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Stratospheric sulfate geoengineering enhances terrestrial gross primary productivity

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Abstract

Stratospheric sulfate geoengineering could impact the terrestrial carbon cycle by enhancing the carbon sink. With an $8\,\mathrm{Tg\,yr^{-1}}$ injection of $\mathrm{SO_2}$ to balance a Representative Concentration Pathway 6.0 (RCP6.0) scenario, we conducted climate model simulations with the Community Earth System Model, with the Community Atmospheric Model 4 fully coupled to tropospheric and stratospheric chemistry (CAM4-chem). During the geoengineering period, as compared to RCP6.0, land-averaged downward visible diffuse radiation increased $3.2\,\mathrm{W\,m^{-2}}$ (11 %). The enhanced diffuse radiation combined with the cooling increased plant photosynthesis by 2.4 %, which could contribute to an additional $3.8 \pm 1.1\,\mathrm{Gt\,C\,yr^{-1}}$ global gross primary productivity without nutrient limitation. This increase could potentially increase the land carbon sink. Suppressed plant and soil respiration due to the cooling would reduce natural land carbon emission and therefore further enhance the terrestrial carbon sink during the geoengineering period. This beneficial impact of stratospheric sulfate geoengineering would need to be balanced by a large number of potential risks in any future decisions about implementation of geoengineering.

1 Introduction

Stratospheric sulfate injection is the most discussed geoengineering strategy to manipulate the climate system to counteract anthropogenic global warming (e.g. Crutzen, 2006; Wigley, 2006). Regularly injected sulfate aerosol precursors could produce aerosols that would stay in the stratosphere for 1–2 years depending on the particle size and emission rate (Rasch et al., 2008a; Niemeier et al., 2011). This would reduce incoming solar radiation and therefore reduce the temperature (e.g. Rasch et al., 2008a; Robock et al., 2008; Jones et al., 2010; Berdahl et al., 2014). How this proposed strategy would change the climate system has been extensively studied (Rasch et al., 2008b; Robock, 2008; Robock et al., 2009), such as enhanced stratospheric ozone depletion (Tilmes et al., 2008; Heckendorn et al., 2009; Pitari et al., 2014) and possible drought in summer monsoon regions (Robock et al., 2008; Bala et al., 2008; Jones et al., 2013; Tilmes et al., 2014). There are also a few studies of its impact on agriculture (Pongratz et al., 2013; Xia et al., 2014; Parkes et al., 2015). However, diffuse radiation perturbations and their biological consequences are only mentioned by Robock (2008) and Robock et al. (2009), and have not been comprehensively studied yet.

Volcanic eruptions as a natural analog of sulfate injection geoengineering provide evidence that sulfate aerosols in the stratosphere cool the surface and largely change the partitioning of downward direct and diffuse solar radiation (Robock, 2000, 2005). After 1991 there was a sharp slowing of the CO_2 atmospheric concentration growth rate, which was mainly due to a strong terrestrial biosphere sink in the middle latitudes of the Northern Hemisphere that balanced the stronger oceanic CO_2 outgassing due to El Niño and the increasing anthropogenic emission (Keeling et al., 1995; Ciais et al., 1995). Cooling due to volcano eruptions (Robock, 2000) might be one reason to explain the unusual biospheric sink, since the cooling benefits tropical plant growth and reduces the release of CO_2 by soil respiration and wildfires (Keeling et al., 1995; Nemani et al., 2003). On the other hand, increased diffuse radiation promotes plant productivity (Gu et al., 1999; Roderick et al., 2001; Cohan et al., 2002; Gu et al., 2002, 2003; Farquhar and Roderick, 2003; Mercado et al., 2009). In total, in 1992 and 1993, an additional 1.2–1.5 $\mathrm{Gt\,C\,yr^{-1}}$ was captured by the continents (Mercado et al., 2009). Global dimming (reduction of downward shortwave radiation due to tropospheric pollution after World War II) is another example of how diffuse radiation fertilizes terrestrial vegetation (e.g. Wild, 2009; Mercado et al., 2009). With the geographically varying changes in diffuse radiation fraction (−20 to −30 %) due to global dimming (1950–1980), the terrestrial carbon sink increased by 0.4 $\mathrm{Gt\,C\,yr^{-1}}$ (Mercado et al., 2009). The most recent study also shows that Amazon fires that generate aerosols and enhance diffuse radiation would benefit the net primary productivity in the Amazon (Rap et al., 2015). Long-term sulfate injection geoengineering, if possible, would produce a permanent sulfate aerosol cloud in the stratosphere, and this long-term diffuse radiation enhancement together with the cooling effect may play an important role in the terrestrial carbon budget.

