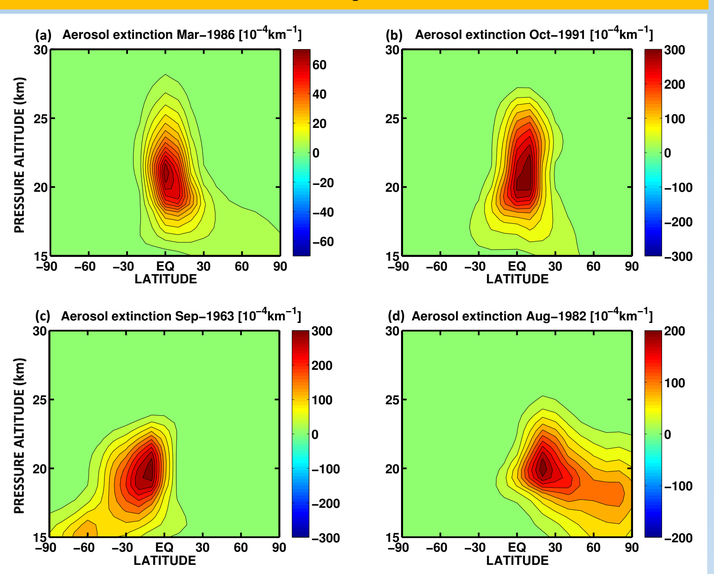

Fig. 2 ULAQ model prediction of zonally averaged aerosol extinction at λ = 0.55 μm, four months after each tropical eruption.

The clear difference in aerosol extinction above 25 km can be seen between Agung and El Chichón on one side (QBO W shear), and Ruiz and Pinatubo on the other side (QBO E shear). The zonal-mean latitudinal sections of the aerosol extinction at 20.5 km during the same months of **Fig. 3a** are presented in **Fig. 3b**, where the more pronounced tropical confinement of the aerosol clouds after Ruiz and Pinatubo eruptions is also clear.

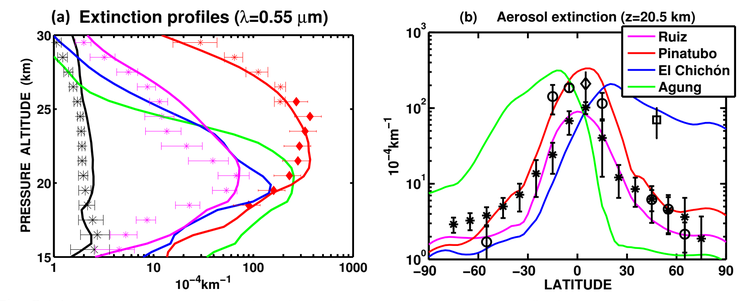

Fig. 3 (**a**) model-calculated vertical profiles of the aerosol extinction at 5˚N for Pinatubo during October 1991 and 5˚S for Ruiz during March 1986; at 10˚N for El Chichón during August 1982 and at 5˚S for Agung during September 1963. Volcanically clean extinction profile at 5˚N is shown in black, averaged over 1999–2000. (**b**) zonal-mean latitudinal section of the aerosol extinction at 20.5 km altitude, compared with SAGE-II data.

Aerosol cloud dispersal and e-folding time

Gas particle conversion processes typically last for approximately 4–6 months from the explosive eruption and produce an optically thick cloud of supercooled sulfuric acid aerosols. At this point, the stratospheric global amount of aerosol mass reaches its maximum and then a continuous slow decrease of the global burden begins, due to particle loss from the stratosphere into the troposphere, where the aerosols are readily removed by wet scavenging. This stratosphere–troposphere exchange follows essentially two pathways: (a) large-scale transport following the downwelling branch of the Brewer˙Dobson stratospheric circulation; and (b) gravitational settling of the particles. The effectiveness of these two processes determines the volcanic aerosol global lifetime, measured as the *e*-folding time of the initial cloud. Process (a) is strongly affected by the length of time the cloud remains in the tropical pipe, where the large-scale atmospheric dynamics is characterized by slow mean zonal upwelling and limited horizontal eddy mixing across the subtropical barriers.

