**Reply to reviews of "Stratospheric Sulfate Geoengineering Could Enhance the Terrestrial Photosynthesis Rate" by Xia, Robock, Tilmes and Ryan, submitted to *Atmospheric Chemistry and Physics*.**

*Comments are repeated in black italics.* Replies are indicated in blue.

**Anonymous Referee #1**

*This paper presents a modeling study where an Earth System Model (CESM-CAM4) was used to examine the response of terrestrial photosynthesis in the context of climate intervention by geo-engineering. The author conducted 2 experiments. In a first experiment (G4SSA), stratospheric sulfate aerosols are injected to counteract global warming from anthropogenic activities assuming a RCP6.0 baseline scenario. An increase of up to +3.8 PgC/year in plant gross primary productivity during the geo-engineering period is reported for G4SSA. In the second experiment (G3S), the authors ran a simulation with reduced solar constant to counteract the global warming from anthropogenic activities assuming the RCP4.5 baseline scenario. In this later experiment, the plant gross primary productivity is virtually unmodified compared to the RCP4.5 control run. Despite using different baseline scenario references between the two experiments, the authors conclude that the increase in the land carbon sink in the G4SSA experiment could be attributed to the diffuse light fertilisation effect introduced by the stratospheric sulfate aerosols. Indeed, aerosols not only reduce the quantity of radiation reaching the surface, but also modify its quality, increasing the diffuse component that supposedly benefits plant growth despite the reduction of total radiation.*

*General comments:*

*Overall, this paper is well written and the subject is relevant for a publication in ACP. Moreover, this paper is trying to address one of the scientific question for which the GeoMIP experiments were specifically designed for - i.e. impact of geo-engineering on the carbon cycle - making the publication of this paper in the ACP - GeoMIP special issue even more appropriate. I appreciate that the paper was initially tailored to be a letter to be submitted to GRL which explains the short format. However, despite the authors making overall reasonable scientific points throughout the manuscript, the reader is left with the feeling that the results presented here may lack robustness due to a very short analysis and a discussion / conclusion that remains quite general. It would be better to further evaluate the contribution of the other impacts of geo-engineering on the C-cycle to put in context the diffuse light fertilisation effect identified in this study. I would support the publication of this paper after considering some of these comments.*

We thank the reviewer for these comments. And we have added more discussion in the manuscript.

*Specific Comments:*
-*Why not run G3S with RCP6.0 as a baseline scenario? This would partially help to disentangle the increase in GPP due to the cooling effect and the increase due to the diffuse fertilisatio effect.*

G3S was proposed before G4SSA in the first Geoengineering Modeling Intercomparison Project (GeoMIP) workshop in 2011 by Simone Tilmes as a comparison of G3 – "In combination with

RCP4.5 forcing, starting in 2020, gradual ramp-up the amount of $SO_2$ or sulfate aerosol injected, with the purpose of keeping global average temperature nearly constant" (Kravitz et al., 2011). Instead of injecting $SO_2$, G3S reduces the solar constant to balance the RCP4.5 forcing. The G3S experiment using CAM4-chem was done before the G4SSA simulations. G4SSA has been proposed to both the GeoMIP and the Chemistry-Climate Model Initiative (CCMI). To encourage more climate chemistry modeling groups to conduct this experiment, it uses RCP6.0 as the reference run since this is the standard reference run for CCMI, and most of the modeling groups have done this reference run already. Since RCP4.5 and RCP6.0 have a very similar anthropogenic forcing, (see for example Tilmes et al., 2015, Figure 1), the baseline for the two experiments is very similar and, G3S can be used to understand how G4SSA-solar affects photosynthesis rate. Figure 1 shows the solar constant reduction of G3S which is ranging from 0.0 W/m$^2$ (2020) to 9.06 W/m$^2$ (2069). For G4SSA-solar, to simulation the radiative forcing of 8 Tg $SO_2$/yr, the solar constant needs to be reduced by 14.55 W/m$^2$ (1.1% dimming). The larger reduction is due to the difference between direct solar dimming and using aerosols to dim the sun. The basic principle, that solar dimming does not affect stratospheric ozone or produce diffuse radiation, is well illustrated by the G3S results.

We have added the following to Model and Experiment Design:

Page 6, Line 136-146

"The reason we used different reference runs (RCP4.5 and RCP6.0) for the two experiments (G3S and G4SSA) is that they come from different phases of GeoMIP. G3S was initiated before G4SSA when GeoMIP just started and the reference run for the first phase of GeoMIP was RCP4.5. G4SSA is participating in both GeoMIP and CCMI. Since RCP6.0 is the standard reference run for CCMI, to encourage more climate chemistry modeling groups to participate in G4SSA and generate robust understanding of how atmospheric chemistry responses to sulfate injection geoengineering, Tilmes et al. (2015) proposed that G4SSA be based on RCP6.0. Since the anthropogenic forcing is very similar between RCP4.5 and RCP6.0 between 2020 and 2070, we expect very little difference between the two experiments. The basic principle, that solar dimming does not affect stratospheric ozone or produce diffuse radiation like stratospheric aerosols do, is well illustrated by the G3S results."

And in the Results:

Page 9, Line 193-205

"Solar constant reduction climate intervention (G3S) efficiently cools the surface as well. Since there is less radiative forcing reduction due to the experiment design of G3S, the annual global averaged temperature reduction (gradually from 0°C to 0.8°C) is less than the reduction in G4SSA. Precipitation and surface evaporation also reduce under G3S. However, 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 slowly decreases because of decreasing emissions (the tropospheric aerosol removal effect, not shown). Although the two experiments have different radiative forcing reductions: 2.5 W/m$^2$ for G4SSA and 0-1.5 W/m$^2$ for G3S, we expect linear changes in temperature and precipitation corresponding to the radiative forcing change (Irvine et al., 2010; Kravitz et al., 2014). We focus on the diffuse radiation effect in this study, which is included in G4SSA and excluded in G3S due to the experiment design. Therefore, it is reasonable to compare the two experiments as to their diffuse radiation effect on photosynthesis."

We have also added references:

Irvine, P. J., Ridgwell, A., and Lunt, D. J.: Assessing the regional disparities in geoengineering impacts, Geophys. Res. Lett., 37, L18702, doi:10.1029/2010GL04447, 2010.

Kravitz, B., et al.: A multi-model assessment of regional climate disparities caused by solar geoengineering, Environ. Res. Lett., 9, 074013, doi:10.1088/1788-9326/7/074013, 2014.

*Are ozone effects on plants included? Is stratospheric ozone reduced in accordance with increased sulfate injections?*

No, the ozone effect on plants is not included in our current simulation. Sulfate injection geoengineering will change the ozone column in the stratosphere (Tilmes et al., 2009), which is the case in the G4SSA simulation and will be discussed in a future study. Further, surface ozone concentrations are changed, which is important to plants and human health. We are writing another manuscript to address this issue.

*- It would be interesting to discuss in more details the individual contribution of the climatic variables (T, precip, Rad, $CO_2$, …) that control the observed changes in photosynthesis (e.g. Beer et al., 2010 DOI: 10.1126/science.1184984)*

We have added Fig. 5 and more discussion.

Page 11, Line 251-Page 12, Line 256:

"Those two positive impacts of diffuse radiation and surface temperature changes from G4SSA counteract with the negative impacts from the regional reduction of soil water content (not shown here) and the global reduction of total solar radiation (Fig. 5b and 5c). In previous study, precipitation is found to be the largest climate factor controlling the global primary productivity during 1998-2005 (Beer et al., 2010)."

Page 12, Line 262-266:

"In high latitude and high altitude regions, although increasing diffuse radiation still increase the photosynthesis rate, temperature reduction has a negative impact on the photosynthesis (Fig. 5a), which is consistent with a previous study (Glienke et al., 2015), and the stronger temperature reduction in the high latitude regions would reduce the photosynthesis rate (Fig. 4a). "

And reference has been added:
"Beer, C., et al.: Terrestrial Gross Carbon Dioxide Uptake: Global Distribution and Covariation with Climate, Science, 329, 834-838, doi:10.1126/science.1184984."

*- In Fig 3, could you indicate the area where changes are statistically significant?*

Fig. 4 has been modified to indicate area with none statistically significant changes.

