The impact of geoengineering aerosols on stratospheric temperature and ozone

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Abstract

Anthropogenic greenhouse gas emissions are warming the global climate at an unprecedented rate. Significant emission reductions will be required soon to avoid a rapid temperature rise. As a potential interim measure to avoid extreme temperature increase, it has been suggested that Earth’s albedo be increased by artificially enhancing stratospheric sulfate aerosols. We use a 3D chemistry climate model, fed by aerosol size distributions from a zonal mean aerosol model, to simulate continuous injection of 1–10 Mt/a into the lower tropical stratosphere. In contrast to the case for all previous work, the particles are predicted to grow to larger sizes than are observed after volcanic eruptions. The reason is the continuous supply of sulfuric acid and hence freshly formed small aerosol particles, which enhance the formation of large aerosol particles by coagulation and, to a lesser extent, by condensation. Owing to their large size, these particles have a reduced albedo. Furthermore, their sedimentation results in a non-linear relationship between stratospheric aerosol burden and annual injection, leading to a reduction of the targeted cooling. More importantly, the sedimenting particles heat the tropical cold point tropopause and, hence, the stratospheric entry mixing ratio of H₂O increases. Therefore, geoengineering by means of sulfate aerosols is predicted to accelerate the hydroxyl catalyzed ozone destruction cycles and cause a significant depletion of the ozone layer even though future halogen concentrations will be significantly reduced.

Keywords: geoengineering, Mt Pinatubo eruption, ozone depletion, stratospheric aerosols, albedo

1. Introduction

Continuing anthropogenic greenhouse gas emissions might lead to dangerous future climate warming characterized by extreme weather events, shifting climatic zones, rising sea level and mass extinction (e.g. Hansen et al. 2006, Solomon et al. 2007). Considering today’s political situation on this issue, doubts arise whether we will be able to reduce anthropogenic greenhouse gas emissions rapidly enough to avoid unfavourable future climatic conditions on Earth. This motivated Crutzen (2006) to suggest reconsidering the geoengineering ideas of Budyko (1977) to enhance Earth’s albedo by increasing sulfate aerosol concentrations in the atmosphere. In a recent report, The Royal Society (2009) notes that such ‘Solar Radiation Management techniques do not treat the root cause of climate change (increased levels of greenhouse gases in the atmosphere) but because they act quickly, they could be useful in an emergency, for example to avoid reaching a climate “tipping point”’.

During major low-latitude volcanic eruptions, significant amounts of sulfur (S) are injected into the global stratosphere. The resulting aqueous sulfuric acid aerosols reflect a portion...
of the incoming shortwave (SW) radiation. The subsequent cooling of Earth’s surface after volcanic eruptions has been known for a long time (e.g. Franklin 1784). The presence of enhanced aerosol loading in the stratosphere, however, not only affects the planetary albedo, but also chemical reactions and the radiative heating budget of the aerosol layer itself. For example, after volcanic eruptions, ozone depletion is observed as a consequence of accelerated heterogeneous reactions leading to depletion of active nitrogen species, and the corresponding increase in halogen catalyzed ozone destruction cycles (Solomon 1999).

Rasch et al. (2008a) give an overview of studies addressing geoengineering by increasing Earth’s albedo. Many of these studies investigated the effect of geoengineering on climate by simply reducing the incoming SW radiation (Govindasamy and Caldeira 2000, Govindasamy et al. 2002, 2003, Matthews and Caldeira 2007, Caldeira and Wood 2008) using medium complexity General Circulation Models (GCMs). They showed that simulations of future climate with increased greenhouse gases resemble the present day climate more if geoengineering is applied.

Other model studies used stratospheric aerosol distributions similar to those observed after the Mt Pinatubo eruption as an analogue for geoengineering. Rasch et al. (2008b) calculated equilibrium experiments with the GCM CAM3 (Community Atmosphere Model) with a slab ocean including a simplified S cycle with prescribed aerosol size distributions. They showed that the effect on surface cooling depends strongly on the size of the particles; assuming the same aerosol mass in the stratosphere for each case, small particles are more efficient scatterers of SW radiation.

Robock et al. (2008) studied the effect of geoengineering with transient GCM simulations including an aerosol module and a coupled ocean, however, using prescribed aerosol size distributions with constant dry effective radius. They pointed out that geoengineering could lead to a reduction in precipitation, specifically the summer monsoons could be reduced. The geoengineering scenarios of Matthews and Caldeira (2007) and Rasch et al. (2008b) also showed a decrease of precipitation in the tropical region. However, all studies suggest that the global mean climate with increased CO2 levels is more similar to today’s climate when geoengineering is applied than without geoengineering.

Tilmes et al. (2009) analysed the effect of geoengineering on the ozone layer with a Chemistry Climate Model (CCM). They used the global model WACCM3 with a slab ocean and prescribed the aerosol loading as in Rasch et al. (2008b). Enhanced aerosol concentrations in the stratosphere are predicted to lead to a delay of the ozone recovery of up to three decades, supporting the results of their earlier study (Tilmes et al. 2008).