2 Model simulation

We used the full tropospheric and stratospheric chemistry version of the Community Earth System Model – Community Atmospheric Model 4 (CESM CAM4-chem) with horizontal resolution of 0.9° × 1.25° lat–lon and 26 levels from the surface to about 40 km (3.5 hPa) (Lamarque et al., 2012; Tilmes et al., 2015a) to simulate two solar radiation managements: a specific sulfate injection scenario and a solar constant reduction scenario. The Community Land Model (CLM) version 4.0 is coupled with CAM4-chem, and with the carbon–nitrogen cycle turned off, it calculates vegetation photosynthesis under the assumption of no nutrient limitations (Bonan et al., 2011). The ocean model does not include any bio-geo-chemical calculations in this study.

The specific sulfate injection scenario is G4 Specified Stratospheric Aerosol (G4SSA), which uses a prescribed stratospheric aerosol distribution to simulate a continuous annual tropical emission into the stratosphere (60 hPa) of 8 Tg SO_2 yr^{-1} from 2020 to 2070. The steady-state aerosol surface area density has the highest value of 33.2 $\mu m^2\,cm^{-3}$ in the tropics at 50–60 hPa and gradually decreases to 10–12 $\mu m^2\,cm^{-3}$ at the poles (Tilmes et al., 2015b). Starting on 1 January 2070 the sulfate injection reduces gradually to zero on 31 December 2071 (Tilmes et al., 2015b). The G4SSA simulation continues after the end of sulfate injection from 2072 to 2089 to study the termination effect. The reference simulation is the Representative Concentration Pathway 6.0 (RCP6.0) (Meinshausen et al., 2011) from 2004 to 2089. We have run three ensemble members for both G4SSA and RCP6.0. The solar constant reduction scenario is G3 solar constant reduction (G3S) which reduces the solar constant to balance the forcing of the Representative Concentration Pathway 4.5 (RCP4.5) (Meinshausen et al., 2011) and keeps the temperature close to 2020 values. That solar reduction geoengineering scenario is from 2020 to 2069, and its reference run is RCP4.5 from 2004 to 2089. Both G3S and RCP4.5 have only one ensemble member each.

3 Results

Under the RCP6.0 scenario, the anthropogenic greenhouse gas radiative forcing increases global average surface air temperature from 288.5 to 290.2 K during the period of 2004–2089 (Fig. 1a). The higher temperature enhances the hydrological cycle, and therefore global precipitation increases as well (Fig. 1b). The global surface downward solar radiation gradually decreases by about 1 W m^{-2} during the period 2004–2089 (Fig. 1c) as the total cloud coverage increases, especially low clouds, which increase by 0.7 % (Fig. 1d). However, the terrestrial visible direct solar radiation shows an upward trend (Fig. 1e) due to the effects of gradual tropospheric aerosol reductions under RCP6.0. The terrestrial total solar radiation (not shown) also has a slight increasing trend from 2004 to 2089, which is opposite with the global surface solar radiation trend. There are two reasons: first, the reduction in aerosol emissions mainly affects the continents; and second, the increasing of cloud coverage is mainly over the ocean. Land average visible diffuse radiation (300–700 nm) decreases in RCP6.0 (Fig. 1f) due to the decreasing of aerosol emission in the RCP6.0 scenario (Meinshausen et al., 2011). With the negative radiative forcing of stratospheric sulfate aerosol (−1.6 W m^{-2}) (Fig. 1c), G4SSA successfully cools the surface by 1 K as compared to RCP6.0 (Fig. 1a). In this model, the global cloud coverage (mainly low clouds) is less (Fig. 1d) and the average precipitation reduces by 0.07 mm day^{-1} (2.5 %) (Fig. 1b), consistent with previous studies (e.g. Jones et al., 2013). Diffuse radiation over the land increases significantly (Fig. 1f) as the sulfate aerosols in the stratosphere (2.0 Tg S equilibrium loading) scatter solar radiation. Therefore although the total solar radiation reduces by 1.6 W m^{-2}, the visible diffuse solar radiation increases by 3.2 W m^{-2} over the land under all-sky conditions. Three months after the eruption of Mt. Pinatubo in 1991, diffuse radiation increased from 40 to 140 W m^{-2} under clear sky conditions at the