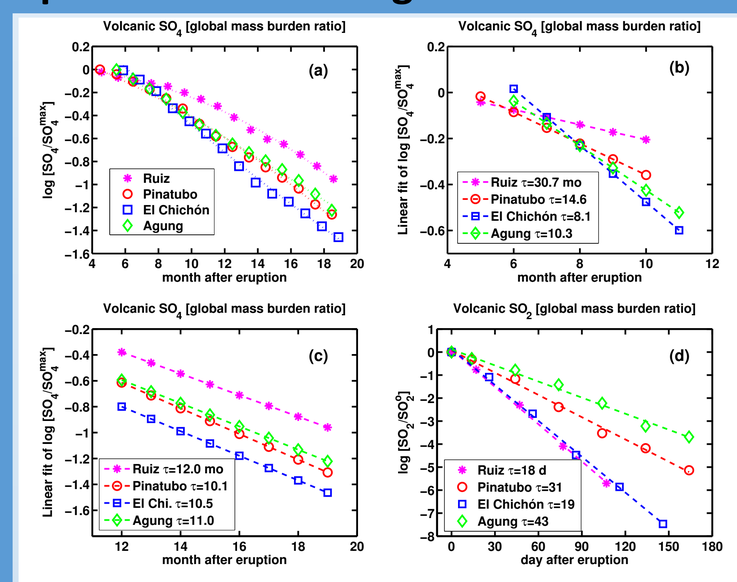

Fig. 4: **(a-c)** time series of volcanic SO_4, as globally integrated mass burden ratio with respect to its maximum value, reached 5–6 months after each eruption (see legend for the line styles adopted for the tropical eruptions considered in this study). Panel (**a**) shows the ULAQ-CCM-calculated values up to approximately 19 months after each eruption; panels (**b**) and (**c**) show the values obtained from a linear fit in the time frame of post-eruption months 4–10 (or 5–11) in (**b**) and months 12–19 in (**c**). In the legends of panels (b–c) the calculated *e*-folding times of volcanic SO_4 are presented. Panel (**d**) is similar to (**b**), but in this case the globally integrated SO_2 mass burden ratio with respect to its initial value is shown, as from the ULAQ-CCM calculations. In the legend, the calculated *e*-folding time of volcanic SO_2 is presented (referring to the decay in the sulfate global mass burden).

The stronger the tropical pipe isolation, the longer the aerosol export time towards mid-high latitudes where large-scale air descent is associated with the downwelling branch of the Brewer˙Dobson circulation. In this case, the aerosols reside longer within the stratosphere, thus favoring a longer *e*-folding time of the volcanic cloud. Process (b) is largely governed by the QBO phase: a longer aerosol lifetime is expected during months with an E shear of the equatorial zonal winds. Process (b) is governed by the average size of the particles, which is in turn related to the magnitude of the initial amount of SO_2 injected in the stratosphere. The larger the SO_2 amount, the larger the effective radius (*i.e.*, the surface-area-weighted particle size across the entire radius spectrum), the faster gravitational settling and the shorter the volcanic cloud *e*-folding time.

