

Differing responses of the QBO to artificial SO₂ injections in two global models

Ulrike Niemeier¹, Jadwiga H. Richter², and Simone Tilmes²

¹Max Planck Institute for Meteorology, Bundesstr. 53, 20146 Hamburg, Germany

²National Center for Atmospheric Research, Boulder, CO, USA

Correspondence: Ulrike Niemeier (ulrike.niemeier@mpimet.mpg.de)

Abstract. Artificial injections of sulfur dioxide (SO₂) into the stratosphere show in several model studies an impact on stratospheric dynamics. The quasi-biennial oscillation (QBO) has been shown to slow down or even vanish, under higher SO₂ injections in the equatorial region. But the impact is only qualitatively, but not quantitatively consistent across the different studies using different numerical models. The aim of this study is to understand the reasons behind the differences in the QBO response to SO₂ injections between two general circulation models, the Whole Atmosphere Community Climate Model (WACCM-110L) and MAECHAM5-HAM. We show that the response of the QBO to injections with the same SO₂ injection rate is very different in the two models, but similar when a similar stratospheric heating rate is induced by SO₂ injections of different amounts. The reason for the different response of the QBO corresponding to the same injection rate is very different vertical advection in the two models, even in the control simulation. The stronger vertical advection in WACCM results in a higher aerosol burden and stronger heating of the aerosols, and, consequently in a vanishing QBO at lower injection rate than in simulations with MAECHAM5-HAM. The vertical velocity increases slightly in MAECHAM5-HAM when increasing the horizontal resolution. This study highlights the crucial role of dynamical processes and helps to understand the large uncertainties in the response of different models on artificial SO₂ injections in climate engineering studies.

Copyright statement. TEXT

1 Introduction

Recent model intercomparison studies of sulfate evolution and transport after volcanic eruptions and after artificial injections of SO₂ into the stratosphere reveal substantial differences between model results. The lifetime of the aerosols after a simulated Tambora-like eruption differs by several months and the aerosol optical depth (AOD) shows different maximum values and decay rates (Zanchettin et al., 2016; Marshall et al., 2018). Similar differences in response are also found in Climate Engineering (CE) studies, in which SO₂ is continuously injected into the stratosphere over a period of many years. Niemeier and Tilmes (2017) show a wide range of radiative forcing values resulting from the same sulfur injection rate but in different models. Radiative forcing results of the two models compared in Kleinschmitt et al. (2017) are closer but vary still by e.g. 0.5 Wm⁻² for

an injection rate of 10 Tg(S)yr^{-1} . Kleinschmitt et al. (2017) assumed differences in aerosol heating and consequent stronger vertical advection as a reason for the differences.

25 Several models show that the artificial injection of SO_2 into the tropical stratosphere over many years impacts stratospheric dynamics. The quasi-biennial oscillation (QBO) is the primary mode of variability in the tropical stratosphere, characterized by downward propagating easterly and westerly shear zones. The QBO affects lower troposphere temperature and constituent concentrations, as well as affects transport of constituents out of the tropics (Baldwin et al., 2001; Punge et al., 2009; Shuckburgh et al., 2001). Model simulations have shown that under tropical injections of 2 TgSyr^{-1} the QBO period decreases, or it
30 may even vanish. The SO_2 injection rate at which this happens is model dependent (4 to 8 TgS yr^{-1} TgSyr^{-1}) in the equatorial region (Aquila et al., 2014; Niemeier and Schmidt, 2017; Richter et al., 2017; Jones et al., 2016). Aquila et al. (2014) showed that the cause of this dynamical change in the tropical stratosphere are changes in temperature resulting from the radiative heating of the aerosols. Sulfate scatters solar (short wave, SW) radiation, which causes the earth surface to cool and absorbs radiation within the SW spectrum in the near infrared, as well as terrestrial (long wave, LW) radiation. This absorption causes
35 the sulfate layer in the stratosphere to warm. Timmreck et al. (1999) and Aquila et al. (2012) have shown the importance of this radiative heating for the transport of sulfate after a volcanic eruption.

The heated sulfate layer is the main driver of the changes in the tropical stratospheric circulation and the QBO. The disturbed thermal wind balance results in an increased zonal westerly wind component (Andrews et al., 1987). Additionally, the heating increases the vertical advection as given in the residual vertical velocity, ω^* , either directly, by changing the density of the air, or
40 indirectly by changing the propagation of waves. in the steady state. Dissipating waves deposit their energy in the stratosphere. Therefore, changing temperature and temperature gradients with artificial sulfur injections at the equator changes stratospheric dynamics and tracer transport. Additionally, a stronger ω^* inhibits the downward propagation of QBO shear zones, resulting in a lengthening or total loss of an oscillation in the presence of larger SO_2 injections (Aquila et al., 2014; Niemeier and Schmidt, 2017; Richter et al., 2017). Changes in the QBO resulting from SO_2 injections subsequently have consequences for aerosol
45 transport, due to the strong westerly jet in the lower stratosphere. A tropical westerly jet results in a stronger equatorward meridional wind component toward the center of the jet (Plumb, 1996) and, together with the enhanced vertical advection, an enhanced tropical confinement of the aerosols (Niemeier and Schmidt, 2017). To decrease the impact on the QBO other injection areas might be favorable. Richter et al. (2017) showed that the QBO period decreases when SO_2 injections are placed at $15^\circ\text{S}/15^\circ\text{N}$ and $30^\circ\text{S}/30^\circ\text{N}$ instead of at the equator. Niemeier and Schmidt (2017) calculated a smaller impact on the QBO
50 for injections along a band between 30°N and 30°S . However, Tilmes et al. (2018) showed that also these different injection strategies also impact the transport of species, e.g. ozone, due to different wave propagation in the stratosphere.

The impact of equatorial SO_2 injections on the QBO is qualitatively, but not quantitatively consistent across the different studies described above. Aquila et al. (2014) showed that the QBO vanishes with a 2.5 Tg(S)yr^{-1} equatorial injection, and Niemeier and Schmidt (2017) at 8 Tg(S)yr^{-1} equatorial injections. Jones et al. (2016) showed still oscillating winds with an
55 injection of 7 Tg(S)yr^{-1} and in Kleinschmitt et al. (2017) the QBO vanishes without developing a westerly jet as in the other models. Richter et al. (2017) showed a disappearance of the QBO with injections of 6 Tg(S)yr^{-1} only when using prescribed

chemistry. When using a fully interactive chemical module the QBO slows down, but does not disappear, at this equatorial injection rate. They related this to the additional heating and partly opposing cooling due to interactive ozone.

In this study we aim to understand the reasons behind the differences in the QBO response to SO₂ injections between two models, WACCM-110L and MAECHAM5-HAM. As none of the studies named above had the same simulation set-up, we perform here simulations with WACCM-110L and MAECHAM5-HAM with the same set-up, SO₂ injection rate, and location. We describe the models and the performed simulations in Section 2, discuss the causes of the differences in Section 3, show in Section 3.5 that the models behave more similar when the amplitude of the aerosol heating is similar, and discuss shortly the impact of different horizontal resolution on the findings in Section 3.6. We end with a summary and discussion (Section 4).

2 Methods

2.1 Model Description

This study compares results of MAECHAM5-HAM and the Whole Atmosphere Community Climate Model (WACCM). The simulations were performed with resolutions of the models used in previous studies (Niemeier and Schmidt, 2017; Richter et al., 2017; Tilmes et al., 2018, e.g.). Both models prescribe a repeating annual cycle of SSTs, present day. Richter et al. (2017) have shown that ozone plays a crucial role in the impact of artificial SO₂ injections on the QBO, but MAECHAM5-HAM has no interactive chemistry for precursors of SO₂ oxidation. Therefore, both models prescribe the precursors on a monthly mean basis, which allows for a direct comparison of the impact of sulfate heating on the QBO. These prescribed fields slightly differ between the two models but are not expected to have much influence on the simulation of the QBO. As described in Mills et al. (2016), the lack of interactive stratospheric chemistry, prevents OH values from depleting while reacting with the injected sulfur. This leads to a slightly faster formation of sulfate closer to the injection location, and with that a different lofting of aerosols in the tropics compared to a full chemistry version, as used in Mills et al. (2017). However, while the aerosol distribution is somewhat different than in the fully interactive chemistry version of WACCM, roughly 10% higher burden maximum in the tropics, the response of sulfur injections on the QBO is the same. Both models are coupled to modal aerosol microphysical models. The number of modes differs: nucleation, Aitken, accumulation and, coarse mode in MAECHAM5-HAM and Aitken, accumulation and, coarse mode in WACCM. The mode widths are similar for the accumulation and coarse mode between the models.

2.1.1 MAECHAM5-HAM

MAECHAM5-HAM, hereafter ECHAM, is general circulation model (GCM) ECHAM, which is interactively coupled to the modal aerosol microphysical model HAM. The simulations for this study were performed with the middle atmosphere (MA) version of the GCM ECHAM (Giorgetta et al., 2006) with 90 vertical layers up to 0.01 hPa. The horizontal resolution was about 2.8°, spectral truncation at wave-number 42 (T42), and 1.8°(T63). ECHAM5 solves prognostic equations for temperature,

surface pressure, vorticity, divergence, and phases of water. The vertical resolution allows the internal generation of the QBO in the tropical stratosphere (Giorgetta et al., 2006).

The prognostic modal aerosol microphysical model in ECHAM is HAM (Stier et al., 2005), which calculates the sulfate aerosol formation including nucleation, accumulation, condensation and coagulation, as well as its removal processes by sedimentation and deposition. A simple stratospheric sulfur chemistry for sulfur oxidation is applied above the tropopause (Timmreck, 2001; Hommel et al., 2011). The radiative direct effect of sulfate is included for both, SW and LW radiation, and coupled to the radiation scheme of ECHAM. The sulfate aerosol influences dynamical processes via temperature changes caused by scattering of shortwave radiation and absorption of near-infrared and longwave radiation. Within this stratospheric HAM version apart from the injected SO₂, only natural sulfur emissions are taken into account. These simulations use the model setup described in Niemeier et al. (2009) and Niemeier and Timmreck (2015). The sea surface temperature (SST) is set to climatological values (Hurrell et al., 2008), averaged over the AMIP period 1950 to 2000, and does not change due to CE.

2.1.2 WACCM-110L

The Whole Atmosphere Community Climate Model WACCM-110L, hereafter WACCM, is a 'high top' version of the atmospheric component of the Community Earth System Model, version 1 (CESM1; Hurrell et al. (2013)) with 110 vertical levels up to $6 \cdot 10^{-4}$ hPa, instead of the default 70-levels. WACCM with 110 levels was developed for the SPARC QBO Initiative (QBOi, Butchart et al. (2018)) and this configuration of the model is in detail described in Garcia and Richter (2019). The horizontal resolution is 0.95° latitude \times 1.25° longitude. The tropospheric physics and parameterizations in WACCM are exactly the same as in the Community Atmosphere Model, version 5 (CAM5), as well as updated physical parameterizations for planetary boundary layer turbulence, cloud microphysics, and aerosols, which has been described in detail by Mills et al. (2017). The gravity wave parameterization in the 110-level version of WACCM has been adjusted to reproduce the observed period and amplitude of the QBO, as well as to produce extratropical stratospheric climate that's close to observed (see Garcia and Richter (2019) for full details).

