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Simulation of the climate impact of Mt. Pinatubo eruption using ECHAM5 – Part 2: Sensitivity to the phase of the QBO

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Abstract

The QBO (quasi-biennial oscillation) is a quasi-periodic oscillation of the equatorial zonal wind between easterlies and westerlies in the tropical stratosphere with a mean period of 28 to 29 months. In this paper, the sensitivity of the impact of Mt. Pinatubo eruption in the tropics and extratropics to different QBO phases is investigated. Mt. Pinatubo erupted in June 1991 during the easterly phase of the QBO at 30 hPa and the phase change to westerly took place in August 1992. Here, the consequences are analyzed if the eruption had taken place in the opposite QBO phase. Hence, in this study simulations are carried out for two cases – one with the observed QBO phase as discussed in part-I of this paper and the other with the opposite QBO phase. The QBO signature in the lower stratospheric temperature is well captured in the pure QBO responses and in the combined (aerosol+ocean+QBO) responses. Our results also show that a deepening of the polar vortex is not simulated during the first winters, but is seen during the second winters irrespective of the QBO phases in the pure QBO responses. However, a strong polar vortex is observed in the second winter when the QBO is in its westerly phase in the combined (aerosol+ocean+QBO) response in agreement with previous studies.

1 Introduction

The quasi-biennial oscillation (QBO) in the zonal winds in the equatorial lower stratosphere is a well known mode of interannual variability. The zonally symmetric easterly and westerly wind regimes alternate regularly with a mean period of 28–29 months. The alternating wind regimes develop in the upper stratosphere near 3 hPa and propagate downward at an approximate rate of 1 km/month to the tropopause. The amplitude of the easterly phase is stronger than the westerly phase. The easterly zonal winds can reach as high as 35–40 m/s, whereas the westerly zonal winds reach 15–20 m/s. The driving force for the QBO is the vertical transfer of momentum from the troposphere to

ACPD

8, 9239–9261, 2008

stratosphere by a broad spectrum of vertically propagating waves including Kelvin and Rossby-Gravity waves (refer Baldwin et al. (2001) for details). There is considerable variability of the QBO in period and amplitude.

The QBO influences the extratropical northern stratosphere. Studies have shown that the geopotential height at high latitudes is significantly lower during the westerly phase of QBO than during the easterly phase (Holton and Tan, 1980, 1982). Labitzke (1987) and Labitzke and Van Loon (1988) found a strong relation of the QBO signal to the 11-year solar cycle during January and February and it was shown that during the easterly phase, for solar maxima, there exists an intensified cold polar vortex and vice versa for solar minima. The QBO also affects the winter stratospheric temperatures depending on the ENSO phase (Garfinkel and Hartmann, 2007), for example, our model simulations with observed SSTs and QBO show that when ENSO is in its warm state, the influence of QBO is reduced (refer to part-I of this paper). Several studies showed that the phase of the QBO influences the weather events in the troposphere. Indian summer monsoon rainfall activity seems to be directly related with the phase of the QBO (Bhalme et al., 1987; Mukherjee at al., 1985). Using General Circulation Model simulations, Giorgetta et al. (1999) showed that the tropical tropospheric circulation is significantly influenced by the QBO wherein less precipitation is observed in the western Pacific, but, more in the Indian subcontinent during the westerly QBO phase. Yasunari (1989) showed that the QBO in the lower stratosphere is coupled with the sea surface temperature anomalies in the equatorial Pacific. Chattopadhyay and Bhatla (2002) showed that the Indian monsoon rainfall is strongly inversely correlated with the SST anomalies over the Niño3 region for all the seasons from the concurrent summer to the following winter during the easterly QBO phase.

The QBO also plays an important role in the distribution of chemical constituents like ozone, water vapor and methane and aerosols (Trepte and Hitchman, 1992; Trepte et al., 1993; Baldwin et al., 2001). Planetary wave activity is much less in the easterly phase of the QBO compared to the westerly phase, which means that the aerosols are trapped in the equatorial belt during the easterly phase of QBO and are dispersed during the westerly phase (Trepte et al., 1993). Lidar observations of the stratospheric aerosol layer at Garmisch-Partenkirchen (47.5° N, 11.1° E) show that for about 3 years, the tropical explosive eruptions such as Mt. Pinatubo (1991) and El Chichon (1982) eruption show the same decay rate of 12 months when the QBO phases of these two eruptions are synchronized (Jaeger, 2005).