Mauna Loa observatory (Robock, 2005), but only the edge of the Pinatubo cloud was over Mauna Loa, and the maximum effect was even larger. The photosynthesis rate increased 23 % in 1992 compared with an unperturbed year (1997) (Gu et al., 2003). Therefore, under this sulfate injection geoengineering scenario, which is equivalent to one Pinatubo eruption every 2.5 years, diffuse radiation enhancement is expected to enhance the terrestrial photosynthesis rate and potentially increase the land carbon sink.

Solar constant reduction climate intervention (G3S) has no effect on diffuse radiation compared with RCP4.5 since there is no additional aerosol injected into the atmosphere. The overall trend of surface visible diffuse radiation in both G3S and RCP4.5 is decreasing because of decreasing emissions (the tropospheric aerosol removal effect, not shown).

Diffuse radiation is more advantageous for plant productivity than direct radiation (e.g. Gu et al., 2002), since diffuse radiation is absorbed by plants more homogeneously and also more efficiently without exceeding photosynthesis capacity of the plants. Increased diffuse radiation within a certain range will promote plant net production productivity and therefore enhance the carbon sink (Niyogi et al., 2004; Misson et al., 2005; Oliveira et al., 2007). However, if the aerosol load exceeds a certain level, it will suppress photosynthesis (Chameides et al., 1999; Cohan et al., 2002). Knohl and Baldocchi (2009) and Mercado et al. (2009) estimated that the tipping point of the diffuse radiation effect is a ratio of 0.40–0.45 between diffuse radiation and total solar radiation, which is the maximum ratio with a positive effect on plant photosynthesis. Under our sulfate injection climate intervention scenario, the ratio of diffuse radiation and total solar radiation increases from 0.296 to 0.333, indicating that the increase of diffuse radiation in our study would have a positive impact on plant photosynthesis.

Without nutrient limitation, simulated land average photosynthesis would continuously increase in the future due to the stronger CO_2 fertilization effect as the CO_2 concentration increases from 377 ppm (2004) to 632 ppm (2089) (Fig. 2a) (e.g. Allen et al., 1987; Leakey et al., 2009). However, this increase is limited by soil nutrients, such as nitrogen and phosphorus (e.g. Vitousek and Howarth, 1991; Elser et al., 2007). Under the G4SSA scenario, photosynthesis increases 0.07 ± 0.02 μmol m^{-2} s^{-1} compared with that in the RCP6.0 scenario (Fig. 2a). This enhancement is due to the combination of the cooling and diffuse radiation effects. Photosynthesis reaches its maximum at an optimal temperature for different plants under different CO_2 concentrations (e.g. Sage and Kubien, 2007). In general the cooling effect from solar radiation management would increase photosynthesis in tropical regions where there might be extreme heat stress under the global warming scenario, and slow down photosynthesis in middle-high latitude regions, since the temperature has not exceeded the optimal temperature even under the global warming scenario.

Figure 2b shows the photosynthesis rate in G3S and RCP4.5. Without the diffuse radiation effect, the land averaged photosynthesis rate has no significant change under solar radiation management (G3S). The cooling effect on photosynthesis has been cancelled out by combining increases in tropical regions and decreases in temperate regions. Therefore, the increase of the photosynthesis rate in Fig. 2a under the G4SSA scenario is mostly caused by the enhancement of diffuse radiation.