Here, we use the specified chemistry version of WACCM, which uses a monthly varying present-day climatology to prescribe ozone, oxidants, and background stratospheric aerosols. Aerosols are prognostically derived using the modal aerosol model (MAM3) (Liu et al., 2012). Direct and indirect effects of radiative effects of aerosols are included. Additionally, geoengineering sulfur injections into the stratosphere are performed similarly to ECHAM. As described in Mills et al (2016) the lack of interactive stratospheric chemistry, prevents OH values from depleting while reacting with the injected sulfur. This leads to a slightly faster formation of sulfate closer to the injection location, and with that a different lofting of aerosols in the tropics compared to a full chemistry version, as used in Mills et al (2017). However, while the aerosol distribution is somewhat different than in the fully interactive chemistry version of WACCM, roughly 10% higher burden maximum in the tropics, the response of sulfur injections on the QBO is the same. The SST is prescribed and set to present day values.

2.2 Simulations

The model simulations for this study follow the same protocol. Both models prescribe a repeating annual cycle of SSTs, present day, and chemical precursors, which are necessary for e.g. sulfur oxidation and radiative processes, on a monthly basis. These fields slightly differ between the two models but are not expected to have much influence on the simulation of the QBO. SO₂ was injected continuously over time into a single grid box at the equator at a height of 60 hPa (about 19 km) with three different amounts of sulfur: 2, 4, 8 Tg(S)yr⁻¹. An injection altitude of 60 hPa has been used in many previous studies (e.g., Niemeier and Timmreck, 2015; Tilmes et al., 2018). Simulations were carried out with ECHAM and WACCM for at least 20 years. Exact number of simulation years used in this study is shown in Table 1. as well as the number of years used to calculate time averages. ECHAM simulations were carried out longer, however no differences have been found between the results averaged over 20 years and the entire simulation length of ECHAM. Figures show either timeseries or zonal averages over time. Anomalies are calculated relative to an average over a control run of 50 years (ECHAM) and 35 years (WACCM).

Table 1. Summary of simulations carried out with WACCM and ECHAM. Given are the number of years used for time averaging in this study Number of total simulation years is shown with the number of years in parentheses indicating the number of years used to calculate time averages of the different variables. The results are not sensitive to the number of years used to calculate time averages.

Injection rate	WACCM	ECHAM (T42)	ECHAM (T63)
Control	35 35 years	50 50 years	47 15
2Tg(S)yr ⁻¹	20 15	47 15	–
4Tg(S)yr ⁻¹	20 15	50 20	47 8
8Tg(S)yr ⁻¹	20 15	40 20	47 8

3 Results

3.1 QBO Changes

Figure 1 shows the zonal mean zonal wind at the equator for the control simulation and two different injection rates for WACCM and ECHAM. Both models simulate the QBO well in the control simulation, without artificial injections of SO₂ (top). The QBO has an observed period of 28 months (Naujokat, 1986) on average. The simulated QBO period is about 27 months in WACCM and about 32 month in ECHAM. In WACCM the wind velocity is higher, slightly in the westerly phase but stronger in the easterly phase especially at altitudes below 20 hPa, and the QBO propagates further down than in ECHAM. After the injection of sulfur into the tropical stratosphere the QBO responds quite differently to the same injection rate in the two models. While ECHAM shows a slower but still existing oscillation of the zonal wind for injections of 4 Tg(S)yr⁻¹, the oscillation of the zonal wind in WACCM completely vanishes, resulting in constant westerlies in the lower stratosphere, and easterlies above ~10 hPa (Fig 1, middle). Increasing the injection rate to 8 Tg(S)yr⁻¹ increases slightly the velocity of

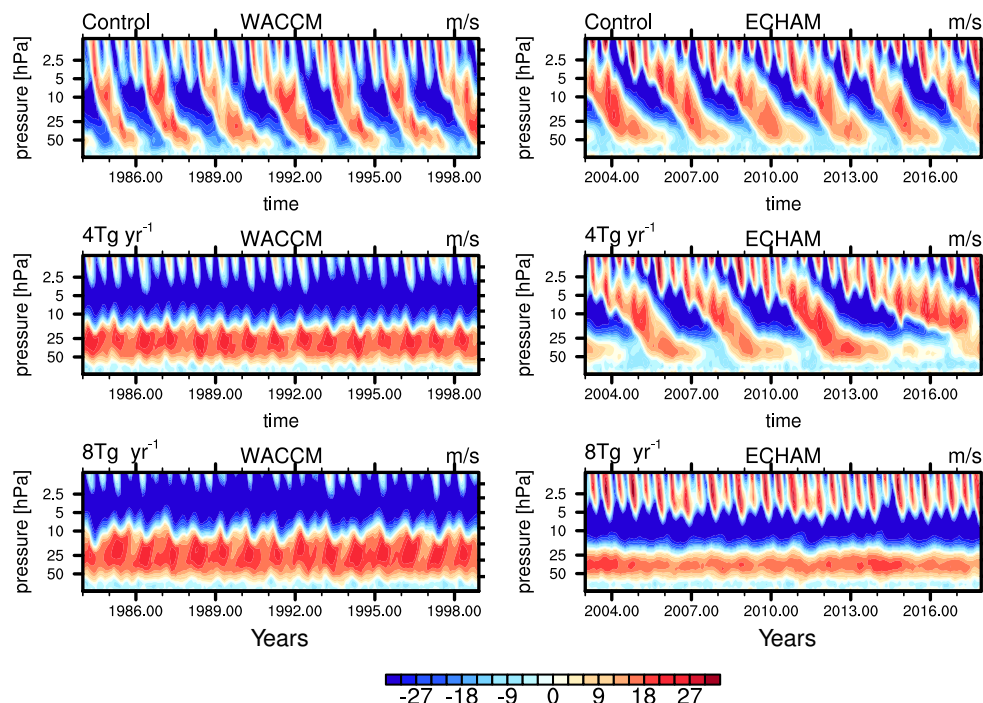


Figure 1. Zonal mean zonal wind [ms^{-1}] at the equator for a control simulation (top) and simulations with sulfur injections of 4 Tg(S) yr^{-1} (middle) and 8 Tg(S) yr^{-1} (bottom). Left: Results of WACCM. Right: Results of ECHAM.

140 the westerlies and the vertical extension of the westerly jet in WACCM (Fig 1, bottom). In ECHAM the oscillation vanishes at 8 Tg(S) yr^{-1} as well but wind velocity and vertical extension of the westerly jet are lower. The stronger westerly jets in WACCM shifts the semi-annual oscillation (SAO) above 5 hPa to higher altitudes. For ECHAM the SAO still reaches 5 hPa for 8 Tg(S) yr^{-1} injections, but gets shifted to higher altitudes, similar to WACCM, when the jets gets stronger with increasing injection rates (Niemeier and Schmidt, 2017). Thus, the QBO disappears in both models as a result of SO_2 injections, but at
145 different injection rates.

3.2 Temperature and heating rate changes

Aquila et al. (2014) identified the absorption of radiation by sulfate aerosols and the consequent heating in the lower stratosphere as the main cause for the changes in the QBO. The heated sulfate layer impacts the thermal wind balance and vertical advection. This heating differs clearly between WACCM and ECHAM as can be seen in the amplitude of temperature anomalies in the stratosphere for both models (Figure 2). WACCM simulates maxima of temperature anomalies of 5.7 and 12.5 K for injections of 4 and 8 Tg(S) yr^{-1} , ECHAM only 2 and 4.5 K. Thus, for the same sulfur injection rate, WACCM shows temperature anomaly roughly three times stronger than ECHAM for the 4 and 8 Tg(S) yr^{-1} injections respectively. Therefore,

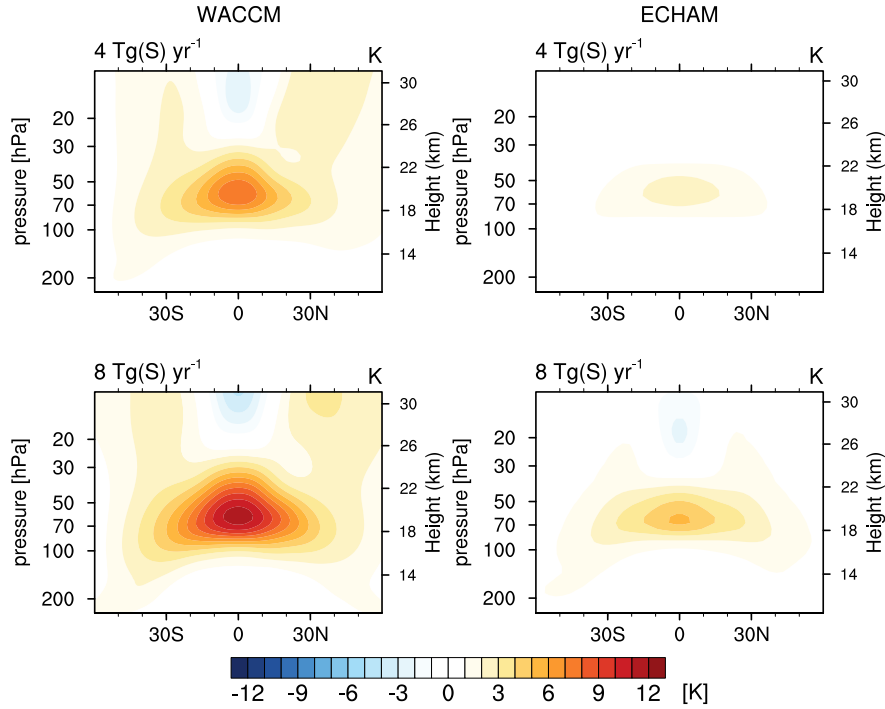


Figure 2. Temperature anomaly [K] caused by injections of 4 Tg(S)yr^{-1} (top) and 8 Tg(S)yr^{-1} (bottom) sulfur. Left: Results of WACCM. Right: Results of ECHAM5-HAM.

the different response of the QBO winds to the injection between the models is not surprising, as the thermal wind balance is much more strongly impacted in WACCM than in ECHAM.