The easterly and westerly phases of the QBO have different effects on the stratospheric extratropical circulation. Here, the sensitivity of the effect of large volcanic eruptions on the high latitude circulation to the QBO phase is evaluated. Mt. Pinatubo erupted on 15 June 1991 during the easterly phase of the QBO at 30 hPa and the change to the westerly phase took place in August 1992 at 30 hPa and remained in the same phase till May 1993. It would be interesting to understand the climate impact of Mt Pinatubo eruption if it had erupted during the opposite phase. Here, the main focus is to see whether the radiative and dynamical responses following Mt. Pinatubo eruption are modulated by the phase of the QBO. Most GCMs are not able to simulate a spontaneous QBO. But, in the recent years, attempts have been made to include QBO forcing in GCMs either by assimilating the observed zonal winds at Singapore to the model winds or by considering a sufficient spatial resolution, a realistic simulation of tropical convection and the consideration of the effects of gravity waves (Hamilton, 1998; Bruhwiler and Hamilton, 1999; Giorgetta et al., 2002; Stenchikov et al., 2004; Giorgetta et al., 2006). For this study, the middle atmosphere version of ECHAM5 is modified to include the QBO forcing by nudging the zonal mean zonal winds in the tropics to the prevailing zonal wind observations at Singapore following Giorgetta and Bengtsson (1999).

The response for individual or combined forcings, including volcanic aerosols and ozone anomalies, observed SSTs and the QBO in two opposite phases are discussed in detail in the following sections. The responses in the observed phase are already discussed in part-I of this paper, but are shown here again for easy comparison.

2 Model, datasets used and experimental set up

The details of the model and datasets used are already discussed in Part-I of this paper. Simulations are carried out for a 2 year period from June 1991 to May 1993 with the middle atmosphere configuration of ECHAM5 (Special section ”Climate models at the Max-Planck Institute for Meteorology” in Journal of Climate, 2006, 19, Issue-16, 3769-3987) at T42 horizontal resolution and 39 vertical layers (Manzini et al., 2006), topmost level at 0.01 hPa. Both the volcanic aerosol forcing data and the ozone anomaly data (Stenchikov et al., 2002) are compiled by G. Stenchikov and are used in this study for the specific model resolution.

For the runs including the QBO, a spin up of 17 months is carried out with observed SST and with the observed QBO phase. Ten ensemble runs are carried out with different initial conditions. The initial conditions are chosen arbitrarily from the 15 year unperturbed run with climatological SST as boundary conditions. To include the QBO forcing in this study, the zonal winds in the tropics are nudged towards the zonal wind observations at Singapore (Giorgetta and Bengtsson, 1999). The nudging is applied uniformly in a core domain and extends with decreasing nudging rate to the boundary of the domain. The latitudinal core domain specified for the study here is 7 N-7 S and the domain boundary is 10 N–10 S. In the vertical the core domain and the boundary is over the levels extending from 70 hPa to 10 hPa. The nudging rate is (10 days)$^{-1}$. The opposite QBO phase is prescribed along with observed SST and sea ice as boundary conditions for both the perturbed and unperturbed runs.

As mentioned before, there is significant variability of the QBO in period and amplitude. To extract the QBO-related zonal winds that are opposite of that occurring during the Pinatubo eruption, the correlation co-efficient is calculated between the 50 hPa zonal mean zonal winds at Singapore for the years 1953–2004 and the 50 hPa zonal winds of 1991/1993. The time period of maximum negative correlation co-efficient is chosen as the opposite QBO phase (hereafter referred to as $\overline{\text{QBO}}$) and in this case, the best anti-correlated years are from June 1975–May 1977. The zonal winds from

ACPD

8, 9239–9261, 2008

observations at Singapore for the period June 1991–May 1993 and for the period June 1975–May 1977 are presented in Fig. 1. The easterly winds are denoted by negative values (blue shades) and westerly winds, by positive values (yellow shades). It can be seen that the amplitudes of the westerly and easterly winds are comparable in both cases. The phase change at 30 hPa takes place in month 14 after June 1991 (around August 1992) and in $\overline{\text{QBO}}$, this phase change occurs in month 11 after June 1975 (around mid May 1976). It can be seen that the zonal winds of opposite sign for the period 1991/1993 are well represented by the period 1975/1977. Since each of the QBO cycles is unique, this is the best correlation possible within the available record.