We have changed the text

Page 11, Line 246-247:

"Without explicit nutrient limitation, the increase of the photosynthesis rate is almost entirely over vegetated land during year 2030-2069 of G4SSA compared with RCP6.0 (Fig. 4a)"

Page 12, Line 274-276:

"Without the diffuse radiation effect, the photosynthesis rate differences between G3S and RCP4.5 are not significant in more regions (Fig. 4b) compared with is the anomalies between G4SSA and RCP6.0."

And Fig. 4 caption has been changed to

"Fig. 4. (a) Photosynthesis rate differences between G4SSA and RCP6.0 during year 2030-2069 (sulfate injection period, exclude the first 10 years) (b) Photosynthesis rate anomaly between G3S and RCP4.5 year 2030-2069 of solar reduction. Hatched regions are areas with p-value > 0.05 (where changes are not statistically significant based on paired T-test)."

- *In atmospheric radiative transfer models, the optical properties of anisotropic scatterers such as aerosols are usually rescaled to provide a better estimate of the total fluxes which are ultimately used to calculate the atmospheric heating rates. This, however, introduces biases for the direct and diffuse components of radiation. Indeed, a fraction of the diffuse radiation that is scattered in the incident direction is then reallocated to the direct beam. In your study, have you considered recalculating the best estimate of surface diffuse radiation (i.e. total radiation with rescaling minus direct radiation without rescaling) to use in the land surface scheme. If so could you comment on the uncertainties that this could introduce?*

While our study does not specifically reevaluate the validity of CESM and the interface of surface and atmospheric models, the interface has been vetted for over 20 years. Our study uses the model "as is" since we do not make changes to that interface.

The optics for sulfate aerosols are specified as unscaled values, even though the subsequent computation for radiative transfer does scale the scattered radiation (as in most delta-Eddington schemes). However, the surface models (and interface between atmosphere and surface) are built and tested using those assumptions. A formal validation of CESM's treatment of diffuse radiation at the surface is beyond the scope of this study, but could be a welcome addition to the validation of this model. It is difficult to know which uncertainties the reviewer wishes would be evaluated.

(This answer is based on communication with Andrew Conley, who is working on radiation models in the Chemistry Climate Working Group at NCAR)

- *As you correctly mentioned the absence of nitrogen limitation in your simulations means that the increase in photosynthesis for G4SSA is an upper limit estimate. I thought that CLM has a configuration with nitrogen limitation that doesn't require to run with the nitrogen scheme. Why not try also running with this to provide a lower estimate of the photosynthesis increase (if any) for G4SSA?*

The CLM used in our G4SSA/RCP6.0 simulations is CLM4SP (prescribed satellite phenology). We also use a present day climatology to prescribe the leaf area index (LAI), which is based on MODIS satellite data.
To study the nitrogen limitation, the only way is to interactively include biogeochemistry in the land model. The CLM does not have a configuration to run with nitrogen limitation in the satellite phenology mode (the one we used). The CLM group do evaluate GPP in both SP and CN/BGC (Carbon-Nitrogen Model / BioGeochemical Cycles) versions of the model, with the goal of having the GPP be similar in both, because they want both to match the observations. (Based on a communication with Danical Lombardozzi and Peter Lawrence, who are working in the Climate and Global Dynamics Laboratory at NCAR)

We are planning another experiment in the future with CN/BGC and dynamic vegetation turned on.

We have added the following text:

Page 5, Line 104-112:

"Since the experiments are branched from the Climate Chemistry Model Initiative (CCMI) runs in which CAM4-chem participates, we used the same configuration as the reference run. Therefore we used the Community Land Model (CLM) version 4.0 with prescribed satellite phenology (CLM4SP) instead of the carbon-nitrogen cycle, coupled with CAM4-chem. This model calculates vegetation photosynthesis under the assumption of prescribed phenology and no explicit nutrient limitations (Bonan et al., 2011). With the satellite phenology option, although nitrogen limitation is not explicitly included, there is some inherent nitrogen limitation because nitrogen availability limits the leaf area index in the measurements used in CLM4SP, and the model has been validated with gross primary production observations."

- *This is a naive question but is this stratospheric $SO_2$ injection great enough to lead to the formation of acid rain, which ultimately could affect plant physiology?*

First, in CAM4-chem, since we specify stratospheric aerosol, fall of injected sulfate aerosol from the stratosphere to the troposphere is not included. Hence there is no extra sulfate in the troposphere, and in our simulation there is no enhancement of acid rain to affect plant physiology. Second, yes, there would be additional acid rain if we consider the fall-out of sulfate aerosol from the stratosphere, but the extra sulfate deposition would not be large enough to have negative impacts on most ecosystems (Kravitz et al., 2009). In our scenario, 8 Tg $SO_2$ in injected into the stratosphere each year (and is therefore removed from the system each year once equilibrium is reached), and this can be compared to the approximate annual human injection into the atmosphere as a result of fossil fuel burning of 100 Tg $SO_2$.

- *As you mentioned, the reduction of surface temperature in a geo-engineered climate should reduce the heterotrophic transpiration therefore reducing a source of carbon for the atmosphere. Why not have look at this parameter in your simulation?*

We have added one more plot of canopy transpiration (Fig.1 (h)) and the text:

Page 8, Line 164-166:

"Under this global warming scenario, vegetated-land averaged canopy transpiration decreases over time mainly due to increasing $CO_2$ (Fig. 1h) (Reddy et al., 1995)."

Page 9, Line 189-192:

"Furthermore, the drier, cooler and more diffuse radiation environment under G4SSA reduces the canopy transpiration comparing with RCP6.0 (Fig. 1h) (Kanniah et al., 2012), which indicates that less $CO_2$ is released back to the atmosphere by plant respiration."

References have been added:

Reddy, V. R., Reddy, K. R., and Hodges, H. F.: Carbon dioxide enrichment and temperature effects on cotton canopy photosynthesis, transpiration, and water-use efficiency, Field Crops Research, 42 (1), 13-23, doi:10.1016/0378-4290(94)00104-K, 1995.

Kanniah, K. D., Beringer, J., North, P., and Hutley, L.: Control of atmospheric particles on diffuse radiation and terrestrial plant productivity: A review, Progress in Physical Geography, 36 (2), 209-237, doi:10.1177/0309133311434244, 2012."

- *You mentioned that the carbon cycle was not allowed to feedback in your simulation (concentration driven run with prescribed CO2). But does the vegetation be allowed to evolve and compete or this is fixed as well? Dynamic vegetation is important as this allows the land surface type to adjust to changes in climate rather than retaining potentially uncompetitive, poorly adapted plant species.*

No, we do not have the dynamic vegetation function turned on. The surface type is fixed during our simulation. Since this experiment is built upon the reference run of the CCMI, which has no dynamic vegetation, we conducted G4SSA with the same settings but only specified stratospheric sulfate aerosols. But thanks very much to point this out. We do plan to run the reference run (RCP6.0) and G4SSA with dynamic vegetation and the carbon-nitrogen cycle turned on, as mentioned above.

***Technical corrections:***

- ***Page 25628, line(s) 4-5:*** *"we conducted climate model simulations with the Community Earth System Model, with the Community Atmospheric Model …". This should be reformulated to make it less confusing.*

We have changed it to “we conducted climate model simulations with the Community Earth System Model – the Community Atmospheric Model 4 fully coupled to tropospheric and stratospheric chemistry (CAM4-chem)” (Page 2, Line 31-33)

- ***Page 25628, line(s) 14-16****: “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.” Add “the” before “implementation”. In my opinion, this sentence doesn’t really add anything to the abstract and could be removed.*

We have added “the” (Page 2, Line 42). In our opinion, it is necessary to remind readers that although we have found a beneficial impact of geoengineering, there remain many reasons not to implement it, and that we do not mean to imply that we support implementation.