155 We investigate the reason for the different stratospheric heating in WACCM and ECHAM by examining the shortwave (SW) and terrestrial or longwave (LW) heating rates in both models for the simulation with 4 Tg(S)yr^{-1} injection. Similar results are found for the 8 Tg(S)yr^{-1} simulation, and hence not shown. Splitting of the heating rates into SW and LW components shows that SW heating rates for both models are of comparable amplitude (Figure 3, top panels) whereas there is a clearly higher heating rate for LW radiation than for near infrared (short wave, SW) radiation in WACCM (Figure 3). The heating

160 rates show that WACCM absorbs more than twice as much in the LW than in SW, while absorption is similar in between LW and SW in ECHAM. In total (SW + LW), WACCM absorbs more than twice as much radiation than ECHAM. Compared to ECHAM, the LW absorption of sulfate in WACCM is three times stronger. We can see different absorption rates in LW and SW between the models, however, The stronger heating rate in WACCM corresponds to the stronger temperature anomaly in WACCM. Both models use the same radiation scheme, hence the differences can not be explained by the radiation scheme and

165 must be caused by other processes in the model. E.g. the heating rate due to absorption of LW radiation depends on the sulfur

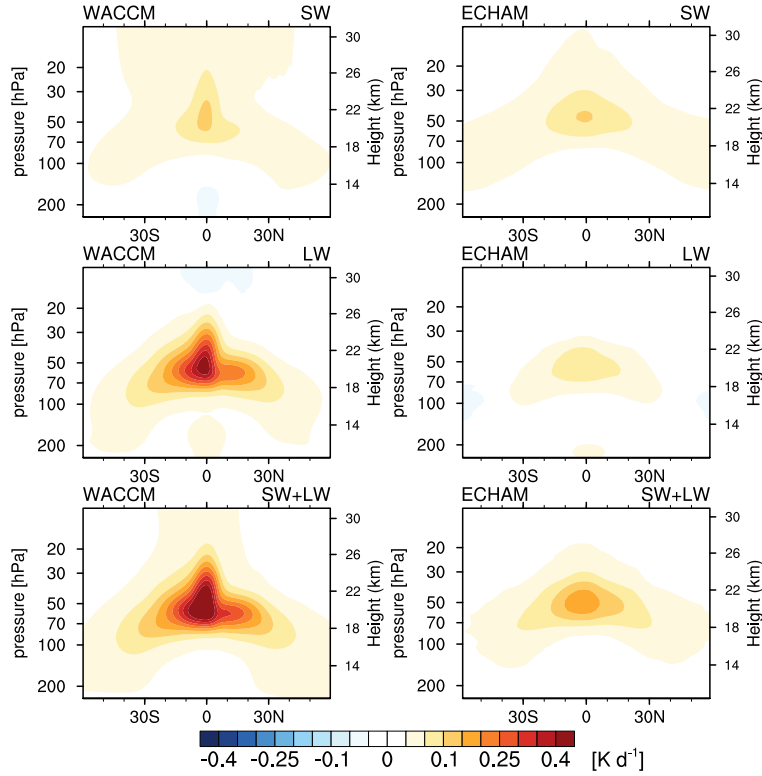


Figure 3. Zonally averaged heating rates of near infrared (SW, top panels), terrestrial (LW, middle panels), and total (bottom panels) radiation of both models after an injection of 4 Tg(S)yr^{-1} .

mass. Therefore, we can assume that these differences in the LW and SW absorption cannot be the reason for the different temperature anomalies.

3.3 Sulfate properties

The zonally averaged sulfate burden, the vertically integrated sulfate concentration, shows at all latitudes a higher burden in WACCM than in ECHAM for the injection rate of 4 Tg(S)yr^{-1} (Figure 4). WACCM shows a distinct peak at the equator while in ECHAM the distribution is much more even with latitude and the secondary maxima, caused by the blocking of meridional transport by the polar vortex in the winter hemisphere, in the extra-tropics are only slightly smaller than the tropical maximum. This three to four times larger tropical sulfate burden in WACCM explains the larger temperature anomaly in WACCM, as more sulfate aerosols can absorb more radiation.

The vertical cross section of the zonally averaged sulfate concentrations reveals more details of the differences in distributions of sulfate in the two models (Figure 5). Not only the tropical concentration is higher in WACCM, in addition, the vertical distribution of aerosols is very different between the two models. In ECHAM the sulfate is vertically advected to 25 hPa, while

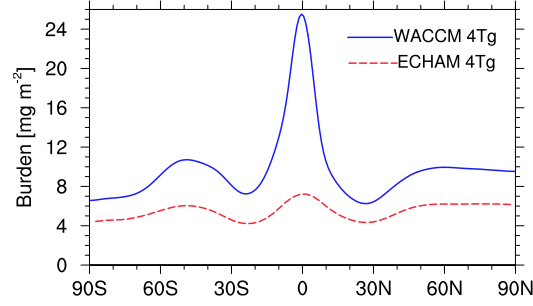


Figure 4. Zonally averaged sulfate burden of injections of 4 Tg(S)yr^{-1} for WACCM and ECHAM.

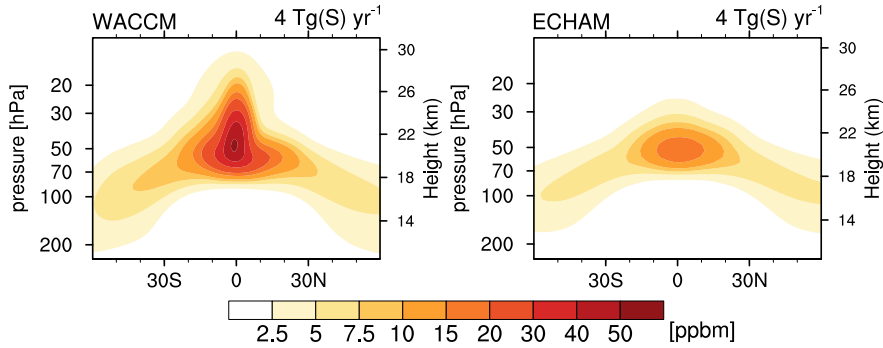


Figure 5. Zonally averaged sulfate concentration [ppbm] of injections of 4 Tg(S)yr^{-1} for WACCM and ECHAM.

in WACCM sulfate reaches much higher altitudes and meridional transport mainly occurs below 50 hPa. Vertical advection has to be much stronger in WACCM than in ECHAM to cause the differences. This is likely caused by a combination of a stronger lofting of aerosols as the result of radiative heating by aerosols, as well as resulting changes in the stratospheric wave propagation which causes an increase in the residual vertical velocity. Thus, from the comparison of the sulfur injection cases only we cannot conclude whether a) the strong vertical advection is a consequence of the stronger heating or b) the cause of higher sulfate mass and, consequently, stronger heating. At this point we can only assume that the stronger tropical aerosol heating in WACCM is related to the higher sulfate load. The heating is a consequence of the sulfate burden, and not the source of the differences between the two models.

To further understand differences in the aerosol distribution and the resulting heating between WACCM and ECHAM, we examine the effective radii of aerosols in both models. This comparison (Figure 6) shows in the tropics twice as large radii for WACCM ($0.6 \mu\text{m}$) than for ECHAM ($0.3 \mu\text{m}$). The higher sulfur load results in larger particle radii, less scattering and, less SW radiative forcing (Dykema et al., 2016). LW radiative forcing depends on the sulfate mass and stays constant per injected

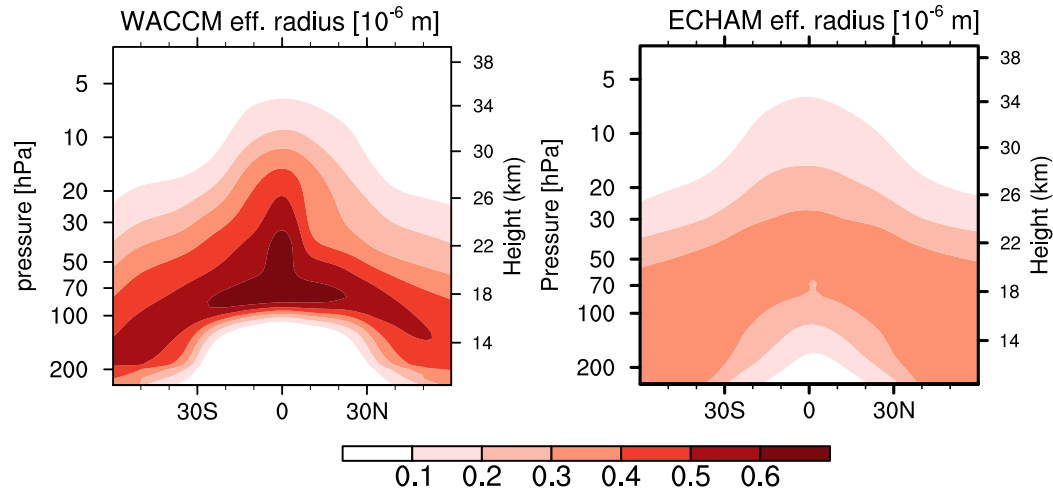


Figure 6. Effective radius [μm] for an injection rate of 4 Tg(S)yr^{-1} of WACCM (left) and ECHAM-HAM (right). WACCM shows only values in the stratosphere.

190 sulfur unit and is not related to particle radii. The different radii are therefore not related to the differences in heating rates between the models. From the larger radii in WACCM we may assume a stronger sedimentation in the tropics in WACCM. But the burden is larger in WACCM. If sedimentation is a major difference between the models, the difference in the tropical burden between the two models should be smaller. An additional process, which determines the lifetime of the aerosols in the tropics is the vertical advection, the residual vertical velocity ω^* .

195 3.4 Dynamical changes

The patterns of the heating rates, sulfate concentrations and particle radii hint towards a stronger vertical advection in WACCM. A proxy for this behaviour is the residual vertical velocity, ω^* . Richter et al. (2017) have shown that vertical advection plays a major role in dynamical changes in the tropical stratosphere. Visionsi et al. (2018) showed a strong relation between the sulfate lifetime and ω^* . Therefore, we compare the residual vertical velocity of the control simulations (Figure 7) to get a more general
 200 impression of the behaviour of the two models, independently of additional updraft caused by the aerosol heating. In the altitude of the sulfur injection (60 hPa) and above shows WACCM an up to 70% stronger ω^* than ECHAM. This stronger ω^* results in a stronger vertical transport of the sulfate aerosols, which increases the tropical sulfate burden in WACCM. Additionally, the minimum of the ω^* profile is located at lower altitude in WACCM (70 hPa and 50 hPa in ECHAM), resulting in a stronger tropical confinement of the aerosols at this altitude.

205 The consequence is twofold: a) a stronger ω^* counteracts more the downward propagation of the QBO shear zones and b) lifts the aerosols to higher altitudes, which increases the burden and, thus causes stronger heating. The heating of the aerosols

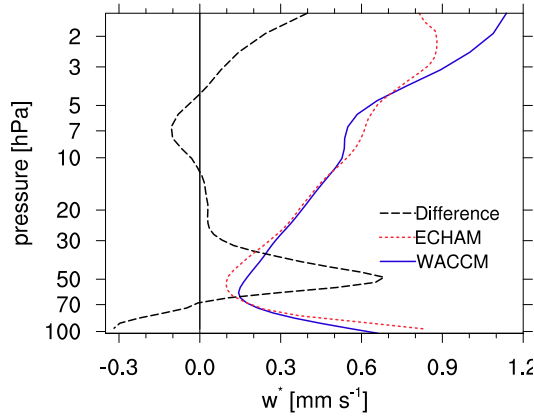


Figure 7. Residual vertical velocity of the control simulations in the tropics (averaged over 5°N to 5°S). Results of ECHAM (red) and WACCM (blue), and in black the difference (WACCM-ECHAM/ECHAM).