Perturbed and unperturbed runs are carried out with observed SST and with the observed/opposite QBO phases as boundary conditions. The differences between these runs give the different forcing experiments presented in Table 1. The individual QBO responses are shown by QBO when the observed QBO phase is prescribed and by $\overline{\text{QBO}}$ when the opposite QBO phase is prescribed. These responses are calculated as a difference between the unperturbed combined ocean+QBO run (combined ocean+$\overline{\text{QBO}}$ run) and the unperturbed run with observed SST as boundary conditions. The combined aerosol+ocean+QBO responses are denoted by AOQ for the observed QBO phase and by AO$\overline{\text{Q}}$ for the opposite QBO phase. These response are calculated as the difference between the combined AOQ/AO$\overline{\text{Q}}$ experiment and the unperturbed run with climatological SST (C_c) as boundary conditions.

3 Results and discussion

The first part discusses the responses in temperature and geopotential height at 30 hPa to the QBO phases alone. The QBO exhibits a clear signature in stratospheric temperature with pronounced signals in tropics and extratropics (Baldwin et al., 2001). The tropical temperature QBO is in thermal wind balance (Andrews et al., 1987) with the vertical shear of the zonal winds. Studies by (Holton and Tan, 1980, 1982) show that

ACPD
8, 9239–9261, 2008

significantly lower geopotential height anomalies are seen in the northern high latitudes in winter during the westerly QBO phase than the easterly phase. It has to be noted that Mt. Pinatubo eruption coincided with an El Niño event in the tropical Pacific during the first winter and it would be interesting to know how different are the responses. The second part of this section discusses the combined aerosol+ocean+QBO radiative and dynamical responses under the influence of the El Niño event and also with different QBO phases.

3.1 Pure QBO and $\overline{\text{QBO}}$ responses

3.1.1 Lower stratospheric temperature response at 30 hPa

The pure stratospheric temperature response to the two QBO phases at 30 hPa, namely one for the phase change from from easterly to westerly (QBO) and the other from westerly to easterly ($\overline{\text{QBO}}$) is investigated. Fig. 2 shows the lower stratospheric temperature response to (a) $\overline{\text{QBO}}$ and to (b) the observed QBO phase. A cooling of about 1–2 K is observed in the latitudinal belt from 10N–10S from June 1991–April 1992 in Fig. 2b and from January 1992–May 1993 in Fig. 2a during the easterly QBO shear and warm anomalies are observed in the mid latitudes. Whereas positive temperature anomalies are observed along the equator and negative anomalies over the subtropics during the westerly shear of QBO. The opposite temperature signals in the subtropics are the result of the compensating branches of the secondary circulation of the QBO. This feature is consistent with previous studies by Baldwin et al. (2001). However, the temperature response associated with the westerly phase of the QBO in Fig. 2a,b is comparatively weaker. To explain this better, the climatological mean differences in the annual cycle of lower stratospheric temperature at 30 hPa between the experiments including and excluding the QBO is shown in Fig. 2c. It can be clearly seen that the stratospheric temperature climatology at 30 hPa is colder by up to –1.5 K in the model without a QBO than with a

ACPD

8, 9239–9261, 2008

QBO (H. J. Punge and M. Giorgetta, personal communication). This explains why the warm temperature anomalies observed during the westerly QBO shear are weaker.

3.1.2 30 hPa geopotential height response in boreal winter

The differences in the 30 hPa geopotential height anomaly in response to the $\overline{\text{QBO}}$ phase is presented in Fig. 3a,b for the two boreal winters following the eruption. The anomalies are weaker in DJF (Dec-Jan-Feb) 1991/1992 in the $\overline{\text{QBO}}$ anomalies where positive anomalies are observed over southern Europe, Russia and Siberia (up to 40 m) and negative anomalies over Scandinavia, parts of Greenland and northern Canada (up to –40 m). The second winter shows a strong and larger area of below normal geopotential height anomalies (as low as –160 m) over northern Eurasia and Greenland and above normal geopotential height anomalies over Canada and North Atlantic. The vortex observed in the winter of 1992/1993 is slightly shifted over northern Eurasia.