A major difference between volcanic eruptions and geoengineering-type S injections is that the latter would have to occur on a continuous basis, with important implications for the microphysical properties of the resulting aerosol. This aspect of the problem may not have received adequate attention to date. Here we use a detailed, two-dimensional microphysical aerosol model to calculate the differences in aerosol characteristics due to different S injection strategies. These results are integrated into the global CCM SOCOL to calculate the global chemical, radiative, and dynamical impacts of geoengineering.

2. Experimental setup and model description

We designed a set of equilibrium experiments with the zonal mean AER (Atmospheric and Environmental Research Inc.) 2D aerosol model (Weisenstein et al. 1997, 1998, 2007) by injecting SO2 into the lower tropical stratosphere. The assumption of zonally homogeneous conditions is adequate for the stratosphere, but may become more problematic in the tropical tropopause layer (Pueglisalter et al. 2009). The aerosol model includes sulfur chemistry and all relevant microphysical processes, including nucleation, condensation, evaporation, coagulation, sedimentation and (tropospheric) washout. The aerosol size distribution is resolved by 40 size bins spanning the range 0.4 nm–3.2 μm by volume doubling. The model uses pre-calculated values of hydroxyl radical (OH) and other oxidants, along with pre-calculated photolysis rates, derived from a model calculation with standard stratospheric chemistry (Weisenstein et al. 1997). Reaction rates are according to Sander et al. (2000) and OH climatologies are adapted from von Kuhlmann et al. (2003). The transport parameters in the model are prescribed as for the year 1992, the year after the eruption of Mt Pinatubo, according to the method described in Fleming et al. (1999).

S was injected in a box centred at the equator and 20 km altitude (5°S–5°N and 19.4–20.6 km). The equator was chosen to achieve global spreading of the emitted S and resulting aerosol via the Brewer–Dobson circulation. Emissions outside the tropics would largely remain in the hemisphere of emission and have shorter residence times, as observed for mid- and high-latitude volcanoes. While the emission of engineered solid particles has been suggested to avoid particle growth by coagulation (e.g. Teller et al. 1997, Keith 2000, Caldeira and Wood 2008) we choose S for our geoengineering simulations based on decades of observations into its behaviour in the stratosphere following volcanic eruptions. Engineered particles may have unknown and unforeseen effects, and their residence time in the atmosphere will be unknown until full-scale atmospheric experiments are conducted.

Model calculations were carried out for two types of S injection strategies: (i) continuous (with fluxes of 1, 2, 5 and 10 Mt/a S; labelled GEO1, …, GEO10), and (ii) pulsed with periods of 1 month (labelled GEO5p12) and 6 months (labelled GEO5p2) with fluxes of 5 Mt/a S. The mechanism for injecting S into the stratosphere is not explored in these calculations. However, a serious consideration of geoengineering operations would require that the impact of the delivery mechanism (aircraft, rockets, balloons) also be evaluated for impacts on ozone and climate.

The optical properties (using Mie theory and the refraction indices from Biermann et al. (2000)) of the calculated aerosol are integrated into the radiative transfer calculations of the global CCM SOCOLv2.0 (SOlar Climate Ozone Links
Table 1. Geoengineering scenarios with different annual stratospheric SO2 emissions.

| Scenario          | S input (Mt/a) | Special features                  |
|-------------------|----------------|-----------------------------------|
| GEO0              | 0              | Background S concentrations       |
| GEO1              | 1              | Continuous S injections           |
| GEO2              | 2              | Continuous S injections           |
| GEO5              | 5              | Continuous S injections           |
| GEO10             | 10             | Continuous S injections           |
| GEO5p12           | 5              | Monthly S injections              |
| GEO5p2            | 5              | Two S injections per year          |
| GEO5_cond         | 5              | Condensation rate/10              |
| GEO5_coag         | 5              | Coagulation rate/10               |
| GEO2_24km         | 2              | Injection altitude = 24 km        |
| GEO2_posed        | 2              | No aerosol sedimentation          |
| GEO5nC           | 5              | SAD = SAD of GEO0                 |
| GEO5nR           | 5              | Radiative effect of aerosols as in GEO0 |
| GEO5lowODS       | 5              | ODS concentrations of 1975        |
| GEO5highCO2      | 5              | Double CO2 concentrations         |
| GEO5lowSST       | 5              | SI + SST climatology from 1900 to 1930 |

a In GEO5nC the heterogeneous reaction on stratospheric aerosol is as for GEO0.

b In GEO5nR the radiative feedback of the aerosols is set to background situation (GEO0).