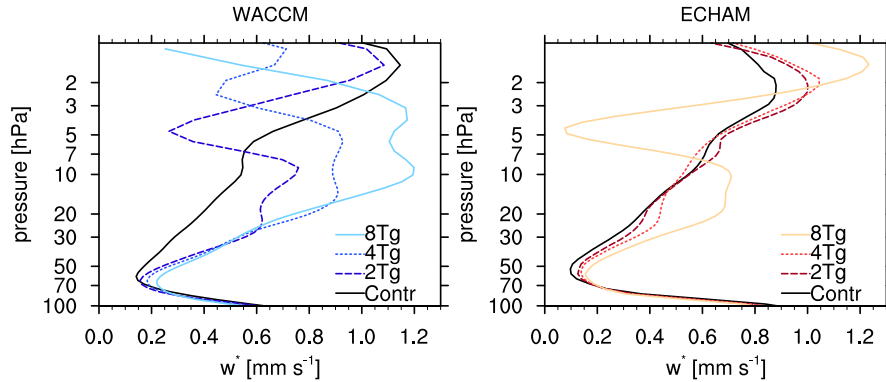


Figure 8. Residual vertical velocity in the tropics for the control simulation and simulations with injections of 2 Tg(S)yr^{-1} , 4 Tg(S)yr^{-1} and 8 Tg(S)yr^{-1} for WACCM (left) and ECHAM (right).

further increases ω^* , which shifts the minimum of ω^* downward (Figure 8). This can be seen in both models, but stronger in WACCM than in ECHAM. This feedback loop finally results in the vanishing of the QBO at an injection rate of 2 Tg(S)yr^{-1} in WACCM compared to 8 Tg(S)yr^{-1} in ECHAM. The reasons for the differences in ω^* in the control may lay in differences
210 in the gravity wave parameterization and the relation how strongly resolved Rossby waves or parameterized gravity waves drive the upward mass flux (Cohen et al., 2014; SPARC, 2010). The better grid resolution in WACCM may also play a role. We conclude that the stronger ω^* in WACCM to be the main reason for the differences between the QBO response in the two models.

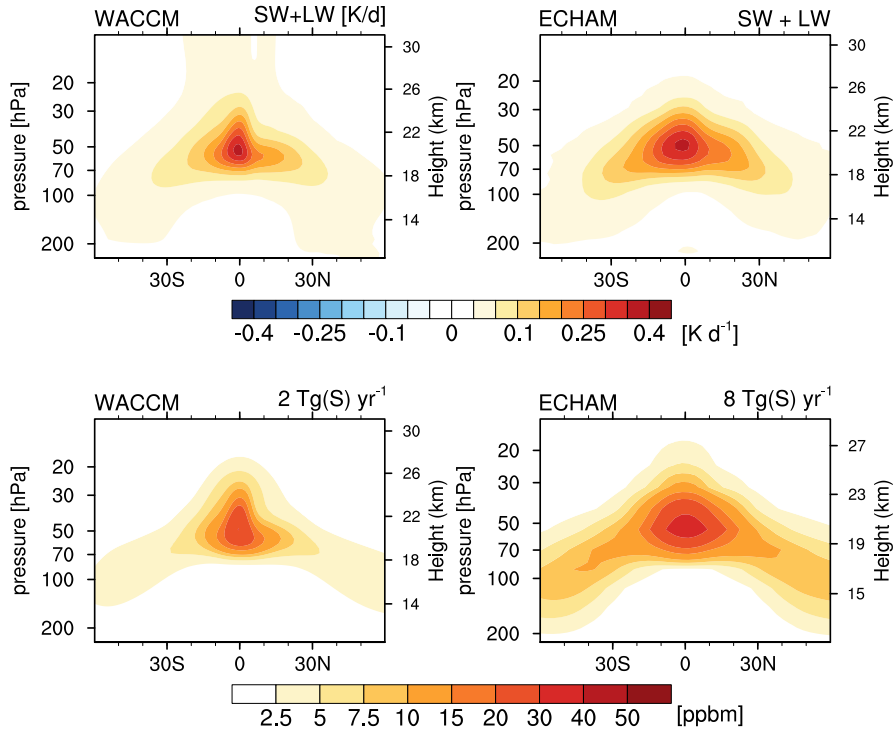


Figure 9. Top: Heating rate [K/d] and Bottom: sulfate concentration of a 2 Tg(S)yr^{-1} injection rate in WACCM (left) and an 8 Tg(S)yr^{-1} injection rate in ECHAM (right). Injection rates were chosen to result in similar temperature anomalies in both models. Intervals of the heating rates (top) are 0.01, 0.05, 0.1, 0.15, 0.2, 0.25, 0.3, 0.35, 0.4 Kday^{-1} .

3.5 Comparison under the same heating conditions

215 Are differences in ω^* between the models the main cause of the difference in QBO impact or does the different heating also play an important role? To answer this question we compare different sulfur injection rates in the models that produce a similar heating rate in the sulfate layer. An injection rate of 2 Tg(S)yr^{-1} in WACCM and 8 Tg(S)yr^{-1} in ECHAM fulfills this criterium (Figure 9, top). Both experiments result in a temperature anomaly of $\sim 4 \text{ K}$ in the tropical stratosphere. The heated area is slightly wider in ECHAM because the sulfate concentration (Figure 9, bottom) is slightly higher in the tropics and
 220 spreads more meridionally around 50 hPa. However, the maximum burden between the two models is rather similar in the tropics (Figure 10). The tropical maximum of the sulfate burden in ECHAM is only 2 mgm^{-2} (12%) higher than in WACCM, despite a factor 4 higher injection rate of sulfur. The differences in the burden are larger in the extratropics ($\sim 50\%$). But the extratropical differences are not the focus of this study as we focus on the tropical stratosphere and the QBO.

The continuous westerly and easterly jets cause a different profile of ω^* than oscillating zonal winds under QBO conditions
 225 (Fig. 8). The clearly different profile of ω^* for the low injection cases to the 8 Tg(S)yr^{-1} in ECHAM and for all three injection

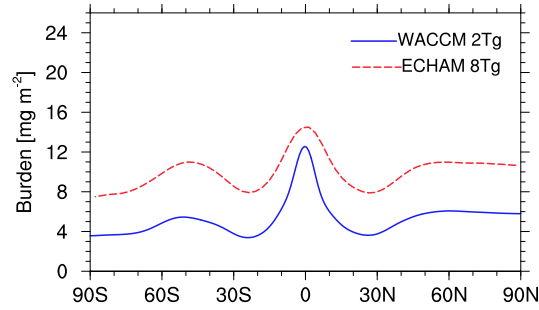


Figure 10. Zonally averaged sulfate burden of a 2 Tg(S)yr^{-1} injection rate in WACCM (blue) and an 8 Tg(S)yr^{-1} injection rate in ECHAM-HAM (red, dashed).

cases to the control in WACCM is a consequence of the disappearance of the QBO. We see a strong correlation of the pattern of the residual vertical velocity to the equatorial zonal wind profiles (Figure 1). The characteristic pattern of the vertical profile of ω^* in WACCM becomes similar in ECHAM-HAM when the oscillation of the equatorial jets vanishes at 8 Tg(S)yr^{-1} (Figure 8). Consequently, the maximum difference of ω^* between the models is only 30% 34% within the sulfate layer (80 to 20 hPa) when comparing the 2 Tg(S)yr^{-1} WACCM and the 8 Tg(S)yr^{-1} ECHAM injection cases (Figure 11). Differences occur mostly due to a vertical shift in the profiles. The constant easterly and westerly jets cause distinct maxima and minima of ω^* below 50 hPa. This compares well to the theory of the meridional and vertical transport processes within the QBO region and the secondary meridional oscillation (Plumb and Bell, 1982), which is caused by equatorward meridional advection in westerly jets and poleward within easterly jets combined with updraft in easterly shear and downdraft in westerly shear. E.g. the position of the maxima around 30 and 20 hPa are the transition zones of the westerly and easterly jets. The heating of the aerosols, and the corresponding increased ω^* , interferes with downdraft tendency in the westerly shear zone below 50 hPa. The result is the ω^* minimum around 60 hPa and the maximum between 30 hPa and 10 hPa agrees alines with the easterly shear zone (Figure 12).

Finally, we can say that the similar heating anomalies result in very similar zonal winds at the equator in both models (Figure 12). Both models show the vanishing of the QBO with a westerly jet in the lower stratosphere combined with an easterly jet at higher altitudes. WACCM simulates slightly higher wind velocities and less vertical extension of the westerly jet than ECHAM, but in general the response of the two models is very similar. Our findings suggest that the stronger tropical aerosol heating in WACCM is related to the higher sulfate load caused by the stronger ω^* . is a consequence of the higher sulfate concentrations. The source of the differences between the two models, and the cause of the higher concentrations in WACCM, is the different ω^* .

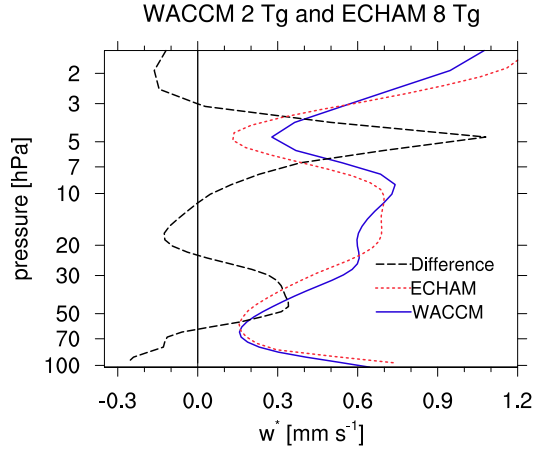


Figure 11. Figure 11: Residual vertical velocity in the tropics for a WACCM simulation with an injection rate of 2 Tg(S)yr^{-1} (blue), ECHAM simulation with an injection rate of 8 Tg(S)yr^{-1} (red), and the difference (black, (WACCM-ECHAM)/ECHAM).

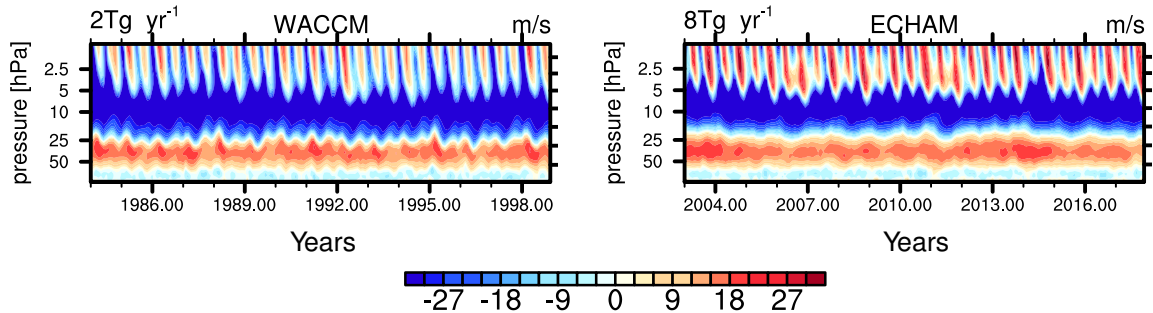


Figure 12. Zonal mean zonal wind at the equator of a 2 Tg(S)yr^{-1} injection rate in WACCM (right) and an 8 Tg(S)yr^{-1} injection rate in ECHAM.