For comparison, the response with the observed QBO phase is shown in Fig. 3c,d. In the first winter following the eruption, the QBO is in its easterly phase and $\overline{\text{QBO}}$ is in its westerly phase at 30 hPa and the opposite is observed during the second winter. During the first winter, the anomaly patterns do not simulate the strengthening of the polar vortex in either of the cases, though the $\overline{\text{QBO}}$ favors a strong polar vortex (Holton and Tan, 1980). This may be because of the strong influence of El Niño. Comparing the response to $\overline{\text{QBO}}$ for the second winter with the response to QBO, the model simulates negative polar geopotential height anomalies in both the QBO phases. This means that the model simulates the anomalously cold polar vortex irrespective of the QBO phase. This contradicts the study by Holton and Tan (1980) that the westerly phase of QBO favors a strengthening of the polar vortex. A possible explanation is that the interactions between the QBO and the vertically propagating wave flux is reduced in the second winter when El Niño effects are reduced, thereby strengthening the polar

ACPD
8, 9239–9261, 2008

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

vortex irrespective of the QBO phase.

3.2 Differences in the response to volcanic aerosol forcing in QBO and $\overline{\text{QBO}}$ phases

3.2.1 Lower stratospheric temperature response

Figure 4 shows the 30 hPa temperature response when the aerosol forcing, El Niño and QBO effects are included for two years following the eruption. The only difference is that Fig. 4a has the observed QBO phase and the Fig. 4b has the opposite phase as can be seen in the color bars given at the bottom of the Figure. The effects due to the contrasting QBO phases are clearly evident. A cooling of about 1–2 K from June 1991–April 1992 in (a) and from January 1992–May 1993 in (b) is seen in the latitudinal belt 10 N–10 S and warmer temperatures are observed in the subtropics. This dual peak with a relative maximum in the subtropics and minimum at the equator during the easterly phase of QBO is well simulated by both experiments. The response in the latitudinal belt 50N - 50S is statistically significant at > 90% significance level.

Colder temperature anomalies are observed during the westerly phase of QBO in northern hemisphere (NH) winter in the polar latitudes as in Fig. 4a,b and this may be associated with the strengthening of the polar vortex. This cooling is more prominent during the westerly phases in AO$\overline{\text{Q}}$ where the cooling is persistent over October-November-December, whereas the cooling is confined to Dec in AOQ. Strong warm anomalies can be seen in January–February–March during the westerly QBO phases in both the experiments, but, the warming in the AOQ forcing is much weaker than seen in AO$\overline{\text{Q}}$ forcing. Significant above normal temperature anomalies are also seen during the easterly phases of QBO in December–January–February months. These anomalies are statistically significant at 90% significance level. As mentioned before, there was an ongoing El Niño and when one compares these results with the pure QBO temperature responses, it can be seen that the strong anomalies in the high latitudes are insignificant meaning that these anomalies are a result of the complex in-

ACPD

8, 9239–9261, 2008

Simulation of Mt. Pinatubo eruption – sensitivity to the QBO phase

M. A. Thomas et al.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀◀ | ▶▶
◀ | ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

teractions between aerosols, QBO and SSTs. It is shown that the change of the QBO phase can also bring about changes in the extratropical winter circulation in the lower stratosphere.

3.2.2 30 hPa geopotential height response

The geopotential height anomalies at 30 hPa for the two winters following the eruption are shown in Fig. 5a,b in $\overline{\mathrm{AOQ}}$ and in Fig. 5c,d in AOQ runs. The anomalies in $\overline{\mathrm{AOQ}}$ during the winters of 1991/1992 and 1992/1993 exhibit a wave number one pattern with positive anomalies over northern Pacific, Canada, Alaska and Siberia and negative anomalies over north western Europe and North Atlantic. The geopotential height anomalies reach as low as –100 m and as high as 140–160 m. There are no notable differences between the anomalies of the two winters except that the anomalies in the second winter following the eruption are relatively stronger than in the first winter. As mentioned before, the westerly phase of the QBO favors a strong polar vortex. But, in $\overline{\mathrm{AOQ}}$, the westerly phase occurs during the El Niño winter, which in turn, disturbs the polar vortex.