3. Preparatory simulations of the eruption of Mt Pinatubo

The eruption of Mt Pinatubo in June 1991 emitted 6–11 Mt S into the lower stratosphere (Guo et al. 2004, Read et al. 1993, McPeters 1993, Stowe et al. 1992, Rosen et al. 1992) and lead to a surface cooling of roughly 0.5 K one year after the eruption (Lacis and Mishchenko 1995). In the framework of the Assessment of Stratospheric Aerosol Properties (ASAP) by SPARC (Stratospheric Processes and their Role in Climate), AER model simulations have been validated with observations and other model simulations (SPARC 2006, Weisenstein et al. 2007). The AER model ranked in this validation among the best models for stratospheric aerosols in quiescent or volcanically perturbed times. Figures 1(a)–(c) show 1 µm extinction profiles from June 1991 to December 1993 derived from LIDAR data (Antuna et al. 2002, 2003) at Mauna Loa in Hawaii (19.54°N, 155.58°W) and Camagüey in Cuba (21.40°N, 77.92°E) and 1 µm extinction profiles of the same period calculated by the AER model at 18°N. The AER model results as calculated for the ASAP report (labelled PIN10_ASP) show a higher peak concentration in the lower stratosphere and more aerosol at higher and lower altitudes than the observations (figures 1(a) and (b)). An AER calculation using an improved transient circulation rather than a climatology and including aerosol and gas washout up to the tropopause rather than just below 10 km is shown in figure 1(c) (labelled PIN10). Latitude–altitude profiles of backscatter ratio for May 1992 are shown in figures 1(d)–(f). Observations are from a NASA DC-8 airborne LIDAR mission during 21st, 24th, 26th of May 1992 under the coordination of Winker and Osborn (1992). Observations indicate efficient horizontal mixing within the tropical pipe but limited vertical dispersion 11 months after the eruption. PIN10_ASP shows limited horizontal mixing and excessive vertical mixing, while the AER result with improved transport and washout (PIN10) partially corrects for this. The other models that participated in ASAP tended to produce even larger extensions in the tropics near 30 km during the Mt Pinatubo period.

Transient SOCOL calculations from 1991 to 1999 with observed boundary conditions and AER aerosols are performed (as described in Schraner et al. 2008), without QBO nudging. At the equator, the radiative properties calculated by SOCOL with the AER aerosols show their largest deviation from measurements in the lower stratosphere where the main aerosol cloud resided. As a consequence, the resulting heating of the lower stratosphere in the ASAP calculation was overestimated by a factor of 3–5 (green dash–dotted line PIN10_ASP in figure 2(a)) in the first year following the eruption. By introducing the improved transient transport instead of a climatology and introducing aerosol and gas washout up to the tropopause, the performance of the AER model was improved remarkably (red dashed curve (PIN10) with 10 Mt S injection and blue solid curve (PIN7) with 7 Mt S injection in figure 2(a)). From 1993 to 1998, the AER + SOCOL results match qualitatively the ERA interim temperature analysis. Figure 2(b) shows the monthly mean,
Lidar (Mauna Loa, Camagüey) PIN10_ASAP
(a) (b) PIN10
(c) (d) (e) (f)

Figure 1. First row: extinction profiles from June 1991 to December 1993 at 1 µm (a) derived from LIDAR measurements at Mauna Loa and Camagüey in comparison with (b), (c) AER simulations at 18°N. Contour lines are at $1 \times 10^{-5}$, $5 \times 10^{-5}$, $1 \times 10^{-4}$, $5 \times 10^{-4}$, $1 \times 10^{-3}$, $5 \times 10^{-3}$, 0.01, 0.02 and 0.05 km$^{-1}$. Second row: backscattering ratio at 532 nm in May 1992 (d) measured by airborne LIDAR mission during 21st, 24th, 26th of May 1992 under the coordination of Winker, in comparison with (e), (f) AER model calculations (contour spacing = 2). PIN10_ASAP denotes calculations assuming 10 Mt S input as in the ASAP report (SPARC 2006), PIN10 is an improved AER calculation (see text).

zonal mean total ozone column averaged from 60°S to 60°N for observation (NIWA: New Zealand National Institute of Water and Atmospheric Research (NIWA) observational total ozone data set compiled by Bodeker et al (2005), TOMS: total ozone mapping spectrometer) and model calculations. PIN10_ASAP overestimates the total ozone loss, because of the overestimated surface area density (SAD). The total ozone loss due to the Mt Pinatubo eruption predicted by the CCM SOCOL using the improved AER simulations (PIN10, PIN7) is in the same range as observed by NIWA and TOMS.