- ***Page 25628, line(s) 18-19****: change “to manipulate” by “for manipulating”*

We have changed it to “for manipulating” (Page 3, Line 48-49)

- ***Page 25628, line(s) 24-25****: change “how this proposed …” by “the way in which this proposed …”*

We have changed it to “Climate changes due to sunshade geoengineering and sulfate injection geoengineering have been extensively studied …” (Page 3, Line 63-64)

- ***Page 25628, line(s) 26****: replace “such as” by “including”*

We have changed it to “including” (Page 3, Line 65)

- ***Page 25629, line(s) 6-7****: replace “have not been comprehensively studied yet” by “have not yet been comprehensively studied”*

We have changed it to “need to be comprehensively studied” (Page 4, Line 72)

- ***Page 25629, line(s) 12****: change “rate, which was mainly due” by “rate. This was mainly due”*

We have changed it to “rate. This was mainly due” (Page 4, Line 77)

- ***Page 25629, line(s) 15****: change “volcano eruptions” by “volcanic eruptions”*

We have changed it to “volcanic eruptions” (Page 4, Line 80)

- ***Page 25629, line(s) 21****: change “by the continents” by “by terrestrial vegetation”*

We have changed it to “by terrestrial vegetation” (Page 4, Line 85-86)

- ***Page 25630, line(s) 2****: add comma before “together” and after “effect”. Replace “may” by “would likely”*

We have changed it to “and this long-term diffuse radiation enhancement, together with the cooling effect, would likely play an important role in the terrestrial carbon budget.” (Page 5, Line 95-97)

- ***Page 25631, line(s) 9***: *replace “especially” with “particularly”*

We have changed it to “particularly” (Page 7, Line 156)

- ***Page 25631, line(s) 12-14***: *“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”. Note that in the land-surface community, the “global radiation” usually refers to the sum of diffuse and direct radiation at surface. You may want to reformulate this sentence in order to avoid ambiguity (e.g. replace terrestrial by averaged over land and global by averaged globally). Also, add “surface” after “terrestrial total” for consistency.*

We have changed it to “The downward total solar radiation averaged over land (not shown) also has a slight increasing trend from 2004 to 2089, which is opposite to the globally-averaged surface solar radiation trend.” (Page 7, Line 159-Page 8, Line 161)

- ***Page 25631, line(s) 14-15***: *change “There are two reasons: first” into “There are two reasons for this, first”. Replace semi column by coma at “; and second, ”. Change “increasing” by “increase”.*

We have changed it to “There are two reasons for this: the reduction in aerosol emissions mainly affects the continents and the increase of cloud coverage is mainly over the ocean.” (Page 8, Line 161-162)

- ***Page 25631, line(s) 16***: *Change with “Averaged visible diffuse radiation (300–700 nm) over land”*

We have changed it to “Averaged visible diffuse radiation (300-700 nm) over land” (Page 8, 162-163)

- ***Page 25631, line(s) 24***: *change “Therefore although the total” for “Therefore, while the ”*

We have changed it to “Therefore, while the …” (Page 8, Line 175)

- ***Page 25632, line(s) 2***: *replace “larger” by “greater”*

We have changed it to “greater” (Page 8, Line 183)

- ***Page 25632, line(s) 2-3***: *“The photosynthesis rate increased 23 % in 1992 compared with an unperturbed year (1997) (Gu et al., 2003)”. Wasn't this result just for Harvard forest?*

We have changed it to "The photosynthesis rate of a northern hardwood forest (Harvard Forest) …" (Page 8, Line 183-Page 9, Line 184)

- ***Page 25632, line(s) 14-15****: replace "since" by "because". I wouldn't say that the absorption of diffuse radiation is "more homogeneously". It is the distribution of radiation that is more homogeneous within the canopy for diffused light conditions, hence, more light to be absorbed is available for shaded leaves. Remove the "also" in "and also more efficiently". Replace "photosynthesis capacity" with "photosynthetic capacity"*

We have changed it to "because diffuse radiation provides more homogeneous distribution of radiation within the canopy and more light can be absorbed by shaded leaves without exceeding the photosynthetic capacity of the plants" (Page 10, Line 208-210)

- ***Page 25632, line(s) 18****: remove coma at the end of "load exceeds a certain level, "*

We have removed the comma (Page 10, Line 212)

- ***Page 25632, line(s) 22****: replace "which is the maximum ratio" by "this is the max…"*

We have changed it to "this" (Page 10, Line 215)

- ***Page 25632, line(s) 24****: replace "indicating that" with "therefore"*

We have changed it to "therefore" (Page 10, Line 218)

- ***Page 25632, line(s) 29****: change for "… increase is limited by the amounts of soil nutrients such as …"*

We have changed it to "However, this model-simulated increase may not be realistic, since the actual photosynthesis rate is limited by the amounts of soil nutrients such as nitrogen and phosphorus (e.g., Vitousek and Howarth, 1991; Davidson et al., 2004; Elser et al., 2007)" (Page 10, Line 223-225)

- ***Page 25633, line(s) 4-5****: Rephrase this with something like: "Photosynthesis is most efficient at an optimal temperature that depends on plant type and CO2 …"*

We have changed it to "Different types of plants show maximum photosynthesis rates at certain optimal temperature depending on CO2 concentrations (e.g., Sage and Kubien, 2007)" (Page 10, Line 229-230)

- ***Page 25633, line(s) 7****: "there might be extreme" replace "might be" to "is likely to be"*

We have changed it to "is likely to" (Page 11, Line 233)

- ***Page 25633, line(s) 16****: use "largely" or "primary" instead of "mostly"*

We have changed it to “primarily” (Page 11, Line 244)

- ***Page 25633, line(s) 17****: “photosynthesis rate is almost all over” replace “all” with “entirely”*

We have change it to “photosynthesis rate is almost entirely over vegetated land” (Page 11, Line 246-247)

- ***Page 25633, line(s) 23****: “will significantly help to bring more carbon” replace “will with “would”*

We have changed it to “would” (Page 12, Line 258)

- ***Page 25634, line(s) 4****: “Since the two climate interventions”, remove “since”*

We have removed “since” (Page 13, Line 278)

- ***Page 25634, line(s) 5-6****: change for “have different assumptions and with different reference runs (RCP6.0 and RCP4.5) and have different …”*

We have change it to “have …” (Page 13, Line 278)

- ***Page 25634, line(s) 7-9****: stop sentence here: “concentrations, we cannot evaluate”. “concentrations. We cannot, therefore, evaluate”. The rest of the sentence is awkwardly phrased, (“exact fraction of the enhancement of diffuse radiation contribution to the increasing …”), please correct that. Don’t start next sentence with “But”! You can say: “When comparing the global averaged photosynthesis change (Fig 2) with the cooling effect, the diffuse …”*

We have changed it to “… and different $CO_2$ concentrations. We cannot, therefore, evaluate how much the enhancement of diffuse radiation contributes to the increase of photosynthesis. When comparing the global averaged photosynthesis change (Fig. 2) with the cooling effect, …” (Page 13, Line 280-282)

- ***Page 25634, line(s) 12****: Delete “briefly”*

We have deleted “briefly” (Page 13, Line 286)

- ***Page 25634, line(s) 13****: remove coma after “our simulations”*

We have changed the sentence to “Using the land area ($1.5\times10^8$ km2) in CLM, for G4SSA, the global land average photosynthesis rate increases $0.07\pm0.02$ µmol C $m^{-2}$ $s^{-1}$ compared with RCP6.0.” (Page 13, Line 287-288)

- ***Page 25634, line(s) 13-16****: This sentence is too long and quite messy. Reorder it and start with listing the assumptions (no Nutr. Lim., area, G4SSA …) and then write the result.*

We have changed the sentence to "Using the land area ($1.5\times10^8$ km$^2$) in CLM, for G4SSA, the global land average photosynthesis rate increases 0.07±0.02 μmol C m$^{-2}$ s$^{-1}$ compared with RCP6.0." (Page 13, Line 281-282)

- ***Page 25634, line(s) 18****: change "estimated" with "estimate"*

We have changed it to "estimate" (Page 13, Line 290)

- ***Page 25634, line(s) 20****: change "which were contributed by both diffuse" for "this was the result of both …"*

We have changed it to "this was the result of both" (Page 13, Line 292)

- ***Page 25634, line(s) 22****: replace "effective" with significant*

We have changed it to "significant" (Page 13, Line 293)

- ***Page 25634, line(s) 22-23****: "Volcanic" instead of "volcano"*

We have changed it to "volcanic" (Page 16, Line 345)

- ***Page 25634, line(s) 22 to Page 25635, line(s) 2****: From "This enhanced land carbon - … " until the end of the Results section; As you don't do the simulations that allow the carbon cycle to feedback on the climate, I would recommend to move this paragraph to the discussion and develop it to make a stronger argument.*

We have moved this part to discussion, and rearranged this paragraph

Page 15, Line 342-348:

"In our simulations, the $CO_2$ concentration is prescribed in both G4SSA and RCP6.0, but we expect that the $CO_2$ concentration of G4SSA might be lower than the global warming scenario due to the diffuse radiation and the cooling effects because this $CO_2$ concentration change has been observed after volcanic eruptions due to enhanced land carbon sinks (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."