3.6 Impact of grid resolution

The horizontal resolution of the two models is very different in this study, $\sim 1^\circ$ for WACCM, and $\sim 2.8^\circ$ for ECHAM. Therefore, we examine the importance of different horizontal model resolutions on our results to reduce the number of uncertainties in our comparison. We increased the resolution of ECHAM from T42 to T63 ($\sim 1.8^\circ$). This is still a coarser horizontal resolution than in WACCM but differences between the two simulations of ECHAM can indicate the impact of the horizontal resolution on the transport of sulfate out of the tropics and on the QBO.

When comparing the vertical velocity of T42 and T63 control simulations of ECHAM in the tropics (Fig. 13, left), we get a slight increase on ω^* (16%) in T63 in the area of the sulfate layer around an altitude of 50 hPa. This is much smaller than the difference to WACCM. Thus, we could expect a still smaller ω^* in ECHAM in case of a similar horizontal resolution. But we also see a slight shift of the minimum of ω^* to a lower altitude. From the differences to WACCM, the minimum of ω^* is at lower altitude in WACCM, we can expect a stronger confinement of the aerosols in the tropics. Indeed we find that the horizontal resolution has an impact on the simulated burden (Fig 13, right). The burden is about 30% higher in the tropics for injections of 8 TgS/yr in the T63 simulation as compared to the T42 simulation. The 4 Tg(S)yr⁻¹ burden comes closer to the 2 Tg(S)yr⁻¹ results of WACCM, with a substantial reduction of the peak in the aerosol burden in the tropics, but does not causes the QBO to vanish (not shown).

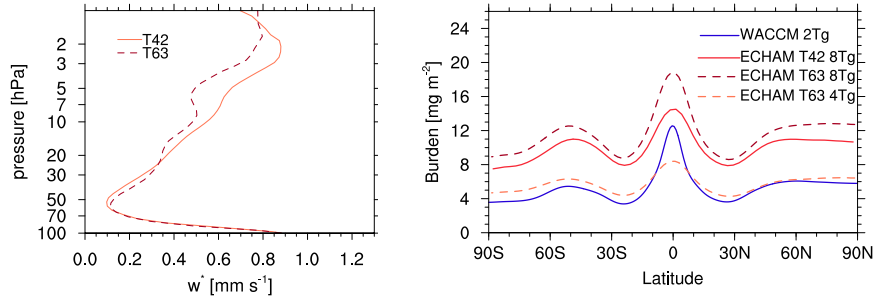


Figure 13. Left: Residual vertical velocity in the tropics of control simulations of ECHAM with T42 and T63 resolution. Right: Zonally averaged sulfate burden of WACCM (blue) and ECHAM T63 (dashed) and T42 (solid).

The vertical resolution of the models differs as well: 110 levels in WACCM and 90 levels in ECHAM. Within the area of interest however, between 100 and 10 hPa, the number of model levels is very similar: 32 levels for WACCM and 27 levels for ECHAM, with approximate grid spacing of 0.5 km for WACCM and 0.6 km for ECHAM. We do not expect a strong impact on ω^* from this small difference in vertical resolution.

Horizontal resolution seems to play a bigger role in the simulation of ω^* . Increasing the resolution to T63 leads to a polar shift of the mid-latitude westerlies in the troposphere (Roeckner et al., 2006) with consequences on large scale wave propagation into the stratosphere. The dynamical changes result in an increase of the sulfate burden at all latitudes, not only in the tropics. The pattern of the burden indicates a slightly smaller residual meridional velocity and different isentropic mixing in the mid-latitudes in T63. Additionally, Brühl et al. (2018) describe a better representation of sedimentation processes at high latitudes in T63. As we concentrate on the impact of sulfate on the QBO in this study, the differences in the extra-tropics will be left for further studies.

4 Summary and Discussion

We performed here simulations with different injection rates of SO_2 at the equator to compare the impact on the QBO in two different general circulation models (WACCM and ECHAM). The QBO typically consists of alternating easterly and westerly zonal mean zonal winds, however in the presence of sulfur injections, the QBO sometimes vanishes, and turns into persistent westerlies in the lower stratosphere and persistent easterlies in the upper stratosphere. Both models used in the study had similar setup (e.g. prescribed SSTs and present day chemical precursors like OH or ozone) and were coupled to an aerosol microphysical model with three modes in WACCM and four modes in ECHAM. Both models qualitatively simulate an impact on the QBO of sulfur injections similar to what was found in previous studies (Niemeier and Schmidt, 2017; Richter et al., 2017), however WACCM shows a disappearance of the QBO at an injection rate of 2 Tg(S)yr^{-1} whereas ECHAM shows the disappearance of the QBO for an injection rate of 8 Tg(S)yr^{-1} .

We have shown that this difference results from different tropical vertical advection and different tropical residual vertical velocity, ω^* , in the two models. ω^* differs not only in the simulations with SO_2 injections, but also in the control simulations without any sulfur injection. In WACCM, ω^* is 70% larger than in ECHAM near the altitude of the SO_2 injection. Additionally, the minimum of ω^* is located at a lower altitude. At altitudes with a small ω^* meridional transport is enhanced, while a strong ω^* causes an enhanced tropical confinement of the aerosols. This confinement is stronger in WACCM above 50 hPa. Thus, the stronger ω^* results in a stronger vertical lifting, higher sulfate burden and, consequently, stronger heating of the stratosphere caused by aerosol absorption. This heating disturbs the thermal wind balance and causes an additional westerly momentum. Finally, this results in the disappearance of the QBO at lower SO_2 injection rates than in ECHAM. This result partly opposes the assumptions of Kleinschmitt et al. (2017), who assumed the heating as main cause for different vertical advection in two models. It would be interesting to compare our results to the ω^* of their control simulation.

In this study we compared injections at 60 hPa (about 19 km) only. This altitude shows the largest differences in ω^* between the two models of all altitudes. Therefore, injections at higher altitude, e.g. 30 hPa (24 km) would, most probably, cause less differences. Comparing results of Niemeier and Schmidt (2017) and Tilmes et al. (2018), both show results of injections at two altitudes, shows smaller differences between the models for the higher altitude injections.

The reason for the different ω^* in the two models is complex. ω^* , or the speed of the upwelling in the Brewer Dobson circulation is driven by a combination of larger scale (Rossby and synoptic-scale waves) and parameterized waves. The propagation of waves and deposition of wave momentum by larger scale waves is impacted by numerous aspects of the model such as horizontal and vertical resolution, diffusion parameterization, physics parameterizations, which all differ between WACCM and ECHAM. Gravity wave parameterization contributions to driving the Brewer-Dobson circulation also vary between models (Butchart et al., 2011). WACCM and ECHAM have very different gravity wave parameterizations. It would be very difficult hence to isolate the reason for the different ω^* between WACCM and ECHAM, but simulations with different horizontal resolution shown in Section 3.6 have shown that horizontal resolution difference between WACCM and ECHAM contributed to the differences in ω^* . Additionally, sedimentation may differ between the models as might be concluded from the difference in deposition when simulating a Tambora like volcanic eruption (Marshall et al., 2018). Sedimentation is a very important sink

process for aerosols, especially at the poles, but three dimensional fields of sedimentation velocities were not available for both models. As we concentrated on the tropical stratosphere only, we leave this topic for further studies.

Finally we conclude that the difference in tropical upwelling even under present climate conditions between two models has a major impact on the projected effects of SO₂ injections on the QBO in WACCM and ECHAM. This is worrisome in terms of level of certainty of effects of SO₂ injections on stratospheric circulation in future climates, especially as the changes in the Brewer-Dobson circulation are uncertain, and in addition changes in gravity waves, which are a big driver of the QBO are even more uncertain in changing climate. [The model intercomparison initiative GeoMIP6 \(Kravitz et al., 2015\) has mainly concentrated on climate impact of CE. A simple SO₂ injection experiment with well defined input parameters for GCM with aerosol microphysical modules, e.g. grid resolution, injection, model setups, may create further understanding on related differences and uncertainties.](#) Hence, a lot more research is needed before agreement is reached on how SO₂ injections could affect the QBO. The reasons for the differences in this variable are too complex to give a recipe for a better agreement of the results.

Code and data availability. Primary data and scripts used in the analysis and other supplementary information that may be useful in reproducing the author's work are archived by the Max Planck Institute for Meteorology and can be obtained by contacting publications@mpimet.mpg.de. Model results of ECHAM are available under: https://cera-www.dkrz.de/WDCC/ui/cersearch/entry?acronym=DKRZ_LTA_550_ds00002 Model results of WACCM, and partly ECHAM, will also be made available via the cera databank of DKRZ.

Author contributions. All authors discussed the idea of the study and the setup of the models. UN performed ECHAM simulations, JR and ST WACCM simulations. UN and JR did the model comparison. UN wrote the manuscript with strong participation of JR and ST.

Competing interests. We declare no competing interests

Disclaimer. TEXT

Acknowledgements. We thank two anonymous reviewers and Andrea Segschneider for their helpful comments. This work is a contribution to the German DFG-funded Priority Program 'Climate Engineering: Risks, Challenges, Opportunities?' (SPP 1689). UN is supported by the SPP 1689 within the project CEIBRAL and CELARIT and DFG Research Unit VollImpact FOR2820 sub project TI344/2-1 UN got support from SPP 1689 and NCAR for an scientific exchange in Boulder in 2016, where we discussed and started the model comparison. The simulations were performed on the computer of the Deutsches Klima Rechenzentrum (DKRZ).

This work was supported by the National Center for Atmospheric Research, which is a major facility sponsored by the National Science Foundation under Cooperative Agreement No. 1852977. WACCM is a component of the Community Earth System Model (CESM), which is supported by NSF and the Office of Science of the U.S. Department of Energy. Computing resources were provided by NCAR's Climate
335 Simulation Laboratory, sponsored by NSF and other agencies. This research was enabled by the computational and storage resources of NCAR's Computational and Information Systems Laboratory (CISL). All simulations were carried out on the Yellowstone high-performance computing platform (CISL 2012).

CISL, 2012: Yellowstone: IBM iDataPlex /FDR-LIB. Computational and Information Systems Laboratory, <http://n2t.net/ark:/85065/d7FD3xhc>.