Without nutrient limitation, the increase of the photosynthesis rate is almost all over vegetated land (Fig. 3a). The strongest increase is in the Amazon rainforest with a value of 1.42 μmol m^{-2} s^{-1} (26.3 %), where multiple layers of the canopy would receive more diffuse radiation, and the cooling helps plant growth during the entire year. Considering that the global forest carbon sink was 2.41 ± 0.42 Gt C yr^{-1} during the period of 1990–2007, and the Amazon rainforest contributes ~ 25 % (Pan et al., 2011), increasing its photosynthesis rate by 4.2 ± 5.9 % will significantly help to bring more carbon out of the atmosphere. In high latitude and high altitude regions, diffuse radiation is not the dominant factor controlling the photosynthesis rate, and the colder environment under G4SSA would reduce the photosynthesis rate (Fig. 3a). The expected reduction in stratospheric ozone column in high latitudes, due to increased heterogeneous reactions promoting ozone-destroying cycles, increases UV radiation (e.g. Pitari et al., 2014), which is not further investigated in this study. Without the diffuse radiation effect, the photosynthesis rate difference between G3S and RCP4.5 is mainly due to the cooling effect (Fig. 3b). The Amazon rainforest still has the largest photosynthesis increase, with a maximum value of 1.24 $\mu mol\,m^{-2}\,s^{-1}$, but the average photosynthesis change in the Amazon region is only 0.7 ± 5.7 %. Since the two climate interventions (G4SSA and G3S) are under different assumptions and with different reference runs (RCP6.0 and RCP4.5) and they have different levels of cooling, different precipitation changes, and different CO_2 concentrations, we cannot evaluate the exact fraction of the enhancement of diffuse radiation contribution to the increasing of photosynthesis. But from the global averaged photosynthesis change (Fig. 2) compared with the cooling effect, the diffuse radiation change does increase the carbon uptake significantly with a p value less than 0.002.

We have briefly calculated the additional carbon sink due to the increase of photosynthesis. Based on our simulations, without nutrient limitation, the global land average photosynthesis rate increases 0.07 ± 0.02 $\mu mol\,m^{-2}\,s^{-1}$ under the G4SSA sulfate injection climate intervention scenario, and the land area used for photosynthesis calculation in CLM is $1.5 \times 10^8\,km^2$. Therefore the increase of the photosynthesis rate without nutrient limitation would increase gross primary productivity of 3.8 ± 1.1 $Gt\,C\,yr^{-1}$ from terrestrial vegetation. Mercado et al. (2009) estimated that after the 1991 eruption of Mt. Pinatubo the land carbon sink increased by 1.13 $Gt\,C\,yr^{-1}$ in 1992 and 1.53 $Gt\,C\,yr^{-1}$ in 1993, which were contributed by both diffuse radiation and the cooling effect. The diffuse radiation effect was the dominant factor in 1992 (1.18 $Gt\,C\,yr^{-1}$), while it was much less effective in 1993 (0.04 $Gt\,C\,yr^{-1}$). This enhanced land carbon sink after volcano eruptions has been observed in the atmospheric CO_2 concentration curve (Keeling et al., 1995; Ciais et al., 1995). The predicted CO_2 concentration increase rate based on industrial emissions in the early 1990s was 1.7 % yr^{-1}, but the observed CO_2 concentration after 1991 declined instead of increasing. In our simulations, the CO_2 concentration is prescribed in both G4SSA and RCP6.0. If we consider the carbon cycle changes after sulfate injection climate intervention, the CO_2 concentration might be lower than the global warming scenario due to the diffuse radiation and the cooling effects.

4 Discussion

Although the calculation here is based on an assumption of no nutrient limitation, which could overestimate the benefits from diffuse radiation in terms of the terrestrial carbon sink, there are other mechanisms that sulfate injection geoengineering might trigger. The cooling effect would suppress plant and soil respiration. After the eruption of Mt. Pinatubo, the terrestrial carbon sink increased due to both the cooling effect (Ciais et al., 1995; Keeling et al., 1995) and the diffuse radiation fertilization effect (Jones and Cox, 2001; Lucht et al., 2002). Mercado et al. (2009) estimated that the cooling effect and diffuse radiation equally contributed to the enhancement of the terrestrial net primary productivity changes, and that the cooling effect also suppresses soil respiration, which reduces carbon emissions as much as increasing of the carbon sink. Moreover, respiration of terrestrial ecosystems, including the decomposition of soil organic carbon, might be more sensitive to temperature change than the gross primary productivity (Jenkinson et al., 1991). Therefore, if we include the reduction of heterotrophic respiration due to the cooling effect, land processes would capture even more carbon in sulfate injection geoengineering scenarios. However, current land models tend to simulate soil organic carbon decomposition under climate changes in a simple way, which might not be able to accurately predict the temperature sensitivity of global soil organic carbon decomposition as well as the terrestrial carbon cycle change under future climate changes (Davidson and Janssens, 2006).