- ***Page 25635, line(s) 4****: "Although the calculation here" too informal*

We have rewritten the discussion, and don't have this sentence.

- ***Page 25635, line(s) 6****: "geoengineering might trigger". Change "might" to "would"*

We have changed it to "would" (Page 15, Line 325)

- ***Page 25635, line(s) 12-13****: "the cooling effect also suppresses soil respiration, which reduces carbon emissions as much as increasing of the carbon sink". Do you mean that the cooling effect decreases the soil respiration to the same quantity as it increases the carbon sink or do you mean it does the two simultaneously?*

We have changed the text to

Page 15, Line 329-332:

"Mercado et al. (2009) estimated that the cooling effect and diffuse radiation equally contributed to the enhancement of the terrestrial net primary productivity changes in 1992, since the cooling effect suppresses soil respiration and reduces carbon emissions. In 1993, the cooling effect actually enhances the land carbon sink more than the diffuse radiation. ".

In Mercado et al. (2009), it said "Our model sugestes a major contribution of diffuse radiation to the land sink anomaly in 1992 of 1.18 Pg C $yr^{-1}$, but a much smaller contribution in 1993 of 0.04 PgC $yr^{-1}$", "Carbon sink anomalies of 1.05 PgC $yr^{-1}$ and 0.92 PgC $yr^{-1}$ are associated with the anomalously cool air temperature, which act to suppress heterotrophic respiration"

- ***Page 25635, line(s) 16-17****: "Therefore, if we include the reduction of heterotrophic respiration due to the cooling effect". Isn't soil respiration a diagnostic from CLM that you could look at in the G3S and its control simulations for instance?*

Since we did not turn on the carbon-nitrogen cycle in our simulation, respiration is not a standard output saved. In our next experiment, we will turn on carbon-nitrogen cycle and dynamic vegetation, and then we will have a better understanding on this issue.

- ***Page 25635, line(s) 23 to Page 25636, line(s) 4****: "The ocean covers most of Earth…". Maybe you should remember the relative contribution of the ocean and the land in removing Carbon from the atmosphere to strengthen the significance of your study results.*

We think that when discussing the possible $CO_2$ concentration change in the atmosphere, it is important to mention another carbon reservoir – Ocean, which may alter $CO_2$ concentration in the atmosphere significantly. Although our study doesn't focus on ocean, it is worth to bring people's attention on sulfate geoengineering impact on ocean, ocean carbon cycle and hence the whole carbon cycle.

- ***Page 25636, line(s) 1****: correct "The ocean model we used does simulate" with "…we used simulates"*

We have changed it to "The ocean model we used simulates" (Page 16, Line 355)

- ***Page 25636, line(s) 5-8****: Reverse the construction of the sentence in order not to end on a negative note - i.e. start by commenting on the hesitation about geo-engineering and then terminate with the main result from your study.*

We have changed it to "Although there have been many reasons to be hesitant about the implementation of geoengineering (Robock, 2012; Robock, 2014), sulfate injection climate intervention may have a great potential to increase 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." (Page 16, Line 359-362)

- ***Page 25636, line(s) 16***: *change "understanding" to "understand*

We have changed it to "understand" (Page 16, Line 362)

**Anonymous Referee #2**

*General Comments:*

*The study uses one Earth System Model (CAM4-chem) to investigate the effect of stratospheric aerosol injections on photosynthesis. It is found that the increase in diffuse radiation from the increase in aerosols combined with cooler temperatures increases the photosynthesis rates and the global mean terrestrial GPP.*
*Overall, I think the topic of the study is important and the effect of diffuse radiation increases from SRM needs further study. This is a valiant start on this line of investigation. The article is suitable for the journal and the GeoMIP special issue after some improvement.*

Thanks for the comment.

*I feel there is a bit of a gap between the title, abstract and what is shown in the paper. The results section is rather brief and could benefit from deeper analysis. Photosynthesis is only one part of the carbon cycle. Analysis of the carbon fluxes and stores would also help shed some light on the response of the terrestrial carbon cycle to stratospheric sulfate geoengineering.*

Thanks for the suggestion. We would like to analyze more variables related to the carbon cycle, but due to the experimental setting (carbon-nitrogen cycle was not turned on), we do not have other variables related to the carbon cycle available. The photosynthesis rate is the only one we can look at. In our next experiment, we will turn on the carbon-nitrogen cycle and the dynamic vegetation to fully investigate how diffuse radiation affects the terrestrial carbon cycle.

*I would recommend doing the G3S scenario on a background of RCP6 instead of RCP4.5, with the same radiative forcing as in G4SSA. This would aid the interpretation of the results.*

G3S was proposed before G4SSA in the first Geoengineering Modeling Intercomparison Project (GeoMIP) workshop in 2011 by Simone Tilmes as a comparison of G3 – "In combination with RCP4.5 forcing, starting in 2020, gradual ramp-up the amount of $SO_2$ or sulfate aerosol injected, with the purpose of keeping global average temperature nearly constant" (Kravitz et al., 2011). Instead of injecting $SO_2$, G3S reduces the solar constant to balance the RCP4.5 forcing. The G3S experiment using CAM4-chem was done before the G4SSA simulations. G4SSA has been proposed to both the GeoMIP and the Chemistry-Climate Model Initiative (CCMI). To encourage more climate chemistry modeling groups to conduct this experiment, it uses RCP6.0 as the reference run since this is the standard reference run for CCMI, and most of the modeling groups have done this reference run already. Since RCP4.5 and RCP6.0 have a very similar anthropogenic forcing (see for example Tilmes et al., 2015, Figure 1), the baseline for the two experiments is very similar and, G3S can be used to understand how G4SSA-solar affects photosynthesis rate. Figure 1 shows the solar constant reduction of G3S which is ranging from 0.0 $W/m^2$ (2020) to 9.06 $W/m^2$ (2069). For G4SSA-solar, to simulation the radiative forcing of 8 Tg $SO_2$/yr, the solar constant needs to be reduced by 14.55 $W/m^2$ (1.1% dimming). The larger reduction is due to the difference between direct solar dimming and using aerosols to dim the sun. The basic principle, that solar dimming does not affect stratospheric ozone or produce diffuse radiation, is well illustrated by the G3S results.

We have added the following to Model and Experiment Design:

Page 6, Line 136-146

"The reason we used different reference runs (RCP4.5 and RCP6.0) for the two experiments (G3S and G4SSA) is that they come from different phases of GeoMIP. G3S was initiated before G4SSA when GeoMIP just started and the reference run for the first phase of GeoMIP was RCP4.5. G4SSA is participating in both GeoMIP and CCMI. Since RCP6.0 is the standard reference run for CCMI, to encourage more climate chemistry modeling groups to participate in G4SSA and generate robust understanding of how atmospheric chemistry responses to sulfate injection geoengineering, Tilmes et al. (2015) proposed that G4SSA be based on RCP6.0. Since the anthropogenic forcing is very similar between RCP4.5 and RCP6.0 between 2020 and 2070, we expect very little difference between the two experiments. The basic principle, that solar dimming does not affect stratospheric ozone or produce diffuse radiation like stratospheric aerosols do, is well illustrated by the G3S results."