340 References

- Andrews, D. G., Holton, J. R., and Leovy, C. B.: Middle Atmosphere Dynamics, Academic Press, San Diego, CA, 1987.
- Aquila, V., Oman, L. D., Stolarski, R. S., Colarco, P. R., and Newman, P. A.: Dispersion of the volcanic sulfate cloud from a Mount Pinatubo-like eruption, *Journal of Geophysical Research: Atmospheres*, 117, <https://doi.org/10.1029/2011JD016968>, <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2011JD016968>, 2012.
- 345 Aquila, V., Garfinkel, C. I., Newman, P., Oman, L. D., and Waugh, D. W.: Modifications of the quasi-biennial oscillation by a geoengineering perturbation of the stratospheric aerosol layer, *Geophys. Res. Lett.*, 41, 1738–1744, <https://doi.org/10.1002/2013GL058818>, 2014.
- Baldwin, M. P., Gray, L. J., Dunkerton, T. J., Hamilton, K., Haynes, P. H., Randel, W. J., Holton, J. R., Alexander, M. J., Hirota, I., Horinouchi, T., Jones, D. B. A., Kinnnersley, J. S., Marquardt, C., Sato, K., and Takahashi, M.: The quasi-biennial oscillation, *Rev. Geophys.*, 39, 179–229, 2001.
- 350 Brühl, C., Schallrock, J., Klingmüller, K., Robert, C., Bingen, C., Clarisse, L., Heckel, A., North, P., and Rieger, L.: Stratospheric aerosol radiative forcing simulated by the chemistry climate model EMAC using Aerosol CCI satellite data, *Atmospheric Chemistry and Physics*, 18, 12 845–12 857, <https://doi.org/10.5194/acp-18-12845-2018>, 2018.
- Butchart, N., Charlton-Perez, A. J., Cionni, I., Hardiman, S. C., Haynes, P. H., Krüger, K., Kushner, P. J., Newman, P. A., Osprey, S. M., Perlwitz, J., Sigmond, M., Wang, L., Akiyoshi, H., Austin, J., Bekki, S., Baumgaertner, A., Braesicke, P., Br¹/₄hl, C., Chipperfield, M.,
355 Dameris, M., Dhomse, S., Eyring, V., Garcia, R., Garny, H., Jöckel, P., Lamarque, J.-F., Marchand, M., Michou, M., Morgenstern, O., Nakamura, T., Pawson, S., Plummer, D., Pyle, J., Rozanov, E., Scinocca, J., Shepherd, T. G., Shibata, K., Smale, D., Teyss¹/₂dre, H., Tian, W., Waugh, D., and Yamashita, Y.: Multimodel climate and variability of the stratosphere, *Journal of Geophysical Research: Atmospheres*, 116, <https://doi.org/10.1029/2010JD014995>, <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2010JD014995>, 2011.
- Butchart, N., Anstey, J. A., Hamilton, K., Osprey, S., McLandress, C., Bushell, A. C., Kawatani, Y., Kim, Y.-H., Lott, F., Scinocca, J.,
360 Stockdale, T. N., Andrews, M., Bellprat, O., Braesicke, P., Cagnazzo, C., Chen, C.-C., Chun, H.-Y., Dobrynin, M., Garcia, R. R., Garcia-Serrano, J., Gray, L. J., Holt, L., Kerzenmacher, T., Naoe, H., Pohlmann, H., Richter, J. H., Scaife, A. A., Schenzinger, V., Serva, F., Versick, S., Watanabe, S., Yoshida, K., and Yukimoto, S.: Overview of experiment design and comparison of models participating in phase 1 of the SPARC Quasi-Biennial Oscillation initiative (QBOi), *Geoscientific Model Development*, 11, 1009–1032, <https://doi.org/10.5194/gmd-11-1009-2018>, <https://www.geosci-model-dev.net/11/1009/2018/>, 2018.
- 365 Cohen, N. Y., Gerber, E. P., and Bühler, O.: What Drives the Brewer-Dobson Circulation?, *Journal of the Atmospheric Sciences*, 71, 3837–3855, <https://doi.org/10.1175/JAS-D-14-0021.1>, 2014.
- Dykema, J. A., Keith, D. W., and Keutsch, F. N.: Improved aerosol radiative properties as a foundation for solar geoengineering risk assessment, *Geophysical Research Letters*, 43, 7758–7766, <https://doi.org/10.1002/2016GL069258>, <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2016GL069258>, 2016.
- 370 Garcia, R. R. and Richter, J. H.: On the Momentum Budget of the Quasi-Biennial Oscillation in the Whole Atmosphere Community Climate Model, *Journal of the Atmospheric Sciences*, 76, 69–87, <https://doi.org/10.1175/JAS-D-18-0088.1>, <https://doi.org/10.1175/JAS-D-18-0088.1>, 2019.
- Giorgetta, M. A., Manzini, E., Roeckner, E., Esch, M., and Bengtsson, L.: Climatology and forcing of the quasi-biennial oscillation in the MAECHAM5 model, *J. Climate*, 19, 3882–3901, 2006.

- 375 Hommel, R., Timmreck, C., and Graf, H. F.: The global middle-atmosphere aerosol model MAECHAM5-SAM2: comparison with satellite and in-situ observations, *Geoscientific Model Development*, 4, 809–834, <https://doi.org/10.5194/gmd-4-809-2011>, <http://www.geosci-model-dev.net/4/809/2011/>, 2011.
- Hurrell, J. W., Hack, J. J., Shea, D., Caron, J. M., and Rosinski, J.: A New Sea Surface Temperature and Sea Ice Boundary Dataset for the Community Atmosphere Model, *Journal of Climate*, 21, 5145–5153, <https://doi.org/10.1175/2008JCLI2292.1>, <https://doi.org/10.1175/2008JCLI2292.1>, 2008.
- 380 Hurrell, J. W., Holland, M. M., Gent, P. R., Ghan, S., Kay, J. E., Kushner, P. J., Lamarque, J.-F., Large, W. G., Lawrence, D., Lindsay, K., Lipscomb, W. H., Long, M. C., Mahowald, N., Marsh, D. R., Neale, R. B., Rasch, P., Vavrus, S., Vertenstein, M., Bader, D., Collins, W. D., Hack, J. J., Kiehl, J., , and Marshall, S.: The Community Earth System Model: A Framework for Collaborative Research, *Bull. Amer. Meteor. Soc.*, 94, 1339–1360, <https://doi.org/10.1175/BAMS-D-12-00121.1>, 2013.
- 385 Jones, A. C., Haywood, J. M., and Jones, A.: Climatic impacts of stratospheric geoengineering with sulfate, black carbon and titania injection, *Atmospheric Chemistry and Physics*, 16, 2843–2862, <https://doi.org/10.5194/acp-16-2843-2016>, <https://www.atmos-chem-phys.net/16/2843/2016/>, 2016.
- Kleinschmitt, C., Boucher, O., and Platt, U.: Sensitivity of the radiative forcing by stratospheric sulfur geoengineering to the amount and strategy of the SO₂ injection studied with the LMDZ-S3A model, *Atmospheric Chemistry and Physics Discussions*, 2017, 1–34, <https://doi.org/10.5194/acp-2017-722>, <https://www.atmos-chem-phys-discuss.net/acp-2017-722/>, 2017.
- 390 Kravitz, B., Robock, A., Tilmes, S., Boucher, O., English, J. M., Irvine, P. J., Jones, A., Lawrence, M. G., MacCracken, M., Muri, H., Moore, J. C., Niemeier, U., Phipps, S. J., Sillmann, J., Storelvmo, T., Wang, H., and Watanabe, S.: The Geoengineering Model Inter-comparison Project Phase 6 (GeoMIP6): Simulation design and preliminary results, *Geoscientific Model Development*, 8, 3379–3392, <https://doi.org/10.5194/gmd-8-3379-2015>, 2015.
- 395 Liu, X., Easter, R. C., Ghan, S. J., Zaveri, R., Rasch, P., Shi, X., Lamarque, J.-F., Gettelman, A., Morrison, H., Vitt, F., Conley, A., Park, S., Neale, R., Hannay, C., Ekman, A. M. L., Hess, P., Mahowald, N., Collins, W., Iacono, M. J., Bretherton, C. S., Flanner, M. G., and Mitchell, D.: Toward a minimal representation of aerosols in climate models: description and evaluation in the Community Atmosphere Model CAM5, *Geoscientific Model Development*, 5, 709–739, <https://doi.org/10.5194/gmd-5-709-2012>, <https://www.geosci-model-dev.net/5/709/2012/>, 2012.
- 400 Marshall, L., Schmidt, A., Toohey, M., Carslaw, K. S., Mann, G. W., Sigl, M., Khodri, M., Timmreck, C., Zanchettin, D., Ball, W. T., Bekki, S., Brooke, J. S. A., Dhomse, S., Johnson, C., Lamarque, J.-F., LeGrande, A. N., Mills, M. J., Niemeier, U., Pope, J. O., Poulain, V., Robock, A., Rozanov, E., Stenke, A., Sukhodolov, T., Tilmes, S., Tsigaridis, K., and Tummon, F.: Multi-model comparison of the volcanic sulfate deposition from the 1815 eruption of Mt. Tambora, *Atmospheric Chemistry and Physics*, 18, 2307–2328, <https://doi.org/10.5194/acp-18-2307-2018>, <https://www.atmos-chem-phys.net/18/2307/2018/>, 2018.
- 405 Mills, M. J., Schmidt, A., Easter, R., Solomon, S., Kinnison, D. E., Ghan, S. J., Neely, R. R., Marsh, D. R., Conley, A., Bardeen, C. G., and Gettelman, A.: Global volcanic aerosol properties derived from emissions, 1990 - 2014, using CESM1(WACCM), *Journal of Geophysical Research: Atmospheres*, 121, 2332–2348, <https://doi.org/10.1002/2015JD024290>, <http://dx.doi.org/10.1002/2015JD024290>, 2015JD024290, 2016.
- Mills, M. J., Richter, J. H., Tilmes, S., Kravitz, B., MacMartin, D. G., Glanville, A. A., Tribbia, J. J., Lamarque, J.-F., Vitt, F., Schmidt, A., Gettelman, A., Hannay, C., Bacmeister, J. T., and Kinnison, D. E.: Radiative and Chemical Response to Interactive Stratospheric Sulfate Aerosols in Fully Coupled CESM1(WACCM), *Journal of Geophysical Research: Atmospheres*, 122, 13,061–13,078, <https://doi.org/10.1002/2017JD027006>, <http://dx.doi.org/10.1002/2017JD027006>, 2017JD027006, 2017.