Comparing the responses for the combined forcings including the observed QBO phase and the opposite QBO phase, it can be seen that the anomaly pattern is more or less similar in the first winter, where positive anomalies positioned over the Arctic circle and the negative anomalies cover a smaller region compared to the anomalies in the $\overline{\mathrm{AOQ}}$ response. This similarity in the responses is due to the fact that the El Niño effects override the effects due to the phase change of QBO. However, the response in the second winter differs considerably with a large center of low geopotential height anomalies over the Arctic circle, Greenland and north eastern Europe and Siberia in AOQ when the QBO is in the westerly phase that favors a strong polar vortex and is not seen in $\overline{\mathrm{AOQ}}$, when the QBO is in the easterly phase, again, supporting the studies by Holton and Tan (1980) and Holton and Tan (1982).

ACPD
8, 9239–9261, 2008

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀◀ | ▶▶
◀ | ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

3.2.3 2 m temperature response

Figure 6a and b show the ensemble mean surface temperature anomalies for the first and second winters respectively in AO$\overline{Q}$. For comparison purposes, the ensemble mean surface temperature anomalies in AOQ are also shown in Fig. 6c and d. It can be seen that one of the main features of the volcanic forcing, the so-called "volcanic winter pattern" (Graf et al., 1993; Kirchner and Graf, 1995; Robock and Mao, 1995; Stenchikov et al., 2002) is not simulated by the model in any of the winters. The tropical warming in the Pacific due to the El Niño event of 1991/1992 is clearly seen in (a). During the first winter, the anomalies in AO$\overline{Q}$ and AOQ are more or less the same, except for some minor differences. The warming over northern North America associated with El Niño is statistically significant in AOQ, though the magnitude of the anomalies are captured irrespective of the phases. The pattern exhibited in Fig. 6a and c is similar to the ocean response (refer Fig. 3g,h of Part-I), thereby clearly signifying the dominance of ENSO effects over the effects due to the change of QBO phase. However, during the second winter when the effects of El Niño are negligible, the combined effects due to aerosols and the change of phase of QBO are seen. The warming over northern parts of Europe, Russia and Greenland and cooling over N. America and parts of Canada are simulated irrespective of the phase of the QBO. But, strong statistically significant cooling in the Middle East, India and China is simulated only during the easterly QBO phase as in Fig. 6b, while these anomalies are weaker and not significant during the westerly phase of QBO as seen in Fig. 6d. Hence, it can be seen that the surface temperature response is independent of the phase of the QBO during the first winter after Mt. Pinatubo eruption due to the presence of El Niño, but differs over Asia during the second winter when El Niño effects are reduced.

ACPD

8, 9239–9261, 2008

4 Conclusions

The sensitivity of the climate impact of Mt. Pinatubo eruption to the different QBO phases is investigated. Here, two cases are considered: one in which the QBO phase is the same as observed during the eruption of Mt. Pinatubo and another, in which the phase is reversed. Mt. Pinatubo erupted during the easterly phase of QBO and the phase change took place 14 months after the eruption. In this study, the resulting climate effect of Mt. Pinatubo eruption is examined if the eruption had taken place in the opposite phase of QBO.

Our results can be summarized as follows:

1. The individual QBO (when observed QBO phase is included) and $\overline{\text{QBO}}$ responses in the lower stratospheric temperature at 30 hPa show a dual peak with cooling along the equator and warming over the subtropics associated with the easterly phase of the QBO and the opposite is shown during the westerly QBO phase. This is in agreement with previous studies.

2. The 30 hPa geopotential height anomalies show a strong polar vortex in the second winter for QBO and $\overline{\text{QBO}}$ phases in the pure QBO responses. The only difference is that the vortex is over northern Europe in $\overline{\text{QBO}}$ when compared with the pure QBO response. The vortex is disturbed in the first winters irrespective of the phase of the QBO. This is suggested to be due to the strong effects of El Niño on the atmospheric planetary waves.

3. Similarly, a stronger polar vortex is not simulated in the combined AOQ response irrespective of the QBO phases in the first winters. This may be because of the increased vertical wave activity during El Niño winters disturbing the vortex. However, the model tries to simulate a relatively weak polar vortex during the second winter when the QBO is in its westerly phase in the AOQ experiment.