And in the Results:

Page 9, Line 193-205

"Solar constant reduction climate intervention (G3S) efficiently cools the surface as well. Since there is less radiative forcing reduction due to the experiment design of G3S, the annual global averaged temperature reduction (gradually from 0°C to 0.8°C) is less than the reduction in G4SSA. Precipitation and surface evaporation also reduce under G3S. However, 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 slowly decreases because of decreasing emissions (the tropospheric aerosol removal effect, not shown). Although the two experiments have different radiative forcing reductions: 2.5 $W/m^2$ for G4SSA and 0-1.5 $W/m^2$ for G3S, we expect linear changes in temperature and precipitation corresponding to the radiative forcing change (Irvine et al., 2010; Kravitz et al., 2014). We focus on the diffuse radiation effect in this study, which is included in G4SSA and excluded in G3S due to the experiment design. Therefore, it is reasonable to compare the two experiments as to their diffuse radiation effect on photosynthesis."

We have also added references:

Irvine, P. J., Ridgwell, A., and Lunt, D. J.: Assessing the regional disparities in geoengineering impacts, Geophys. Res. Lett., 37, L18702, doi:10.1029/2010GL04447, 2010.

Kravitz, B., et al.: A multi-model assessment of regional climate disparities caused by solar geoengineering, Environ. Res. Lett., 9, 074013, doi:10.1088/1788-9326/7/074013, 2014.

*Are ozone effects on plants included? Is stratospheric ozone reduced in accordance with increased sulfate injections?*

No, the ozone effect on plants is not included in our current simulation. Sulfate injection geoengineering will change the ozone column in the stratosphere (Tilmes et al., 2009), which is the case in the G4SSA simulation and will be discussed in a future study. Further, surface ozone concentrations are changed, which is important to plants and human health. We are writing another manuscript to address this issue.

*There is little discussion on the hydrological impacts on productivity.*

We have added Fig. 5 to illustrate the partial correlation between the photosynthesis rate change and the changes of surface temperature, soil water content, total solar radiation and visible diffuse radiation. And we have added more discussion.

Page 11, Line 251-Page 12, Line 256:

"Those two positive impacts of diffuse radiation and surface temperature changes from G4SSA counteract with the negative impacts from the regional reductions of soil water content (not shown here) and the global reduction of total solar radiation (Fig. 5b and 5c). In previous study, precipitation is found to be the largest climate factor controlling the global primary productivity during 1998-2005 (Beer et al., 2010)."

Page 12, Line 262-266:

"In high latitude and high altitude regions, although increasing diffuse radiation still bring up the photosynthesis rate, temperature reduction has a negative impact on the photosynthesis (Fig. 5a) and the stronger temperature reduction in the high latitude regions would reduce the photosynthesis rate (Fig. 4a). "

And reference has been added:
"Beer, C., et al.: Terrestrial Gross Carbon Dioxide Uptake: Global Distribution and Covariation with Climate, Science, 329, 834-838, doi:10.1126/science.1184984."

*What about carbon fluxes and stores?*

Due to the experimental design (carbon-nitrogen cycle was not turned on), we cannot study the carbon fluxes and stores. We are planning the next experiment in the future with the carbon-nitrogen cycle and dynamic vegetation turned on.

***Title:*** *Considering the limitations of the study I would recommend amending the title of the article to reflect that there are uncertainties around this statement. Also you are not showing any GPP figures (or tables) in the paper.*

We have changed the title to "Stratospheric Sulfate Geoengineering Could Enhance the Terrestrial Photosynthesis Rate"

***P 25628 Abstract:***
*Line 2 - 3: "With an 8 Tg yr−1 injection of SO2 to balance a Representative Concentration Pathway 6.0 (RCP6.0) scenario" - What is meant by this? What are you balancing. Please clarify.*

We have added some words “With an 8 Tg $yr^{-1}$ injection of $SO_2$ to produce a stratospheric aerosol cloud to balance anthropogenic radiative forcing from the Representative Concentration Pathway 6.0 (RCP6.0) scenario” (Page 2, Line 29-31)

***Introduction**:*
*Line 18 – 19: “Stratospheric sulfate injection is the most discussed geoengineering strategy to ma-nipulate the climate system to counteract anthropogenic global warming”: Do you mean out of all RSM options? Or is it your opinion that it is more discussed than carbon dioxide removal methods too? Amend accordingly.*

We have changed it to “Stratospheric sulfate injection is one of the most discussed geoengineering strategies for manipulating the climate system to counteract anthropogenic global warming” (Page 3, Line 48-49). Both solar radiation management (SRM) and carbon dioxide removal are under extensive investigation. The U.S. National Academy of Science released two climate intervention reports on February 14, 2015 – one is on Carbon Dioxide Removal and Reliable Sequestration and the other is on Reflecting Sunlight to Cool Earth. We think both strategies are important to study and stratospheric sulfate injection the most discussed SRM technique.

***P 25629***
*Line 11: “After 1991 …”: Specify what happened in 1991. Most readers know about Mt. Pinatubo erupting then, but it is polite to remind them.*

We have changed it to “After the Mt. Pinatubo eruption in 1991” (Page 4, Line 75-76)

*Line 21: “ … by the continents ...” : change this to the terrestrial biosphere – if that is what is meant.*

We have changed it to “by terrestrial vegetation” (Page 4, Line 85-86)

*Line 24: change “fertilizes terrestrial vegetation” to “ … promotes terrestrial vegetation growth ...”, as diffuse radiation is not really a fertilizer.*

We have changed it to “promotes terrestrial vegetation growth” (Page 4, Line 88)

*Line 17: Rap et al. (2015): put the fires and resulting aerosols more into context by providing a sentence or two more on the topic. I.e. effect largest during dry season. And removing vegetation reduces carbon fluxes since it removes vegetation.*

We have added more words on this “The most recent study also showed that Amazon fires of 1998-2007 increased the annual mean diffuse radiation by 3.4-6.8% due to the biomass burning aerosol, which would benefit the net primary productivity by 1.4-2.8% in the Amazonian forests and balance 33-65% of the annual carbon emissions from biomass burning (Rap et al., 2015)” (Page 4-5, Line 91-94)

***P25630 Model simulation:***

*Section 2 might be better re-labeled: Model and experiment design. Or similar.*

We have changed the section tile to "Model and Experiment Design" (Page 5, Line 98)

*Some comment on the limitations of the model and experiment design should be made: Including: if 26 vertical levels is sufficient; The usage of prescribed aerosols; The choice of switching off carbon – nitrogen cycling.*
*Also are you using prescribed vegetation cover or dynamic vegetation? Some more description of the CLM is needed.*

A "High-Top" model such as WACCM would have better vertical resolution and the full atmosphere, which can better simulate atmospheric dynamics in the upper atmosphere, but 26 levels is certainly sufficient for the present study. The model has been evaluated (Tilmes et al., 2016) and shows very good agreement of chemical tracers, in particular ozone with observations in both troposphere and stratosphere and is therefore well suited for this study.

We have added more words on the usage of prescribed aerosols

Page 6, Line 123-128:

"Using specified stratospheric aerosols, tropospheric aerosols are not changed, and therefore we cannot evaluate how the geoengineered stratospheric sulfate aerosols would be transported into the troposphere and affect tropospheric chemistry. Using a fixed stratospheric aerosol distribution to compare the effect of geoengineered stratospheric aerosols in different models is similar to what has been done to investigate the impact of volcanic eruptions in chemistry climate model comparison projects in the past."

And for the choice of switching off the carbon-nitrogen cycling, whether dynamic vegetation is on:

Page 5, Line 104-113

"Since the experiments are branched from the Climate Chemistry Model Initiative (CCMI) runs in which CAM4-chem participates, we used the same configuration as the reference run. Therefore we used the Community Land Model (CLM) version 4.0 with prescribed satellite phenology (CLM4SP) instead of the carbon-nitrogen cycle coupled with CAM4-chem. This model calculates vegetation photosynthesis under the assumption of prescribed phenology and no explicit nutrient limitations (Bonan et al., 2011). With the satellite phenology option, although nitrogen limitation is not explicitly included, there is some inherent nitrogen limitation because nitrogen availability limits the leaf area index in the measurements used in CLM4SP, and the model has been validated with gross primary production observations. Dynamic vegetation is not turned on in this study."