- Naujokat, B.: An update of the observed quasi-biennial oscillation of the stratospheric winds over the tropics, *J. Atmos. Sci.*, 43, 1873–1877, 1986.
- 415 Niemeier, U. and Schmidt, H.: Changing transport processes in the stratosphere by radiative heating of sulfate aerosols, *Atmospheric Chemistry and Physics*, 17, 14 871–14 886, <https://doi.org/10.5194/acp-17-14871-2017>, <https://www.atmos-chem-phys.net/17/14871/2017/>, 2017.
- Niemeier, U. and Tilmes, S.: Sulfur injections for a cooler planet, *Science*, 357, 246–248, <https://doi.org/10.1126/science.aan3317>, <http://science.sciencemag.org/content/357/6348/246>, 2017.
- 420 Niemeier, U. and Timmreck, C.: What is the limit of climate engineering by stratospheric injection of SO₂?, *Atmospheric Chemistry and Physics*, 15, 9129–9141, <https://doi.org/10.5194/acp-15-9129-2015>, <http://www.atmos-chem-phys.net/15/9129/2015/>, 2015.
- Niemeier, U., Timmreck, C., Graf, H.-F., Kinne, S., Rast, S., and Self, S.: Initial fate of fine ash and sulfur from large volcanic eruptions, *Atmospheric Chemistry and Physics*, 9, 9043–9057, <http://www.atmos-chem-phys.net/9/9043/2009/>, 2009.
- Plumb, R. A.: A tropical pipe model of stratospheric transport, *J. Geophys. Res.*, 101, 3957–3972, 1996.
- 425 Plumb, R. A. and Bell, R. C.: A model of quasibiennial oscillation on an equatorial beta-plane, *Q. J. R. Meteorol. Soc.*, 108, 335–352, 1982.
- Punge, H. J., Konopka, P., Giorgetta, M. A., and Müller, R.: Effects of the quasi-biennial oscillation on low-latitude transport in the stratosphere derived from trajectory calculations, *J. Geophys. Res.*, 114, D03 102, <https://doi.org/10.1029/2008JD010518>, 2009.
- Richter, J. H., Tilmes, S., Mills, M. J., Tribbia, J. J., Kravitz, B., MacMartin, D. G., Vitt, F., and Lamarque, J.-F.: Stratospheric Dynamical Response and Ozone Feedbacks in the Presence of SO₂ Injections, *Journal of Geophysical Research: Atmospheres*, pp. n/a–n/a, <https://doi.org/10.1002/2017JD026912>, <http://dx.doi.org/10.1002/2017JD026912>, 2017JD026912, 2017.
- 430 Roeckner, E., Brokopf, R., Esch, M., Giorgetta, M., Hagemann, S., Kornblueh, L., Manzini, E., Schlese, U., and Schulzweida, U.: Sensitivity of simulated climate to horizontal and vertical resolution in the ECHAM5 atmosphere model, *J. Climate*, 19, 3771–3791, 2006.
- Shuckburgh, E., Norton, W., Iwi, A., and Haynes, P.: Influence of the quasi-biennial oscillation on isentropic transport and mixing in the tropics and subtropics, *J. Geophys. Res.*, 106, 14 327–14 337, 2001.
- 435 SPARC: SPARC Report on the Evaluation of Chemistry-Climate Models, <https://doi.org/http://www.atmosp.physics.utoronto.ca/SPARC>, SPARC Report No. 5, WCRP-132, WMO/TD-No. 1526, V. Eyring, T. G. Shepherd, D. W. Waugh (Eds.), 2010.
- Stier, P., Feichter, J., Kinne, S., Kloster, S., Vignati, E., Wilson, J., Ganzeveld, L., Tegen, I., Werner, M., Balkanski, Y., Schulz, M., Boucher, O., Minikin, A., and Petzold, A.: The aerosol-climate model ECHAM5–HAM, *Atmos. Chem. Phys.*, 5, 1125–1156, 2005.
- Tilmes, S., Richter, J. H., Mills, M. J., Kravitz, B., MacMartin, D. G., Vitt, F., Tribbia, J. J., and Lamarque, J.-F.: Sensitivity of Aerosol Distribution and Climate Response to Stratospheric SO₂ Injection Locations, *Journal of Geophysical Research: Atmospheres*, 122, 12,591–12,615, <https://doi.org/10.1002/2017JD026888>, <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2017JD026888>, 2017.
- 440 Tilmes, S., Richter, J. H., Mills, M. J., Kravitz, B., MacMartin, D. G., Garcia, R. R., Kinnison, D. E., Lamarque, J.-F., Tribbia, J., and Vitt, F.: Effects of Different Stratospheric SO₂ Injection Altitudes on Stratospheric Chemistry and Dynamics, *Journal of Geophysical Research: Atmospheres*, 123, 4654–4673, <https://doi.org/10.1002/2017JD028146>, <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2017JD028146>, 2018.
- 445 Timmreck, C.: Three-dimensional simulation of stratospheric background aerosol: First results of a multiannual general circulation model simulation, *J. Geophys. Res.*, 106, 28 313–28 332, 2001.
- Timmreck, C., Graf, H.-F., and Kirchner, I.: A one and half year interactive MA/ECHAM4 simulation of Mount Pinatubo Aerosol, *J. Geophys. Res.*, 104, 9337–9360, <https://doi.org/10.1029/1999JD900088>, 1999.

- 450 Visioni, D., Pitari, G., di Genova, G., Tilmes, S., and Cionni, I.: Upper tropospheric ice sensitivity to sulfate geoengineering, *Atmospheric Chemistry and Physics*, 18, 14 867–14 887, <https://doi.org/10.5194/acp-18-14867-2018>, <https://www.atmos-chem-phys.net/18/14867/2018/>, 2018.
- Zanchettin, D., Khodri, M., Timmreck, C., Toohey, M., Schmidt, A., Gerber, E., Hegerl, G., Robock, A., Pausata, F., Ball, W., Bauer, S., Bekki, S., Dhomse, S., LeGrande, A., Mann, G., Marshall, L., Mills, M., Marchand, M., Niemeier, U., Poulain, V., Rozanov, E., Rubino, A., Stenke, A., Tsigaridis, K., and Tummon, F.: The Model Intercomparison Project on the climatic response to Volcanic forcing (VolMIP): experimental design and forcing input data for CMIP6, *Geoscientific Model Development*, 9, 2701–2719, <https://doi.org/10.5194/gmd-9-2701-2016>, <https://www.geosci-model-dev.net/9/2701/2016/>, 2016.

Appendix A: Answers to reviewer

We thank two anonymous reviewer for their helpful comments. We considered the recommendations carefully and made some changes in the text. The questions are in bold, answers in italic and changes in the text in blue.

A1 Reviewer 1

Thank you for the kind words. Your comment related to the discussion of Figure 8 made us aware of a wrong legend in the figure. This was very helpful.

An approximate altitude for 60 hPa would be useful.

465 *60 hPa is about 19 km and is the upper range that can be reached with currently available planes. We added in the text: of 60 hPa (about 19 km) with three different amounts of sulfur: 2, 4, 8 Tg(S)yr⁻¹. An injection altitude of 6 hPa has been used in many previous studies (Niemeier and Timmreck, 2015; Tilmes et al., 2018).*

Page 4, line 17 (and Table 1): Which years are used to calculate the time averages -presumably the final "n" years in each case?

470 *Yes. We changed the table and show the number of years used for the time average only.*

Page 6, line 2: This line makes no sense to me.

Thank you, a word was missing. We added: For ECHAM the SAO still reaches 5 hPa for 8 Tg(S)yr⁻¹ injections, but gets shifted to higher altitudes, similar to WACCM, when the jets gets stronger with increasing injection rates (Niemeier and Schmidt, 2017).

475 **Page 8, lines 1-6: You show that the LW heating rate is larger in WACCM than in ECHAM but then say that this difference is not the cause of the larger temperature anomaly in WACCM. I think I understand what you're saying - that because the radiation codes are the same, the difference in LW heating rate must come from the inputs to the radiation scheme, but it still sounds odd. It's like saying "this heats up more but that'snot why it's warmer". I suggest a re-write.**

480 *We rewrote the end of the paragraph: In total (SW + LW), WACCM absorbs more than twice as much radiation than ECHAM. The stronger heating rate in WACCM corresponds to the stronger temperature anomaly in WACCM. Both models*

use the same radiation scheme, hence the differences can not be explained by the radiation scheme and must be caused by other processes in the model. E.g. the heating rate due to absorption of LS radiation depends on the sulfur mass.

Page 10, lines 19-20: You say that the QBO vanishes in WACCM at an injection rate of 2 Tg(S)/yr but Figure 8 shows
485 the vertical profile of ω^* in WACCM for 2 Tg to be very similar to the 2 and 4 Tg profiles in ECHAM, which you imply further on (Page12, paragraph beginning line 3) are profiles characteristic of the presence of a QBO (which doesn't disappear in ECHAM until 8 Tg). So if the WACCM 2 Tg ω^* profile looks like the ECHAM 2 and 4 Tg profiles which still have a QBO, why is the QBO absent at 2 Tg in WACCM despite it having a similar ω^* profile?

Thank you for mentioning the problem. Your comment is absolutely correct. The legend in Figure 8 was not correct. The
490 figure showed 'CONTROL, 2Tg, 4Tg' In this combination the text made no sense. We corrected the legend and added the results of the 8 Tg simulation. Now the text describes the figure better and our findings can be see in the figure.

Page 12, lines 3-5 and Figure 8: In trying to see the impact of the absence of the QBO on the profile of ω^* it would be helpful to have the profiles from the Control simulations also plotted (perhaps in black) on Figure 8.

See our comment above.

Page 14, line 11: "...a slight increase on ω^* " - only from 60 to 30 hPa: above that T63 has smaller values.

Yes. 60 to 30 hPa is the altitude of the sulfate layer. We added to the text: When comparing the vertical velocity of T42 and T63 control simulations of ECHAM in the tropics (Fig. 13, left), we get a slight increase on ω^* (16%) in T63in the area of the sulfate layer around an altitude of 50 hPa.

Page 9, Figure 5 (and Fig. 9[lower]): the intervals on the colour scale are very odd: first the interval is 3 ppb (up to 15
500 ppb), then it reduces to 2 ppb (to 17 ppb), then increase to 9 ppb and finally to 10 ppb. I've no problem with intervals which gradually change but I don't think one should use intervals which begin being constant, then decrease and then increase.

Yes, we agree. Thank you for mentioning. There was a typo in the script. We changed the intervals.

Page 10, line 8: "proxy" not "proxi". Done

Page 10, fig. 7: A vertical line to differentiate positive from negative values would be helpful. Done

Page 10, line 20: "lay" not "lie". Done

Page 15, line 15: Insert "in WACCM" before "is 70% larger". Done

Page 16, line 12: "simulating" not "simulation". Done

A2 Reviewer 2

510 Thank you very much for the kind words and reviewing the paper. We went through all comments and tried to answer you questions carefully.

Although the models have a somewhat similar number of vertical levels (90 vs. 110), is there any major difference in the vertical resolution of the models in the stratosphere and do your results depend on the vertical resolution of the models? It would be useful to know if/how the vertical levels differ between the models.

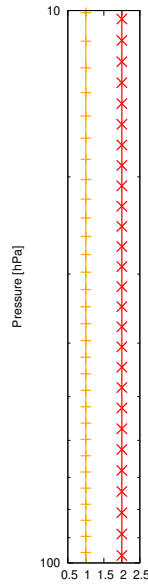


Figure A1. Vertical levels of WACCM (orange, left) and ECHAM (red, right) between 100 and 10 hPa.