4. The dynamical response simulated by the model at the surface is more or less

ACPD

8, 9239–9261, 2008

Simulation of Mt. Pinatubo eruption – sensitivity to the QBO phase

M. A. Thomas et al.

similar during the first winters irrespective of the QBO phases and the patterns exhibited are similar to the ocean response. This clearly shows the dominance of ENSO over the effects of the change of phase of QBO. But, major differences pertaining to the change of QBO phase can be observed in the tropics and mid-latitudes during the second winters, i.e. when the El Niño is weakened. No notable changes are observed over North America and Greenland and in the polar latitudes by the phase change during the second winters.

5. The combined lower stratospheric temperature response of volcanic forcing with observed SSTs and QBO phases shows notable changes in the high latitudes. Colder temperature anomalies are observed during the westerly phase of the QBO in NH winter in the polar latitudes associated with the strengthening of the polar vortex. Strong warm anomalies are observed in northern high latitudes in late winter during the easterly phase of the QBO. This warming is statistically significant at 90% confidence level and is also evident during the westerly QBO phase in the $AO\overline{Q}$ experiment.

Our results show that the climate response after explosive tropical eruptions is significantly modulated by the QBO phase. Major differences owing to the QBO phase are observed in the tropics and extratropics in the lower stratosphere temperature response. While significant differences in the dynamical response at the surface are seen in the tropics and the subtropics, this study shows that the modulation by the QBO is minimal beyond 60N. The use of prescribed aerosol and nudged QBO in this study restricts the understanding of the the effects of the different QBO phases on the transport and mixing of the aerosols. However, studies will be carried out to investigate the effect of aerosols on the QBO.

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Table 1. Ensemble mean differences between perturbed and unperturbed runs. The text in bold within the table are the difference between the corresponding perturbed runs and unperturbed control runs.

Unperturbed runs		Perturbed runs	
O_u	–	OQ_p	$O\overline{Q}_p$
C_u	AOQ	$AO\overline{Q}$	
QBO	OQ_u		
$\overline{QBO}$	$O\overline{Q}_u$		

ACPD

8, 9239–9261, 2008

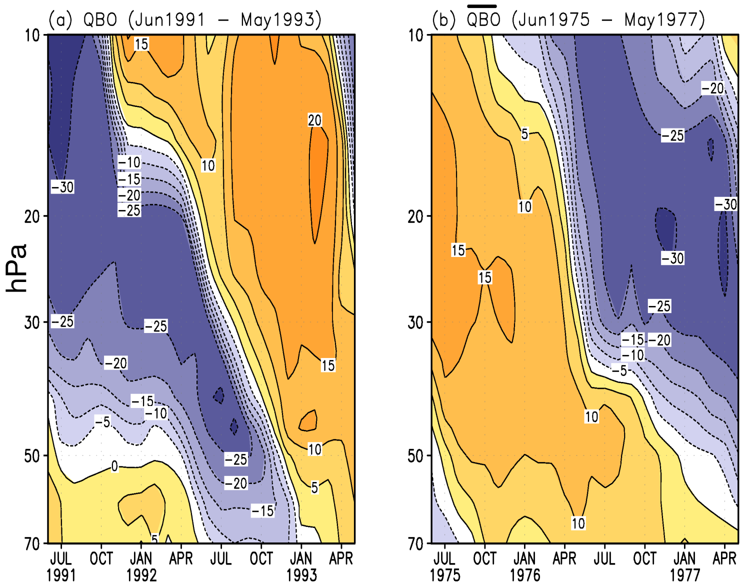

Fig. 1. Zonally averaged observed zonal winds (m/s) at Singapore for **(a)** June 1991–May 1993 and **(b)** June 1975–May 1977. Negative values are shaded in colors of blue and are easterlies and the positive values are shaded in colors of yellow and are the westerlies. The contour intervals are 5 m/s.