4. Geoengineering aerosol particle distributions

The total S loading and the particle size are the key variables for the radiative and chemical impact of the aerosols from geoengineering. Particles with radii in the range of 0.1 µm are most efficient in cooling the Earth’s surface, as these particles have the largest backscattering cross section per unit mass. The number density and the size distribution of the aerosol defines the surface area density (SAD) which is crucial for the changes in chemistry. Figure 3 shows the SAD of the sulfuric acid aerosols formed after the injection of 1–10 Mt/a S calculated by the AER aerosol model. The largest values of SAD and hence the largest concentration of stratospheric aerosols is in the tropical region. The more S is continuously emitted, the larger the SAD gets. GEO5 shows SAD larger than 40 µm$^2$ cm$^{-3}$ near the injection region (20 km, equator, figure 3(d)). If the S injection takes place only twice a year (GEO5p2), the annual mean SAD in the injection region gets larger than 100 µm$^2$ cm$^{-3}$ (figure 3(f)). Below the injection region, the SAD is strongly enhanced due to geoengineering, indicating the importance of sedimentation of the particles to lower altitudes.

Figure 4(a) shows the annual global mean aerosol loading (in Mt S) for the different scenarios when steady state is reached. The dash–dotted line in the figure represents the
aerosol burden that would be expected if the stratospheric residence time were one year in all cases, which was observed for the 1992–1993 period immediately following the Mt Pinatubo eruption (McCormick et al 1995). We find that smaller (larger) particles have a longer (shorter) residence time. For 1 Mt/a S emission (GEO1), the equilibrium aerosol burden in the atmosphere is 1.4 Mt S, slightly above the line. For all other simulations the stratospheric residence time of the aerosol is shorter than one year: the aerosol burden for GEO2 is 2.1 Mt S, for GEO5 3.7 Mt S and for GEO10 6.0 Mt S. If the S emission occurs at higher altitude, the residence time of the aerosol increases; the annual emission of 2 Mt/a (5 Mt/a) S at 24 km yields a mean aerosol burden of 2.5 Mt S (4.6 Mt S).

These results are very different from those of Rasch et al (2008b) (and consequently also Tilmes et al 2009), who calculate an S loading of 5.9 Mt S for 2 Mt/a S injected at 24 km for an aerosol distribution with fixed effective radius of 0.43 μm. In our calculations, aerosol particles grow sufficiently large to allow gravitational settling to become an important sink. If aerosol sedimentation is turned off in the model (GEO2nosed), the aerosol burden increases to 7.8 Mt S. These dramatic differences in calculated aerosol loading require thorough analysis, as they have a large impact on the consequences of geoengineering.

After volcanic eruptions, the mode radius of the aerosol size distribution is typically in the range of 0.3–0.5 μm, roughly 5–8 times larger than during quiescent times (e.g. Steele and Hamill 1983, Thomason 1992, Deshler et al 1992). Crutzen (2006) and Robock et al (2008) assumed that the effective radius would be rather smaller for geoengineering.
than for the Mt Pinatubo eruption, due to a continuous supply of S and the resulting ‘reduction of coagulation’. The AER model results show, in contrast, depending on the S loading, that the geoengineering aerosols could grow larger than particles formed after the Mt Pinatubo eruption. Figure 5 shows the aerosol size distribution (in differential number density) in the equatorial stratosphere for different AER simulations. In the lower stratosphere, the mode radius increases with increasing amounts of S emission from 0.1 to 0.6 µm when going from GEO1 to GEO10 (figures 5(a)–(c)). At the equator and 55 hPa altitude, the annual mean aerosol loading of GEO5 is comparable to the mean aerosol loading the first year of the Mt Pinatubo simulation (PIN10), however, GEO5 produces larger mode radii than PIN10 (figure 5(e)).

Aerosol growth depends on competition between nucleation, condensation and coagulation. The freshly formed H2SO4 molecules either stay in the gas phase, nucleate together with H2O molecules to form stable clusters, or condense on pre-existing aerosols. In the injection region, the gas-to-particle flux by condensation is 4–6 orders of magnitudes larger than the flux by nucleation. The growth of the large particles (r > 1 µm) is either due to condensation or to coagulation. We performed sensitivity tests with reduced condensation and coagulation rates to test the importance of these two processes (table 1). If the coagulation rate is reduced by a factor 10 (GE05.condition), the mode radius is reduced by roughly a factor of 2 (figures 5(g)–(i)). Consequently the gravitational loss of the aerosol is reduced, and with the same annual S input, GE05.condition has a 46% larger aerosol burden than GEO5 (figure 4(a)). In scenario GEO5.condition the condensation rate is reduced by a factor 10, which leads to a shift in importance of the gas-to-particle flux from condensation towards nucleation. Hence, more tiny particles are formed which grow by coagulation. The mode radius of the GEO5.condition size distribution (with reduced condensation rate by a factor 10) is smaller than the mode radius of GEO5 (see figures 5(g)–(i)) and consequently the gravitational loss is reduced by 17%.