*Line 16: What is the radiative forcing of 8 Tg $SO_2$ $yr^{-1}$*

In different models, 8 Tg $SO_2$ $yr^{-1}$ results in different radiative forcing. This amount of sulfate loading counteracts the total anthropogenic radiative forcing of about -1.1 W $m^{-2}$ based using ECHAM6 (Niemeier et al., 2013) and about -1.5 W $m^{-2}$ based on the early study using the Community Earth System Model (CESM) (Tilmes et al., 2015) assuming a fixed radius of sulfate aerosol. In this simulation, this amount of sulfate causes larger radiative forcing of -2.5 W $m^{-2}$ based on a double radiation call run because we count the different sizes of aerosols.

We have added words "which produces a radiative forcing of about 2.5 W $m^{-2}$" (Page 6, Line 117-118).

*Line 21: " … 2072 to 2089 to study the termination effect." This is rather a short period for the termination effect. Some of the terrestrial carbon cycle feedbacks occur on longer time scales.*

We agree and thanks for this point. This 20-year period is short for some of the climate response and biogeochemical feedbacks. The reason we used 20 years is based on the original experimental design of the Geoengineering Modeling Intercomparison Project (GeoMIP), which ran geoengineering simulations for 50 years and then contined for another 20 years after the end of geoengineering to study the termination effect (Kravitz et al., 2011). According to previous studies (e.g., Jones et al., 2013), many climate variables, such as temperature, rapidly go up within a couple years after the end of geoengineering. We are continuing the G4SSA run for another 10 years to reach 2100, and in our future experiment design with the carbon-nitrogen cycle turned on and with the dynamic vegetation, we will more carefully inspect how the terrestrial carbon cycle responds to the termination of geoengineering and may continue the run for longer period.

*G3S only first mentioned here. Some mention on solar constant reductions as proxy for stratospheric sulfur injections or mirrors in space earlier would be useful. You should also say why you are running the G3S and RCP4.5 experiments.*

We have added to the introduction,

Page 3, Line 54-63:

"As explained in the initial design of the Geoengineering Model Intercomparison Project (GeoMIP) experiment (Kravitz et al., 2011), reducing the solar constant is another way to simulate sulfate injection geoengineering, and is easier to implement in a climate model. It was used in earlier geoengineering simulations (e.g., Govindasamy and Caldeira, 2000), and also can be thought of as a model of satellites in space blocking sunlight, as proposed by Angel (2006). Although the two methods both could both potentially cool the surface, if they could ever be implemented, they would produce different climate responses, including on the hydrological response, stratospheric ozone depletion, troposphere ozone change, downward ultraviolet radiation, and downward diffuse radiation (e.g., Niemeier et al., 2013; Kalidindi et al., 2015; Nowack et al., 2015)."

And we have added the new references.

*Would it not make more sense to do the same experiment design as G4SSA with the solar constant reduction? I strongly recommend doing this.*

G3S was proposed before G4SSA in the first Geoengineering Modeling Intercomparison Project (GeoMIP) workshop in 2011 by Simone Tilmes as a comparison of G3 – "In combination with RCP4.5 forcing, starting in 2020, gradual ramp-up the amount of $SO_2$ or sulfate aerosol injected, with the purpose of keeping global average temperature nearly constant" (Kravitz et al., 2011). Instead of injecting $SO_2$, G3S reduces the solar constant to balance the RCP4.5 forcing. The G3S experiment using CAM4-chem was done before the G4SSA simulations. G4SSA has been proposed to both the GeoMIP and the Chemistry-Climate Model Initiative (CCMI). To encourage more climate chemistry modeling groups to conduct this experiment, it uses RCP6.0 as the reference run since this is the standard reference run for CCMI, and most of the modeling groups have done this reference run already. Since RCP4.5 and RCP6.0 have a very similar anthropogenic forcing (see for example Tilmes et al., 2015, Figure 1), the baseline for the two experiments is very similar and, G3S can be used to understand how G4SSA-solar affects photosynthesis rate. Figure 1 shows the solar constant reduction of G3S which is ranging from 0.0 $W/m^2$ (2020) to 9.06 $W/m^2$ (2069). For G4SSA-solar, to simulation the radiative forcing of 8 Tg $SO_2$/yr, the solar constant needs to be reduced by 14.55 $W/m^2$ (1.1% dimming). The larger reduction is due to the difference between direct solar dimming and using aerosols to dim the sun. The basic principle, that solar dimming does not affect stratospheric ozone or produce diffuse radiation, is well illustrated by the G3S results.

We have added the following to Model and Experiment Design:

Page 6, Line 136-146

"The reason we used different reference runs (RCP4.5 and RCP6.0) for the two experiments (G3S and G4SSA) is that they come from different phases of GeoMIP. G3S was initiated before G4SSA when GeoMIP just started and the reference run for the first phase of GeoMIP was RCP4.5. G4SSA is participating in both GeoMIP and CCMI. Since RCP6.0 is the standard reference run for CCMI, to encourage more climate chemistry modeling groups to participate in G4SSA and generate robust understanding of how atmospheric chemistry responses to sulfate injection geoengineering, Tilmes et al. (2015) proposed that G4SSA be based on RCP6.0. Since the anthropogenic forcing is very similar between RCP4.5 and RCP6.0 between 2020 and 2070, we expect very little difference between the two experiments. The basic principle, that solar dimming does not affect stratospheric ozone or produce diffuse radiation like stratospheric aerosols do, is well illustrated by the G3S results."

And in the Results:

Page 9, Line 193-205

"Solar constant reduction climate intervention (G3S) efficiently cools the surface as well. Since there is less radiative forcing reduction due to the experiment design of G3S, the annual global averaged temperature reduction (gradually from 0°C to 0.8°C) is less than the reduction in G4SSA. Precipitation and surface evaporation also reduce under G3S. However, 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 slowly decreases because of decreasing emissions (the tropospheric aerosol removal effect, not shown). Although the two experiments have different radiative forcing reductions: 2.5 W/m$^2$ for G4SSA and 0-1.5 W/m$^2$ for G3S, we expect linear changes in temperature and precipitation corresponding to the radiative forcing change (Irvine et al., 2010; Kravitz et al., 2014). We focus on the diffuse radiation effect in this study, which is included in G4SSA and excluded in G3S due to the experiment design. Therefore, it is reasonable to compare the two experiments as to their diffuse radiation effect on photosynthesis."

We have also added references:

Irvine, P. J., Ridgwell, A., and Lunt, D. J.: Assessing the regional disparities in geoengineering impacts, Geophys. Res. Lett., 37, L18702, doi:10.1029/2010GL04447, 2010.

Kravitz, B., et al.: A multi-model assessment of regional climate disparities caused by solar geoengineering, Environ. Res. Lett., 9, 074013, doi:10.1088/1788-9326/7/074013, 2014.

***P 25631***

***Results:***

*Line 13: Define what is meant by "The terrestrial total solar radiation".*

We have changed it to "The downward total solar radiation averaged over land" (Page 7, Line 159)

*Line 16: new paragraph where you go on to describing the differences in G4SSA, such that the first paragraph describes the baseline scenario RCP6.*

We have separated the RCP6.0 and G4SSA climate descriptions. (Page 8, Line 167 – Page 9, Line 192)

*Line 18: the downwelling solar radiation at the surface change is not the "radiative forcing". Change text.*

We have changed it to "With 1.6 W/m$^2$ less total surface solar radiation (Fig. 1d), G4SSA successfully cools the surface by 0.8 ± 0.2 K as compared to RCP6.0 (Fig. 1a)" (Page 8, Line 167)

*Line 19: increase the precision of the temperature reduction estimate.*

We have changed it to "G4SSA successfully cools the surface by 0.8 ± 0.2 K as compared to RCP6.0 (Fig. 1a)" (Page 8, Line 168)

***P 25632***

*Line 8: "Solar constant reduction climate intervention", see comment above. You need to clarify this experiment design and explain what is done and why.*

We have added to the introduction,

Page 3, Line 54-63:
"As explained in the initial design of the Geoengineering Model Intercomparison Project (GeoMIP) experiment (Kravitz et al., 2011), reducing the solar constant is another way to simulate sulfate injection geoengineering, and is easier to implement in a climate model. It was used in earlier geoengineering simulations (e.g., Govindasamy and Caldeira, 2000), and also can be thought of as a model of satellites in space blocking sunlight, as proposed by Angel (2006). Although the two methods both could both potentially cool the surface, if they could ever be implemented, they would produce different climate responses, including on the hydrological response, stratospheric ozone depletion, troposphere ozone change, downward ultraviolet radiation, and downward diffuse radiation (e.g., Niemeier et al., 2013; Kalidindi et al., 2015; Nowack et al., 2015)."
And we have added the new reference.