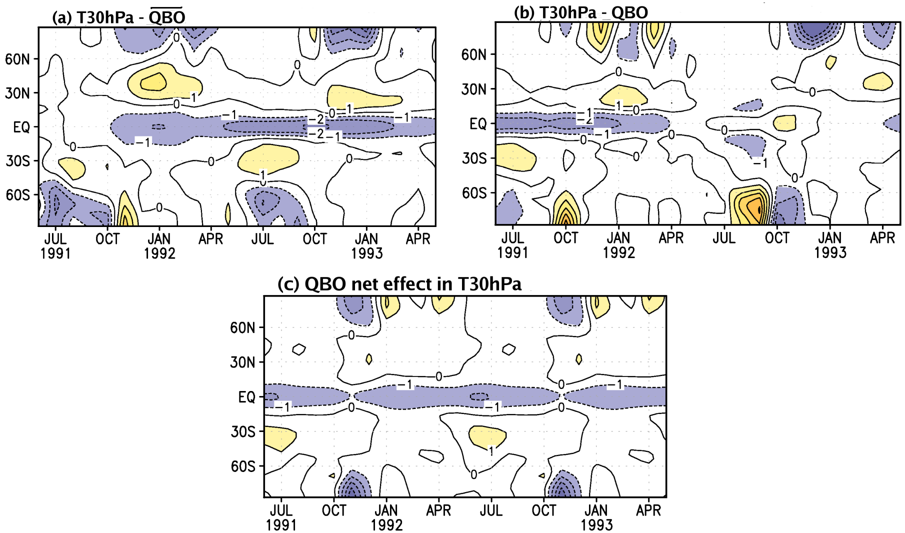

Fig. 2. Zonally averaged lower stratospheric temperature anomalies (K) at 30 hPa for **(a)** QBO in the opposite shear **(b)** QBO in the observed shear and **(c)** the net QBO effect in 30 hPa temperature.

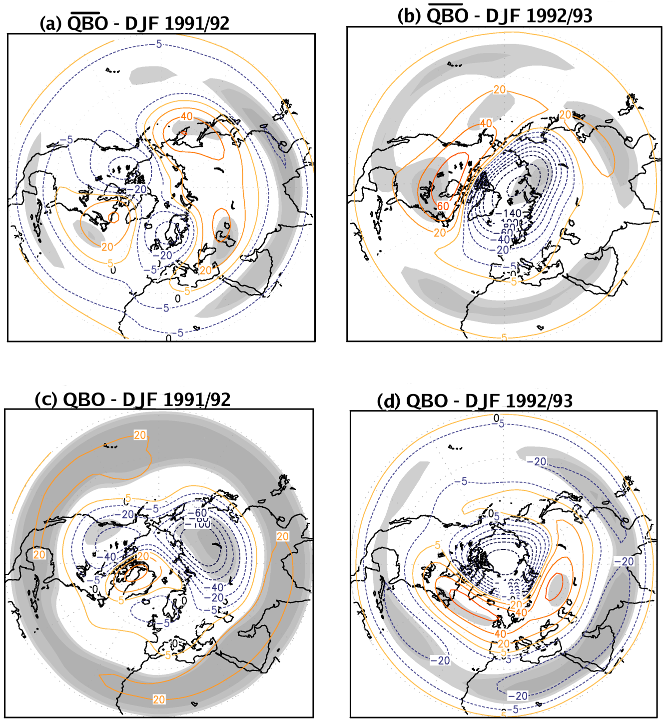

Fig. 3. Geopotential height anomalies (m) at 30 hPa for **(a)** $\overline{\text{QBO}}$: DJF 1991/1992 **(b)** $\overline{\text{QBO}}$: DJF 1992/1993, when the opposite QBO phase is prescribed; and for **(c)** QBO: DJF 1991/1992 and **(d)** QBO: DJF 1992/1993, when the observed QBO phase is prescribed. The shading denotes three levels (99%, 95% and 90%) of statistical significance in the order of lighter shading.

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8, 9239–9261, 2008

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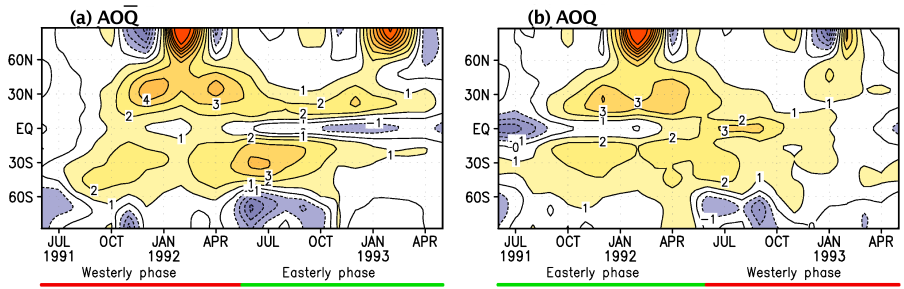

Fig. 4. Zonally averaged lower stratospheric temperature anomalies (K) at 30 hPa for two years following Mt. Pinatubo eruption for **(a)** $AO\overline{Q}$ with the opposite QBO phase and **(b)** AOQ experiment with observed QBO phase. The QBO phases encountered during (a) and (b) are shown by the colored lines.