The geoengineering scenarios with continuous S supply lead to a continuous supply of H2SO4, and therefore continuous particle growth by condensation. But even more important for the growth of large particles is the continuous supply of freshly nucleated small particles (r < 0.03 µm) which coagulate rapidly with larger particles, leading to even larger particles (r > 0.4 µm). In contrast to the volcanic case where coagulation is self-limited by number densities that decrease with time, the abundance of small particles is never depleted under geoengineering emissions. Thus coagulation is the most important process in the formation of large particles (r > 1 µm) in our calculations. Because gravitational fall speed scales with the square of the particle radius, the formation of large particles strongly increases gravitational removal of the aerosol and decreases its residence time relative to the volcanic case.

The temporal and spatial distribution of S injection has a strong influence on the particle size distribution. In our experiments the S is distributed over a zonal band of 9.5° wide and 1.2 km high. To test the dependence of particle growth on the spatial distribution we performed three more geoengineering calculations with the source of 5 MT/aS: In the first experiment the SO2 is injected at the equator as well but spread vertically from 20 to 25 km, the second spread emissions from 30°S to 30°N, with emissions at 20 km only and the third spread emissions in the same latitudinal range as the second but additionally spread emissions vertical from 20 to 25 km. The first produced a burden of 4.5 Mt S, the second a burden of 4.3 Mt S, the third a burden of 4.8 Mt S. Thus the spreading of emissions is one potential method to improve the efficiency of geoengineering injections, though the
Figure 5. Annual mean differential number density \( dN/\log r \) in \( \text{cm}^{-3} \) at the equator at 39 hPa (first column), 55 hPa (second column) and 90 hPa (third column). (a)–(c) Continuous S injection into the lower stratosphere of 0, 1, 2, 5 and 10 Mt/a (GEO0–GEO10). (d)–(f) Continuous and pulsed emission of 5 Mt/a S emissions (GEO5, GEO5p12, GEO5p2) and annual mean aerosol size distribution for PIN10 from June 1991 to May 1992. (g)–(i) GEO5, GEO5pcond with reduced condensation rates and GEO5pcoag with reduced coagulation rates.

5. Changes in the stratosphere

When assuming present day halogen concentrations, all of the geoengineering scenarios listed in table 1 lead to reductions in the total \( O_3 \) column. Figure 6 shows the change in annual mean zonal mean total \( O_3 \) column as a function of latitude; the global mean values are listed on the plots. For GEO5 (GEO10) the annual mean global total \( O_3 \) column is predicted to decrease by 4.5% (5.3%) in comparison to GEO0. This is more than the annual mean global total \( O_3 \) loss due to the emission of anthropogenic ODS, which was \(-3.5\%\) averaged from 2002 to 2005 in comparison to the 1964–1980 average as determined from observations (WMO 2007, chapter 3) or \(-3.8\%\) calculated by SOCOL (for nine members in an ensemble calculation) averaged from 1996 to 1999 in comparison to the 1964–1980 average (Fischer et al 2008). In the same period the observed tropical \( O_3 \) loss was negligible, but for the geoengineering scenarios the tropical \( O_3 \) loss is remarkable: in GEO5 (GEO10) the annual tropical mean total \( O_3 \) column (25\( \degree S–25\degree N \)) is reduced by 3.5% (4.3%).

On the sulfate aerosols the \( N_2O_5 \) hydrolysis leads to the formation of the stable reservoir species \( HNO_3 \):

\[
N_2O_5(g) + H_2O(l, s) \xrightarrow{\text{HET}} 2HNO_3(s).
\] (1)

This leads to a lowering in the \( NO_x/NO_3 \) ratio. Hence the \( NO_x \) catalyzed \( O_3 \) destruction cycles become less important and the formation of the reservoir gas \( ClONO_2 \) is reduced, yielding an increase in the \( ClO_x/Cl_y \) ratio. At the same time chlorine is
Figure 6. Predicted geoengineering-induced changes in annual mean zonal mean total ozone column. Listed values show annual global mean values. (a) Standard scenarios (solid curves) and pulsed scenarios (dotted: monthly; dashed: semiannually) relative to GEO0. (b) Scenarios with no surface enhancement (nC) and no radiative enhancement (nR) relative to GEO0. (c) Special scenarios with low CFC, high CO2 or low SST relative to GEO0. (d) Same as in (c), but relative to special scenarios without geoengineering. The orange GEO5–GEO0 curve is shown in all panels for clarity.

Further activated due to the heterogeneous reaction:

\[ \text{ClONO}_2(g) + \text{HCl}(s) \xrightarrow{\text{HET}} \text{Cl}_2(g) + \text{HNO}_3(s). \]  

These processes enhance ClOx-induced ozone destruction. Ozone destruction by bromine is enhanced through similar mechanisms, but to a much smaller extent.