We have added the following to Model and Experiment Design:

Page 6, Line 136-146:

"The reason we used different reference runs (RCP4.5 and RCP6.0) for the two experiments (G3S and G4SSA) is that they come from different phases of GeoMIP. G3S was initiated before G4SSA when GeoMIP just started and the reference run for the first phase of GeoMIP was RCP4.5. G4SSA is participating in both GeoMIP and CCMI. Since RCP6.0 is the standard reference run for CCMI, to encourage more climate chemistry modeling groups to participate in G4SSA and generate robust understanding of how atmospheric chemistry responses to sulfate injection geoengineering, Tilmes et al. (2015) proposed that G4SSA be based on RCP6.0. Since the anthropogenic forcing is very similar between RCP4.5 and RCP6.0 between 2020 and 2070, we expect very little difference between the two experiments. The basic principle, that solar dimming does not affect stratospheric ozone or produce diffuse radiation like stratospheric aerosols do, is well illustrated by the G3S results."

And in the Result:

Page 9, Line 193-205

"Solar constant reduction climate intervention (G3S) efficiently cools the surface as well. Since there is less radiative forcing reduction due to the experiment design of G3S, the annual global averaged temperature reduction (gradually from 0°C to 0.8°C) is less than the reduction in G4SSA. Precipitation and surface evaporation also reduce under G3S. However, 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 slowly decreases because of decreasing emissions (the tropospheric aerosol removal effect, not shown). Although the two experiments have different radiative forcing reductions: 2.5 $W/m^2$ for G4SSA and 0-1.5 $W/m^2$ for G3S, we expect linear changes in temperature and precipitation corresponding to the radiative forcing change (Irvine et al., 2010; Kravitz et al., 2014). We focus on the diffuse radiation effect in this study, which is included in G4SSA and excluded in G3S due to the experiment design. Therefore, it is reasonable to compare the two experiments as to their diffuse radiation effect on photosynthesis."

We have also added references:

Irvine, P. J., Ridgwell, A., and Lunt, D. J.: Assessing the regional disparities in geoengineering impacts, Geophys. Res. Lett., 37, L18702, doi:10.1029/2010GL04447, 2010.

Kravitz, B., et al.: A multi-model assessment of regional climate disparities caused by solar geoengineering, Environ. Res. Lett., 9, 074013, doi:10.1088/1788-9326/7/074013, 2014.

Niemeier, U., Schmidt, H., Alterskjær, K., and Kristjánsson, J. E.: Solar irradiance reduction via climate engineering: Impact of different techniques on the energy balance and the hydrological cycle, J. Geophys. Res. Atm., 118 (21), 11,905-11,917, doi:10.1002/2013JD020445.

***P 25633***

*Line 1. You should be a bit clearer about when you are referring to the real world and to the model. Nitrogen and phosphorus fertilization is not included in CLM4. Nitrogen cycle you said was turned off, and phosphorus is not included in any case.*
*Nuance the discussion on the temperature effects more. You start the geoengineering in year 2020, and the plants are not under extreme heat stress at this stage.*

We have added words "However, this model-simulated increase under certain assumptions may not be true in the real world, since photosynthesis rate is limited by the amounts of soil nutrients such as nitrogen and phosphorus (e.g. Vitousek and Howarth, 1991; Elser et al., 2007)" (Page 10, Line 223-225)

We have added Fig. 5a, which is the partial correlation between the change of photosynthesis and the change of surface temperature.

We have added Fig. 3, which is the regional averaged photosynthesis rate change to illustrate in different climate zones, G4SSA has different impact on photosynthesis rate change.

We have added text:

Page 11, Line 230-239:
"Fig. 3 showed that photosynthesis rate in regions responds to G4SSA differently and temperature plays an important role. In general the cooling effect from solar radiation management would increase photosynthesis in tropical regions where there is likely to be extreme heat stress under the global warming scenario, and slow down photosynthesis in high latitude regions, since the temperature has not exceeded the optimal temperature even under the global warming scenario. In the Tropics, photosynthesis rate change has an increasing trend (Fig. 3), because the cooling effect of G4SSA benefits photosynthesis more when global warming gets severe. And the large multi-decadal variation of the photosynthesis rate change in the Tropics might be related to the strong sensitivity of tropical forest to precipitation change (Phillips et al., 2009; Tjiputra et al., 2015)"

*Lines 13 – 15 refer here to Figure 3 (b).*

We have added "(Fig. 4b)" (Page 11, Line 243)

*Line 19: Increase in diffuse radiation is most important for the highest level canopy, as the lower layers are already shaded. But, typically it is the tallest canopy that can absorb and store the most carbon, through longer trunks and developed root systems.*

We have added "where multiple layers of the canopy, especially the tallest canopy, would receive more diffuse radiation, and the cooling helps plant growth during the entire year" (Page 11, Line 250-251)

*Line 24: Could there also be a decrease in photosynthesis from an increase in snow cover with colder temperatures from the climate intervention?*

We have made a map of the snowfall rate different (Figure 2) which shows that the greatest snow rate increase is over the ocean, and over land, snow fall reduces except for high altitude regions such as the Himalayas and Rocky Mountains. In Fig. 3a of the manuscript, the high latitude photosynthesis reduction is around 60°N, and over that region, the snowfall rate over the land reduces (Figure 2). However, snow may stay longer under the cooler environment of G4SSA even when less snow falls. Figure 3 shows that comparing with RCP6.0, under G4SSA, the snow depth decreases over the high latitudes of East Asia, while it increases over other high latitude regions and high altitude regions. Therefore, snow cover change during winter might contribute to the decrease in the photosynthesis rate over the mountain regions but not over the high latitudes of East Asia.

We have added words in the text "Over the high altitude regions, such as the Rocky Mountains and Himalayas, increased snow cover contributes to the reduction of photosynthesis under G4SSA as well." (Page 12, Line 266-268)

***P 25634***
*Photosynthesis is also dependent on available moisture / water. Would a spatial correlation to temperatures and moiture availability be useful?*

Global averaged soil water content (the top 10 cm) (including ice and liquid water) has been added in Fig.1i.

***P 25636***
*The paper would benfit from finishing with an overall conclusion.*

We have added the text
Page 16, Line 363 – Page 17, Line 375

"**5 Conclusions**

With our experimental design, simulated stratospheric sulfate geoengineering with 8 Tg $yr^{-1}$ injection of $SO_2$ would change the partitioning of solar radiation with an increase of surface diffuse radiation about 3.2 $W/m^2$ in visible wavelengths over land. This enhanced diffuse radiation combining with other climate changes, such as cooling, soil water content change, and total solar radiation reduction increase plant photosynthesis rates significantly in temperate and tropical regions, and reduce the photosynthesis rate in high latitude and mountain regions. Overall, the increase of the land-averaged photosynthesis rate is 0.07 ± 0.02 μmol C $m^{-2}$ $s^{-1}$, which could contribute to an additional 3.8 ± 1.1 Gt C $yr^{-1}$ global carbon sink. These results are affected by the experimental design, since the carbon-nitrogen cycle and dynamic vegetation are not included. Further investigation is needed to fully understand the contribution of enhanced diffuse radiation due to sulfate geoengineering on the terrestrial carbon sink."

*The discussion could also say something about how this model compares to the rest of the GeoMIP models. Was it included in Glienke et al. (2015) or Jones et al. (2013)? Was there not a large spread in primary productivity responses amongst the models?*

We have added to the discussion

Page 13, Line 296 – Page 15, Line 326:

"Our result of increasing of gross primary productivity due to enhanced stratospheric aerosols has uncertainties and needs to be further evaluated with new experiments using multiple Earth System Models. Since the carbon-nitrogen cycle in CLM4 is turned off, leaf area index (LAI) cannot be diagnosed by the climate changes due to G4SSA and hence the photosynthesis response may be biased. However, even if we use CLM4CN with the carbon-nitrogen cycle modeled, the photosynthesis response would still be imperfectly modeled, since there are a high bias in the LAI simulation and structural errors in the leaf photosynthesis process (Lawrence et al., 2011). Also, without dynamic vegetation, our study keeps a prescribed plant functional type during the whole simulation, and cannot simulate plant type change under a different climate.