The ocean covers most of Earth, and CO_2 feedbacks from geoengineering will also occur in the ocean, including responses dependent on the ocean surface temperature, ocean biological processes, and changing ocean dynamics. For example, an El Niño will cause the ocean to temporarily emit more CO_2 to the atmosphere. However, idealized geoengineering experiments have not shown any significant effect on

El Niño (Gabriel and Robock, 2015). The ocean model we used does simulate dynamical and temperature responses, but does not include a carbon cycle simulation. Such responses will need to be included for an integrated assessment of the impacts of geoengineering on the global carbon budget.

Sulfate injection climate intervention has a great potential to increase the land gross primary productivity, reduce the terrestrial carbon source, and change the ocean carbon cycle. More studies are needed to further understand the details of each process. But there are still many reasons to be hesitant about implementation of geoengineering (Robock, 2012, 2014).

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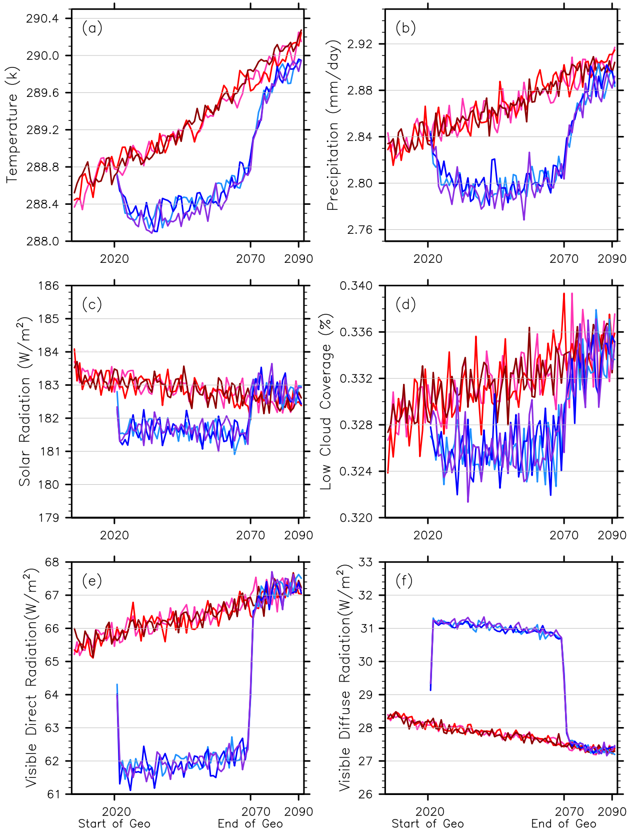

Figure 1. Global average temperature **(a)**, precipitation **(b)**, surface downward solar radiation **(c)** and low cloud coverage **(d)** under sulfate injection geoengineering – G4SSA (red lines) and under RCP6.0 (blue lines). Land average surface downward visible direct radiation **(e)** and diffuse radiation **(f)** under G4SSA (red lines) and RCP 6.0 (blue lines). The three red lines and blue lines indicate three ensemble members of G4SSA and RCP6.0. Sulfate injection starts at 2020 and ends at 2069.