515 WACCM has 32 levels and ECHAM 27 levels between 100 hPa and 10 hPa, the main area of interest of this study. The added plot shows the altitude of the vertical levels of both models. The spacing is regular in the relevant altitude (100 to 10 hPa). Previous studies have shown an increase of ω^* when increasing the number of vertical levels in ECHAM (Niemeier and Tilmes, 2017), but the simulation with lower resolution does not generate an QBO in this paper. Thus the main differences can be related to the impact of the QBO.

520 *We added to the text in Section 3.6: The vertical resolution of the models differs as well: 110 levels in WACCM and 90 levels in ECHAM. Within the area of interest however, between 100 and 10 hPa, the number of model levels is very similar: 32 levels for WACCM and 27 levels for ECHAM, with approximate grid spacing of 0.5 km for WACCM and 0.6 km for ECHAM. We do not expect a strong impact on ω^* from this small difference in vertical resolution.*

It would be clearer if ‘geoengineering’ was included in the title, to avoid confusion with a volcanic SO₂ injection pulse. It would also be useful to add a final sentence to the abstract that highlights the implications of this study.

We added ‘artificial’ to the title and added to the abstract: The vertical velocity increases slightly in MAECHAM5-HAM when increasing the horizontal resolution. This study highlights the crucial role of dynamical processes and helps to understand the large uncertainties in the response of different models on artificial SO₂ injections in climate engineering studies.

How, in addition to the horizontal resolution, the vertical resolution may contribute to the differences.

530 WACCM has five more levels in the area of interest. Following from the discussion above we assume the impact of this difference as small. We added text to Section 3.6.

Do you expect your results to be sensitive to the altitude of the injection?

Thank you for mentioning this aspect. As different previous studies show injections at different altitudes, the impact of an injection at another altitude should be mentioned.

535 The meridional transport of the sulfate aerosols out of the tropics depends on the altitude of the injection. The subtropical transport barrier is more permeable in the lower stratosphere. Therefore, the stratospheric confinement of the aerosols in the tropics is stronger when injecting at higher altitudes. This is also related to a higher value of the residual vertical velocity ω^* .

Figure 7 shows that the differences of ω^* in the control simulations of both models is largest around the injection altitude of 60 hPa. At higher altitudes, like 30 hPa, the injection would occur into an area with smaller differences in ω^* . Thus we might
540 expect smaller differences between the models. Niemeier and Tilmes (2017) and Tilmes et al. (2017) show results of zonally averaged sulfate burdens for two similar injection altitudes. The factor between the maxima, the higher injection altitude results in higher burden, is 2.2 in ECHAM and 1.7 in WACCM. Thus, we expect the results to be more similar when injecting at higher altitude.

We added to the discussion: In this study we compared injections at 60 hPa (about 19 km) only. This altitude shows the
545 largest differences in ω^* between the two models of all altitudes. Therefore, injections at higher altitude, e.g. 30 hPa (24 km) would, most probably, cause less differences. Comparing results of Niemeier and Schmidt (2017) and Tilmes et al. (2018), both show results of injections at two altitudes, shows smaller differences between the models for the higher altitude injections.

P2L5: ‘higher SO2 injections’ – what sort of magnitude does this refer to?

We changed the text to: Model simulations have shown that under tropical injections of 2 TgSyr^{-1} the QBO period decreases,
550 or it may even vanish. The SO2 injection rate at which this happens is model dependent (4 to $8 \text{ TgS yr}^{-1} \text{ TgSyr}^{-1}$).

P2L15: I do not quite follow by what you mean by ‘in the steady state’ in this context. Could you clarify?

Yes, it sounds a bit odd. The sentence is better without these words.

P3L7: Please include the full model names. What is the height to which the WACCM levels reach?

ECHAM-HAM is name, not an abbreviation. We included the full name of WACCM in the text and added the altitude of
555 0.0006 hPa.

P4L5: You mention that OH values in WACCM are not depleted – I understand this is also the case in ECHAM, so would be useful to mention here also. It would be helpful in the methods to explicitly state why you have chosen to use specified chemistry.

We added some lines before the detailed descriptions of the models: The setup of the models aims on the best comparability
560 of the results. Therefore, the single features of the models were chosen to be alike. E.g. one model has no interactive chemistry for precursors of SO₂ oxidation. Therefore prescribe both models the precursors on a monthly mean basis. They prescribe also a repeating annual cycle of SSTs, present day. These fields slightly differ between the two models but are not expected to have much influence on the simulation of the QBO. Both models are coupled to modal aerosol microphysical models. The number of modes differs, nucleation, Aitken. accumulation and, coarse mode in MAECHAM5-HAM and Aitken, accumulation and,
565 coarse mode in WACCM.

L4L15: Can you add the approximate altitude of the 60 hPa injection? Why was this height chosen?

60 hPa is about 19 km. We added in the text: ...of 60 hPa (about 19 km) with three different amounts of sulfur: 2, 4, 8 Tg(S)yr⁻¹. An injection altitude of 60 hPa has been used in many previous studies (Niemeier and Timmreck, 2015; Tilmes et al., 2018, e.g.). This is the upper range that can be reached with currently available planes.

570 **Table 1: Please consider only reporting the number of years used for the averages or state why not all years were taken. It would also be interesting to know how long it takes for the QBO changes to occur – does this differ between the models? Why was a 2(T63) not included?**

We followed your recommendation and changed the table. A 2 Tg experiment for ECHAM was not available and is not used this study.

575 **P6L9: It would be useful to state the magnitude of the heating**

We added to the text: WACCM simulates maxima of temperature anomalies of 5.7 and 12.5 K for injections of 4 and 8 Tg(S)yr⁻¹, ECHAM only 2 and 4.5 K. Thus,

P8L2-4: I did not fully follow these sentences and the use of ‘however’. Why are the different heating rates not a reason for different temperature anomalies?

580 We changed the text: In total (SW + LW), WACCM absorbs more than twice as much radiation than ECHAM. The stronger heating rate in WACCM corresponds to the stronger temperature anomaly in WACCM. Both models use the same radiation scheme, hence the differences can not be explained by the radiation scheme and must be caused by other processes in the model. E.g. the heating rate due to absorption of LS radiation depends on the sulfur mass.

P8L10: What causes this secondary maxima?

585 Transport to the high latitudes is blocked in winter. The consequence are higher concentrations in mid-latitudes. We added to the text: WACCM shows a distinct peak at the equator while in ECHAM the distribution is much more even with latitude and the secondary maxima , caused by the blocking of meridional transport by the polar vortex in the winter hemisphere, in the extra-tropics are only slightly smaller than the tropical maximum.

P10L1: How would different radii be related to differences in the heating rates? Do the different aerosol microphysical schemes between the models play a role? The different modes are mentioned in section 4 but I think would be better placed in the methods.

590 You understood the sentence differently as it was supposed. We say in the sentence before that LW absorption is independent of the particle size. As a consequence, we cannot relate LW heating rate and particle size. To prevent a misunderstanding, we changed the text: LW radiative forcing depends on the sulfate mass and stays constant per injected sulfur unit and is not related to particle radii.

Figure 8: It would be useful to show the control line to compare.

The legend in Figure 8 was not correct. The figure showed 'CONTROL, 2Tg, 4Tg". We corrected the legend and added the results of the 8 Tg simulation. Now text and figure are fitting. We added a control line as well.

600 **P11L14 (and P14L23): Could the extra tropical differences in sulfate burden not also contribute to differences in the tropical QBO response? Can you comment on this?**

The main transport follows the Brewer-Dobson circulation in the stratosphere, rising air masses in the tropics and transport toward the poles. Exchange between the tropics and extra-tropics is hindered by the sub-tropical transport barrier. Even wave driven turbulent transport occurs against the BDC, transport into the tropics is small. Therefore, we do not expect that the differences in the extra-tropics can influence the situation in the tropics.

605 **P12L8: Where does the 30% maximum occur? It looks like the largest difference is much higher.**

This maximum occurs between 50 and 30 hPa. We changed the text to: Consequently, the maximum difference of ω^ between the models, in the main area of the sulfate layer between 70 and 20 hPa, is only 34% when comparing the 2 Tg(S)yr⁻¹ WACCM and the 8 Tg(S)yr⁻¹ ECHAM injection cases (Figure 11).*

610 **P14L1: It follows that the heating is a consequence of the sulfate burden, but it seems unclear to me by what you mean that it is not a source of the differences since the heating goes on to cause the QBO disruption.**

Yes, the heating is the source of the QBO disruption, but the differences between the models are caused by the different ω^ . We changed the sentence to: Our findings suggest that the stronger tropical aerosol heating in WACCM is a consequence of the higher sulfate concentrations. The source of the differences between the two models, and the cause of the higher concentrations in WACCM, is the different ω^* .*

615 **P14L11: It appears the increase is below 30 hPa but not above. Could you clarify which altitudes you are referring to and why? It would also be useful to comment on the overall implications of the differing horizontal resolution results at the end of this section.**

We added the altitude of the area of interest to the text: When comparing the vertical velocity of T42 and T63 control simulations of ECHAM in the tropics (Fig. 13, left), we get a slight increase on ω^ (16%) in T63 in the area of the sulfate layer around an altitude of 50 hPa.*

620 *We changed the last paragraph of this section to: Increasing the horizontal resolution to T63 leads to a polar shift of the mid-latitude westerlies in the troposphere (Roeckner et al., 2006) with consequences on large scale wave propagation into the stratosphere. The dynamical changes result in an increase of With T63 resolution the sulfate burden increases at all latitudes, not only in the tropics. The pattern of the burden indicates a slightly smaller residual meridional velocity and different isentropic mixing in the mid-latitudes in T63. Additionally, Brühl et al. (2018) describe a better representation of sedimentation processes at high latitudes in T63. As we concentrate on the impact of sulfate on the QBO in this study, the differences in the extra-tropics will be left for further studies.*

625 **P16L20: The study has highlighted that the reasons for the differences in vertical advection are too complex to isolate in this study, but can some recommendation be given for future work to investigate this?**

630 *We added at the end of the conclusion: The model intercomparison initiative GeoMIP6 (Kravitz et al., 2015) has mainly concentrated on climate impact of CE. A simple SO₂ injection experiment with well defined input parameters for GCM with aerosol microphysical modules, e.g. grid resolution, injection, model setups, may create further understanding on related differences and uncertainties.*

P2L4: affects -> affecting Done

635 **P2L14: direct -> directly, indirect -> indirectly** Done

P2L26: ‘also’ would be better placed after ‘strategies’ Done

P2L28: shows -> showed. QBO vanishes at -> QBO vanishes with a 2.5 equatorial injection Done

P3L20: value -> values Done

640 **P4L3: effects of effects. Can this be rephrased?**

P4L4: ‘additionally’ can be removed Done

P5L5: month -> months Done

P5L7: as in -> than? Done

P6L2: missing word after injections Done, see above.

645 **P8L16: two instances of ‘mainly’** Done

P13L5: agrees -> aligns? Done

16L12: simulation -> simulating Done