Figure 7 shows the vertical profiles of the zonal mean O3 changes due to geoengineering for the south polar region (a), for the tropics (b) and for the north polar region (c). Figure 8 shows the change in O3 destruction rates (in percentage) due to the injection of 5 Mt/a S (GEO5–GEO0) for different destruction cycles. In the middle stratosphere the most dominant O3 destruction cycle is catalyzed by NOx. The slowing of this cycle due to geoengineering leads to less O3 destruction, hence an increase in the tropical mean O3 concentration between 30 and 35 km (figures 7(b) and 8(b)). In the lowermost stratosphere the halogen and HOx catalyzed destruction cycles are more important, hence the increased ClOx and BrOx concentrations lead to O3 destruction in this region. In the polar spring region the O3 depletion is enhanced especially in the lowermost stratosphere (200–80 hPa) (figures 7(a) and (c)). This corresponds about to the observed O3 loss in the polar spring regions after Mt Pinatubo eruption (e.g. Deshler et al 1994, 1992, Hofmann and Oltmans 1993).

5.1. Heating of the lower stratosphere and increase of stratospheric water vapour

Another feedback on stratospheric O3, which has not been discussed previously, is caused by the heating of the tropical tropopause region and the subsequent increase of stratospheric water vapour (H2O). All AER scenarios show an increased level of stratospheric aerosols near the tropical tropopause due to injection of SO2 at 20 km. This results in heating of the tropical tropopause region, mainly due to absorption of longwave (LW) radiation. The more sulfate aerosol is present in the tropical tropopause region, the larger is the resulting heating; this relationship is shown in figure 9. The temperature at 90 hPa at the equator is 2.8 K higher in GEO10 than in the base run (GEO0). In GEO5 the temperature near the tropopause rises by 1.3 K. With the same optical aerosol properties, but SADs equal to background concentrations (GEO5nC), the temperature increase would be 0.4 K larger than for GEO5, because in scenario GEO5 the O3 decrease, due to enhanced heterogeneous reactions, cools the tropical tropopause. Therefore the cold point temperature for GEO5nR is 0.3 K lower than for the base run. As the stratospheric
Figure 7. Annual zonal mean O$_3$ (in 10$^6$ molecules cm$^{-3}$) changes with respect to GEO0 (a) in the south polar region (60°S–90°S), (b) in the tropics (30°S–30°N), (c) in the north polar region (60°N–90°N). Plus signs indicate changes to be statistically significant on the 95%-confidence interval ($t$-test).

Figure 8. Change in annual zonal mean ozone destruction rate due to injection of 5 Mt/a S (GEO5) in the lower stratosphere. (a) Southern high latitudes (60°S–90°S), (b) tropics (30°S–30°N), (c) northern high latitudes (60°N–90°N). Change of loss rate in per cent relative to the total chemical destruction rate (sum of all destruction cycles) of base run GEO0. Black curve: change in total chemical ozone destruction. Coloured lines: nitrogen (NO$_x$), chlorine (ClO$_x$), hydrogen (HO$_x$), bromine (BrO$_x$) catalyzed destruction cycles and cannibalistic reactions (O$_x$). The BrO$_x$ catalyzed destruction includes the destruction by the coupled BrO$_x$–ClO$_x$-destruction cycle. Plus signs indicate statistically significant changes on the 95%-confidence interval ($t$-test).

H$_2$O concentration depends on the minimum temperature in the profile, the annual mean H$_2$O concentrations interpolated at 90 hPa are smaller than the corresponding temperatures at this altitude would suggest (Fueglistaler et al. 2005). The non-linear warming of the tropical tropopause with increasing S injection leads consequently to a non-linear increase of stratospheric H$_2$O. For GEO5, H$_2$O concentrations at 90 hPa increase by 0.7 ppmv and for GEO10 by 1.6 ppmv.

As a consequence, the HO$_x$ catalyzed O$_3$ destruction cycles are intensified, which leads to a decrease in O$_3$ in the upper and lower stratosphere (figure 8(b)). GEO5nR (with slightly decreasing stratospheric H$_2$O concentrations) shows a small increase in O$_3$ above 38 km. Additionally the increased stratospheric H$_2$O intensifies the formation of HNO$_3$ and decreases further the NO$_y$/NO$_x$ ratio. Therefore, even without increased N$_2$O$_5$ hydrolysis (GEO5nC), O$_3$ concentrations in the tropical middle stratosphere increase. In the tropical area, three fifths of the total O$_3$ loss can be attributed to the stratospheric warming and subsequent increase of stratospheric H$_2$O (GEO5nC), whereas two fifths is attributed to enhanced heterogeneous reactions on sulfate aerosols and a shift in ClO$_x$/Cl$_y$ ratio (GEO5nR).
The increased meridional temperature gradient in the stratosphere tends to intensify the polar vortex. The resulting cooling of the polar region and the higher stratospheric H$_2$O concentrations enhance PSC formation (statistical significant increase on the 95% confidence interval of up to 100%). Therefore the O$_3$ in the polar spring region is additionally depleted due to enhanced ClO and BrO catalyzed ozone destruction cycles (figures 7(a), (c) and 8(a), (c)).