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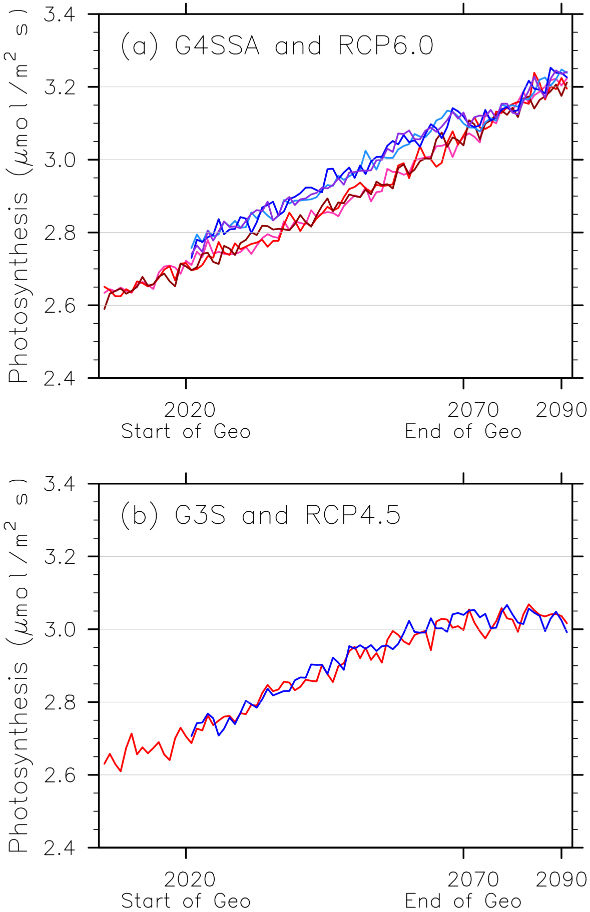

Figure 2. Land average photosynthesis rate without nutrient limitation under sulfate injection geoengineering (G4SSA) (blue lines) and RCP6.0 (red lines) **(a)** and under solar constant reduction geoengineering (G3S) (blue line) and RCP4.5 (red line) **(b)**.

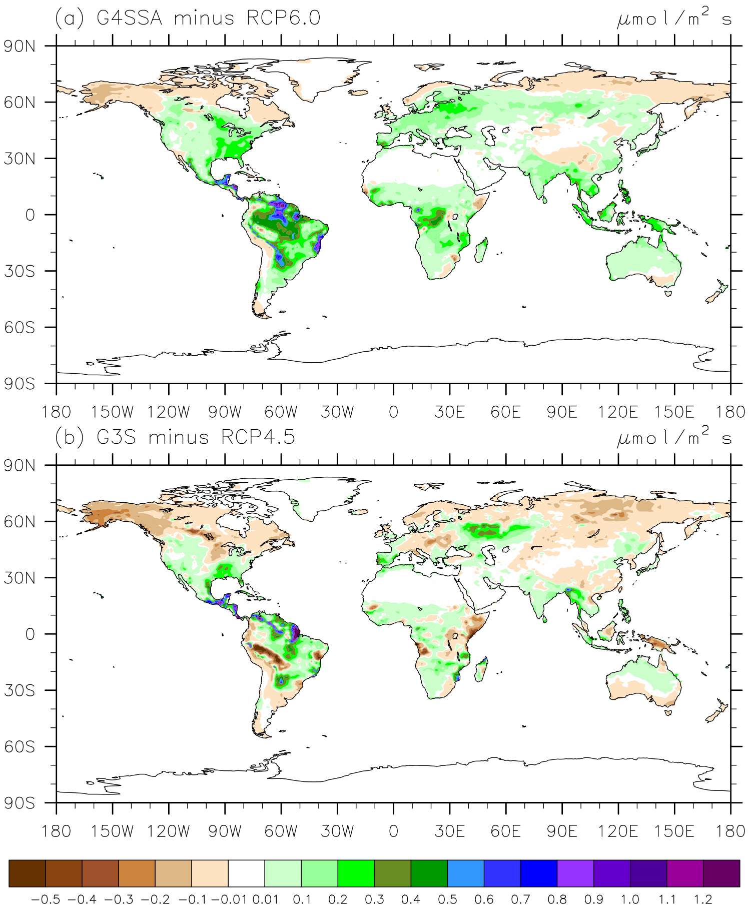

Figure 3. (a) Photosynthesis rate differences between G4SSA and RCP6.0 during the last 10 years of sulfate injection (2060–2069). **(b)** Photosynthesis rate anomaly between G3S and RCP4.5 during the last 10 years of solar constant reduction (2060–2069).