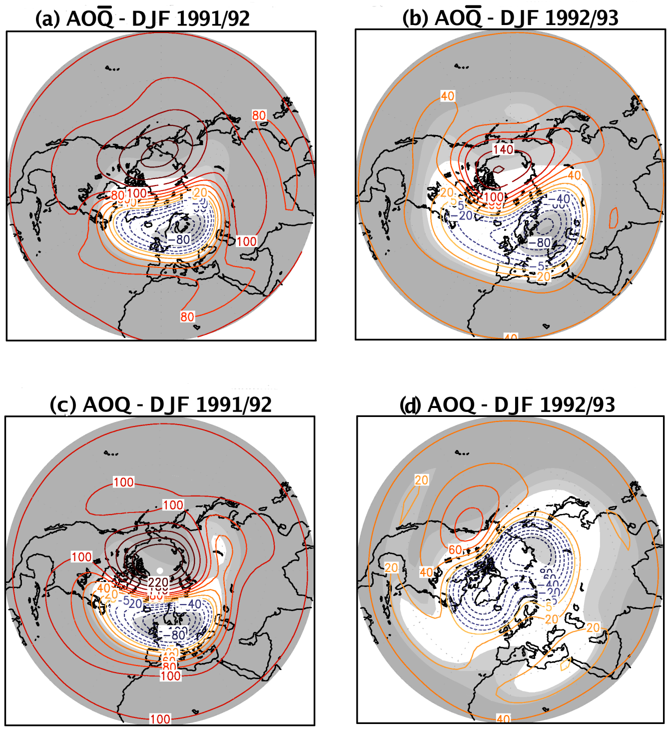

Fig. 5. Geopotential height anomalies (m) for **(a)** AO$\overline{Q}$: DJF 1991/1992 **(b)** AO$\overline{Q}$: DJF 1992/1993, when the opposite QBO phase is prescribed and for **(c)** AOQ: DJF 1991/1992 and **(d)** AOQ: DJF 1992/1993, when the observed QBO phase is prescribed. The shading denotes three levels (99%, 95% and 90%) of statistical significance in the order of lighter shading.

ACPD

8, 9239–9261, 2008

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◂ | ▸
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

ACPD

8, 9239–9261, 2008

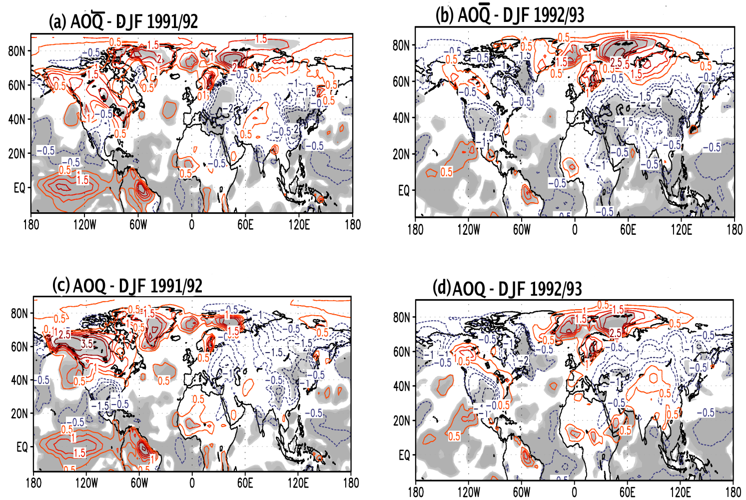

Fig. 6. 2 m temperature anomalies (K) for **(a)** AO$\overline{Q}$: DJF 1991/1992 **(b)** AO$\overline{Q}$: DJF 1992/1993, when the opposite QBO phase is prescribed; and for **(c)** AOQ: DJF 1991/1992 and bf (d) AOQ: DJF 1992/1993, when the observed QBO phase is prescribed. The shading denotes three levels (99%, 95% and 90%) of statistical significance in the order of lighter shading.