5.2. Sensitivity of O$_3$ loss to future halogen and CO$_2$ concentrations and SSTs

In the future, halogen concentration will decrease and therefore O$_3$ destruction will be reduced. The sensitivity run GEO5lowCFC has the same boundary conditions as GEO5 except for lower halogen concentrations (as in 1975). The global total ozone column of GEO5lowCFC is 1.5% higher than of GEO0, but compared to low halogen concentrations without geoengineering (GEO0lowCFC) the global total ozone column would still decrease by 2.6% (figures 6(c) and (d)). In contrast to the finding of Tilmes et al (2009), that the tropical total ozone layer will increase with geoengineering and lower CFCs, we find that due to the strong warming of the lower stratosphere (and the following moistening of the stratosphere) the tropical total ozone column is predicted to decrease, even with future low halogen concentrations.

To test the sensitivity of stratospheric changes due to geoengineering to changes in SST we performed a run with SST and SI climatology from 1900 to 1930 (GEO5lowSST). With lower SSTs, the cold point temperature is lower and therefore the stratosphere is dryer than in GEO5 (figure 9). As a consequence, less O$_3$ is destroyed by HO$_x$ destruction cycles (figures 7(a), (c) and 8(a), (c)).

In the future the CO$_2$ concentration will increase. GEO5highCO2 is a geoengineering scenario like GEO5 but with doubled CO$_2$ concentrations. In our experiment GEO5highCO2 has a higher temperature at the tropical tropopause and leads to a wetter stratosphere. Therefore in a doubled CO$_2$ world the total O$_3$ depletion would be larger when geoengineering is applied (figure 6(d)).

6. Changes in surface radiation by geoengineering

Figure 10 shows changes in annual mean zonal mean surface net clear-sky SW flux (with wavelength of 0.25–4 µm) calculated by SOCOL for the different geoengineering scenarios. The largest changes occur in the tropics, as the largest part of the aerosol mass is located in this region. The global mean clear-sky SW flux of GEO2 is 1.2 W m$^{-2}$ lower than of GEO0 (table 2), which is in the same range as today’s radiative forcing due to direct and indirect aerosol effects (Forster et al 2007). GEO5 (GEO10) leads to a change in global mean clear-sky SW flux of −1.8 W m$^{-2}$ (−2.7 W m$^{-2}$). In the presence of clouds the SW flux change (all-sky) is smaller than for clear-sky condition. In figure 4(b) the change in global annual mean SW flux as a function of injected S is shown (see also table 2). Both the nonlinear loss by gravitational settling with increasing S loading and the distribution of condensed mass on larger particles cause the SW flux to grow non-linearly with S injections.

Table 2. Change in global mean annual mean net SW flux at the surface plus/minus standard deviation due to geoengineering in comparison with GEO0. Calculated by SOCOL for clear-sky and all-sky conditions.

| Scenario     | Clear-sky SW Flux change (W m$^{-2}$) | All-sky SW Flux change (W m$^{-2}$) |
|--------------|---------------------------------------|-------------------------------------|
| GEO0         | −0.78 ± 0.10                          | −0.37 ± 0.42                        |
| GEO2         | −1.16 ± 0.11                          | −0.78 ± 0.38                        |
| GEO5         | −1.81 ± 0.09                          | −1.06 ± 0.31                        |
| GEO10        | −2.67 ± 0.11                          | −1.68 ± 0.42                        |
| GEO5p12      | −2.00 ± 0.08                          | −1.29 ± 0.35                        |
| GEO5p2       | −2.66 ± 0.08                          | −1.64 ± 0.23                        |
| Robock08$^*$ | −1.8                                  |                                     |
| Robock08$^*$ | −3.6                                  |                                     |

$^*$ Additionally listed are SW downward flux changes due to geoengineering as proposed by Robock et al (2008).
GEO5p2 has a 20% smaller S loading than GEO10, but as GEO5p2 contains much more small particles (which more efficiently scatter SW radiation) the surface SW flux change of GEO5p2 and GEO10 are almost equal. GEO10 shows a net all-sky SW flux change of $1.7 \pm 0.4$ W m$^{-2}$ compared to GEO0. This flux is approximately equal to the radiative forcing introduced by geoengineering (when changes in the LW budget are neglected). The estimates of the climate sensitivity (defined as the equilibrium temperature response following the doubling of CO$_2$) range between 2 and 4.5 K with the most likely value of 3 K (Hegerl et al. 2007). Assuming that CO$_2$ doubling leads to a forcing of 3.8 W m$^{-2}$ (Meehl et al. 2007), the climate sensitivity parameter (defined as the fraction of the temperature change and applied forcing ($dT/dF$)) is 0.5–1.2 K/(W m$^{-2}$) with the most likely value of 0.8 K/(W m$^{-2}$). Hence the global mean temperature due to GEO10 would decrease by $-0.7$–$2.5$ K with the most likely value of $-1.4$ K.