Sensitivity of the aerosol cloud to different QBO regimes

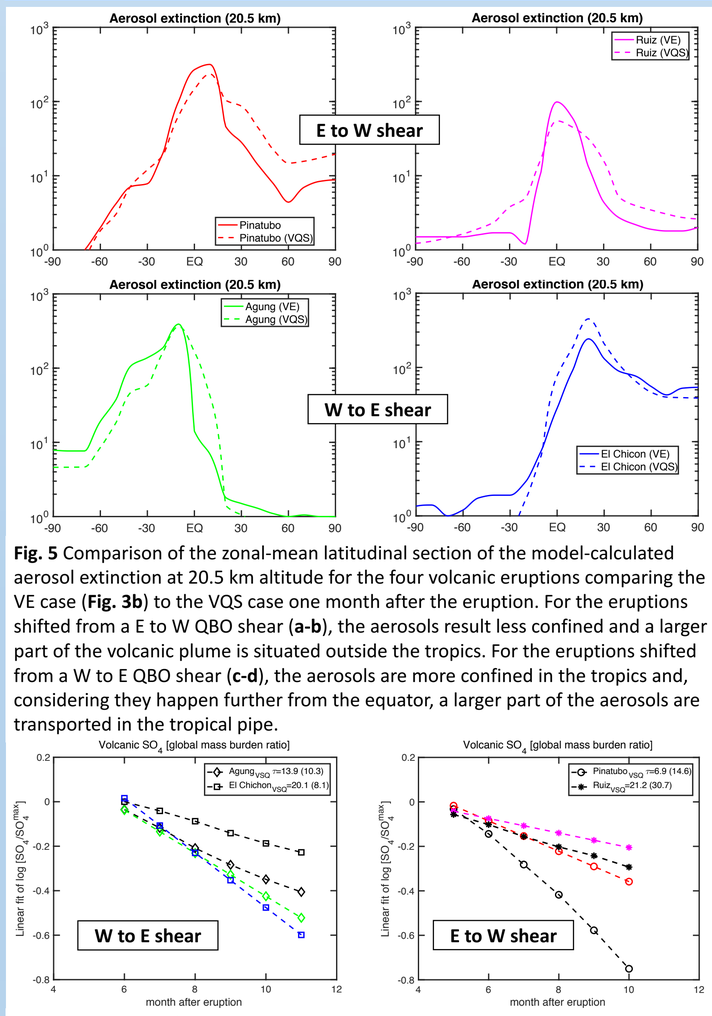

Fig. 5 Comparison of the zonal-mean latitudinal section of the model-calculated aerosol extinction at 20.5 km altitude for the four volcanic eruptions comparing the VE case (**Fig. 3b**) to the VQS case one month after the eruption. For the eruptions shifted from a E to W QBO shear (**a-b**), the aerosols result less confined and a larger part of the volcanic plume is situated outside the tropics. For the eruptions shifted from a W to E QBO shear (**c-d**), the aerosols are more confined in the tropics and, considering they happen further from the equator, a larger part of the aerosols are transported in the tropical pipe.

Fig. 6 Time series of the volcanic SO_4 as in **Fig. 4b** comparing VE and VSQ simulations for eruptions happening under a E shear instead of a W shear **(a)** and for eruptions happening under a W shear instead of under a E shear **(b)**. The e-folding time is shown for the VSQ simulations compared for the e-folding time for the VE simulation (in brakets).

Lastly we compare the VE simulations for the volcanic eruptions happening under the two QBO shears against the same eruptions in the VQS simulation, where the eruption is happening under the opposite QBO phase. This is done in order to prove the sensitivity of the aerosol cloud distribution and e-folding time, keeping constant the eruption magnitude, time of the year and location while only modifying the QBO phase. **Fig. 5** show the differences in the aerosol distribution. The differences between same eruptions happening under different QBO regimes are evident: under a W shear, the tropical pipe is leakier, so a larger part of the aerosols are distributed outside the tropical barrier (this is more evident in the hemisphere where the isentropic transport is more effective). This produces changes also in the e-folding time of the aerosol plume. As shown in **Fig.6**, the e-folding time differences VQS-VE is positive for eruption shifting from a W to an E QBO shear, meaning that the stronger tropical confinement causes a longer lifetime for the SO_4 aerosols injected in the stratosphere. On the other hand, for eruptions shifting from a E to W shear, the VQS-VE difference is negative, meaning that the stronger transport out of the tropical pipe speeds up the aerosol removal processes. The differences in confinement and e-folding time between the two regimes is found to be indipendent of the magnitude, location and time of the year of the eruption for all four considered cases.

As discussed in Visioni et al. (2018) [ACP, https://doi.org/10.5194/acp-18-2787-2018], changes in tropical confinement also affect the particle size distribution with an impact on the aerosol lifetime going in the opposite direction. According to our model, the large scale transport effect tends to dominate.

Conclusions

- **The QBO phase under which an explosive volcanic eruption happens may have a huge importance on the e-folding time of the aerosol cloud and on its zonal distribution**
- **Together with the magnitude, this might help to predict what kind of climatic impact a future eruption might have on the global climate**
- **The importance of the QBO-aerosol cloud interaction might also be rather important when considering sulfate geoengineering experiments**

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