Robock et al. (2008) calculated a linear increase in SW flux change with increasing S injections: according to their simulation a 2.5 Mt/a S injection yields a global reduction of downward SW radiation at the surface of $-1.8$ W m$^{-2}$. They assume an effective radius of 0.30–0.35 µm (which is most probably underestimated) and therefore the gravitational loss is very small.

Changes in stratospheric H$_2$O and O$_3$ also influence the temperature change at the surface. With increasing S injections, stratospheric H$_2$O increases, leading to an increased positive LW radiative forcing at the surface. The stratospheric H$_2$O in GEO10 increases by roughly 1.5 ppmv (figure 9). Forster and Shine (2002) showed that an increase of 1 ppmv H$_2$O above 10 hPa leads to RF of 0.3 W m$^{-2}$, which means that the cooling achieved by the increased albedo might be reduced significantly. However, the loss in stratospheric O$_3$ at the same time decreases the greenhouse gas forcing. Detailed radiative forcing calculation are beyond the scope of this letter and should be addressed in the future.

### 7. Discussion and conclusions

The 2D AER aerosol model was used to simulate geoengineering scenarios where global albedo is reduced with the help of stratospheric sulfuric acid aerosol enhancements. The AER model resolves all relevant microphysical processes in the formation of sulfuric acid aerosols after injection of SO$_2$ into the stratosphere. In a model–observation comparison by SPARC (2006), the AER model ranked among the best models for the description of the stratospheric aerosol formation after volcanic eruptions. As already mentioned above, in the tropical tropopause layer (TTL) zonally inhomogeneous processes (as for instance washout by convective systems) could become important and then the zonal mean model might be problematic. In the tropics, where the uncertainties in the aerosol observation after the Mt Pinatubo eruption are largest, the model overestimates the extinction by the aerosol. This could be caused by deficiencies in the microphysics or by too slow transport of the aerosol to higher latitudes. However, the clear distinction that the model allows to draw between the various geoengineering scenarios and unperturbed conditions suggests that the conclusions reached in this letter are robust.

We performed hypothetical geoengineering experiments where S in the form of SO$_2$ is continuously emitted at the equator at 20 km altitude. The continuous emission of S leads to aerosol size distributions with larger mode radii than observed and modelled after volcanic eruptions. Continuous coagulation of the freshly nucleated geoengineering particles with the already grown background particles is identified to be the most important process for the formation of large particles, and condensation further adds to the aerosol growth. The geoengineering particles grow to such sizes that they experience substantial gravitational settling and have accordingly shorter residence times in the stratosphere. This results in a non-linear relationship between stratospheric sulfate aerosol burden and SO$_2$ emission. Another drawback of the formation of large aerosols is the reduced SW scattering efficiency with increasing size of the particles. Hence larger amounts of S would be needed in order to counteract global warming.

The continuous emission of S in the tropical lower stratosphere could lead to a heating of the tropical tropopause region. According to our model simulations, the tropical cold point temperature increases by half (one) a degree due to the emission of 5 Mt/a S (10 Mt/a S). A warming of this sensitive region induces a moistening of the stratosphere. As a caveat, analyses of the Mt Pinatubo eruption show that the lower stratospheric warming is possibly overestimated by our model. However, many CCMs presently suffer from this problem, see Eyring et al. (2006). This suggests that current models have a problem which may not yet have received the attention it deserves.

If the S would be deposited only twice per year instead of continuously, the mode radius of the aerosol size distribution would be smaller and hence less S would be lost. However, the injection of such large amounts of S in a short time would be unfavourable from a technical point of view. Spreading the emissions over a larger area is another strategy to reduce the particle size and improve the efficiency of geoengineering by S injection. Furthermore, use of particles other than sulfate to reduce the global SW surface flux could perhaps avoid some of the drawbacks and side-effects presented here, provided these particles could escape coagulation, but additional unknowns would then need to be investigated.

For present-day halogen concentrations, the stratospheric O$_3$ is depleted in our geoengineering scenarios, with most intense loss in the tropical and polar regions. The global mean total O$_3$ column is depleted by 4.5% due to the emission of 5 Mt/a S. Three quarter of the increase in global total O$_3$ loss could be attributed to heterogeneous reactions, resulting in a shift in the NO$_x$/NO$_y$ ratio and in halogen activation. One quarter could be attributed to the increase of temperature in the lower stratosphere and the moistening due to increased tropical cold point temperature. In the tropics, heterogeneous reactions cause a smaller fraction ($\sim 40\%$) of the O$_3$ loss than the heating of the lower stratosphere ($\sim 60\%$). Experiments with reduced halogen concentration (as in 1979) suggest O$_3$ loss in the tropics is caused by temperature increase and moistening of the stratosphere. Another drawback of the potential moistening of the stratosphere due to geoengineering is the additional positive LW forcing, which reduces the surface cooling.
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