Another source of uncertainty is the use of only one climate model. Jones et al. (2013) and Glienke et al. (2015) showed that there is a large range of simulated net primary productivity (NPP) changes as the $CO_2$ concentration increases or under solar reduction geoengineering using different land models, which is mainly due to the availability of a nitrogen cycle. With a nitrogen cycle, there is a much smaller $CO_2$ fertilization effect on plant growth. We expect that with the carbon-nitrogen cycle turned on, the upward trend of the photosynthesis rate under both G4SSA and RCP6.0 in Fig. 2a will be reduced. Furthermore, models respond to different climates at the same atmospheric $CO_2$ concentration differently. Eight models participating in the GeoMIP G1 (instantaneously quadrupling of the $CO_2$ concentration (abrupt4xCO2) while simultaneously reducing the solar constant to balance the forcing) (Kravitz et al., 2011) showed different and even opposite trends of NPP changes between abrupt4xCO2 and G1 because of different behaviors in GPP and respiration (Glienke et al., 2015). In G1, GPP as well as NPP reduced under G1 compared with abrupt4xCO2 using CCSM4 (CAM4 coupled with CLM4CN). However, G1 has a much stronger temperature reduction and no diffuse radiation change. Considering the inconsistent responses of models to geoengineering induced climate changes even with the same $CO_2$ concentration, multiple model study is necessary to better understand how photosynthesis and NPP changes under sulfate injection geoengineering.

Sulfate injection geoengineering would potentially change the terrestrial carbon sink since it might increase GPP compared with the global warming scenario due to the diffuse radiation and other climate changes. However, to further investigate this issue, we need to consider other mechanisms that sulfate injection geoengineering would trigger. The cooling effect would also suppress plant and soil respiration."

And we have added the references:

Glienke, S., Irvine, P. J. and Lawrence, M. G.: The impact of geoengineering on vegetation in experiment G1 of the GeoMIP, J. Geophys. Res. Atmos., 120, 10,196–10,213, doi:10.1002/2015JD024202, 2015.

***Figures****:*
*Also plot P-E, or in place of P in Figure 1 (b).*

We have added ground evaporation in Figure 1g. And have added text

Page 7, Line 152-154:

"The higher temperature enhances the hydrological cycle, and therefore global precipitation as well as land average evaporation (Figs. 1b, 1g) increase. Global soil water content (10 cm, including liquid water and ice) slightly increase with global warming (Fig. 1i)."

Page 8, Line 168-171:
"This cooling slows down the hydrology cycle with less average precipitation (-0.07 mm/day (2.5%)) (Fig. 1b), less ground evaporation (Fig. 1g) and less global low cloud coverage (Fig. 1c) which is consistent with previous studies (e.g., Niemeier et al., 2013; Tilmes et al., 2013; Jones et al., 2013; Kalidindi et al., 2015)."

*Legend on Figure 3. Make numbers larger. They are hard to read.*

We have changed the numbers below the color bar to larger font.

*Figure 3: Show statistical significance. Why are only 10 years shown? Why not use 30 – 40 years?*

Fig. 4 has been modified to indicate area with none statistically significant changes. And we have changed the last ten year average to 40 year (2030-2069) average.

We have changed the text Page 11, Line 246-247

"Without explicit nutrient limitation, the increase of the photosynthesis rate is almost entirely over vegetated land during year 2030-2069 of G4SSA compared with RCP6.0 (Fig. 4a)"

Page 12, Line 274-276

"Without the diffuse radiation effect, the photosynthesis rate differences between G3S and RCP4.5 are not significant in more regions (Fig. 4b) compared with is the anomalies between G4SSA and RCP6.0."

And Fig. 4 caption has been changed to

"Fig. 4. (a) Photosynthesis rate differences between G4SSA and RCP6.0 during year 2030-2069 (sulfate injection period, exclude the first ten years) (b) Photosynthesis rate anomaly between G3S and RCP4.5 year 2030-2069 of solar reduction. Hatched regions are areas with p-value > 0.05 (where changes are not statistically significant based on paired T-test)."

**Review by E. van Schaik**

***Disclaimer:*** *This review was written by MSc students Erik van Schaik and Lars van Galen as part of their course work on "scientific reviewing", under supervision of Prof Wouter Peters from Wageningen University. The comments were submitted because they can contribute to the scientific process, and because they contain helpful questions and suggestions for the authors. Although the structure of this review follows the formal conventions, it is thus not a solicited peer-review from the editor of ACPD.*

Thanks very much for the effort of writing the comments!

*Injection of sulphate aerosols in the stratosphere can reduce incoming global radiation, but increase the diffuse fraction of solar radiation at the surface. Higher levels of incoming diffuse solar radiation at the surface and lower surface temperatures caused by aerosol injection are associated with increased plant productivity, especially in the tropics. Using the Community Atmospheric Model (CAM4-chem) coupled with the Community Land Model (CLM) it is calculated that the global gross primary productivity would increase with 3.8±1.1 Gt C* $yr^{-1}$*, under the assumption of no nutrient limitation. This increase is mainly due to the increased fraction of incoming diffuse solar radiation rather than decreases in surface temperature.*

*The paper by Xia et al. gives a novel insight in how the terrestrial carbon sink could change under different radiative conditions, introduced by the injection of sulphate aerosols into the stratosphere. The addressed topic is a logical step from the current state-of-the-art in anthropogenic-induced diffuse radiation perturbations, and has not yet been investigated as comprehensible before. The writing style is clear and the authors make good use of the available literature. The paper does include some assumptions and choices that should be addressed prior to publication, such as the different baseline scenarios for the two experiments and the limited number of ensembles. In addition, the title presents the final conclusion as a fact, whilst the large number of uncertainties associated within this study do not justify such a claim. The abstract is well-written and does provide a more nuanced overview of the study and its findings.*

*In short, this paper provides new insight in a topic relevant for publication in Atmospheric Chemistry and Physics. We suggest a number of revisions to help make this paper suitable for publication.*

Thanks for the comments. We have added more discussion regarding to the different baseline problem. And we have changed the title to "Stratospheric Sulfate Geoengineering Could Enhance the Terrestrial Photosynthesis Rate".

*1. In the paper two different scenarios are tested (G4SSA and G3S). The two scenarios use different baselines for both scenarios (based on RCP6.0 and RCP4.5). As stated on p25634 l4- 8 these different reference runs do not allow for direct comparison of the fractional impact of diffuse radiation on the increasing photosynthesis rate. In the paper itself we can not find arguments that support the use of two different baseline scenarios. But it looks like the G3S scenario comes from an earlier phase of the GeoMIP project when the reference run was RCP4.5, and it was easier to re-use this than to recreate the G3S scenario based on RCP6.0.*

*But it would be very interesting to quantify the effect of both processes (increased diffuse radiation and decreased surface temperatures) on the gross primary production. Direct comparison of the scenarios would allow for additional analysis of the results, in both space and time. Such an analysis can help give insight in the response of ecosystems on a diffuse perturbation event and determine spatial and temporal variability in a more direct manner.*

*Our suggestion would be to redo the G3S solar reduction experiment with the RCP6.0 as a baseline, and use the results from this experiment to separate the changes caused by diffuse radiation and surface cooling.*

*Alternatively, we noted that in the earlier GeoMIP phase, there was also a G4 scenario that includes 5Tg of SO2 emissions into the stratosphere. So for a fair comparison of the cooling vs diffuse radiation effect the authors could try to include those runs in this analysis as well.*

G3S was proposed before G4SSA in the first Geoengineering Modeling Intercomparison Project (GeoMIP) workshop in 2011 by Simone Tilmes as a comparison of G3 – "In combination with RCP4.5 forcing, starting in 2020, gradual ramp-up the amount of $SO_2$ or sulfate aerosol injected, with the purpose of keeping global average temperature nearly constant" (Kravitz et al., 2011). Instead of injecting $SO_2$, G3S reduces the solar constant to balance the RCP4.5 forcing. The G3S experiment using CAM4-chem was done before the G4SSA simulations. G4SSA has been proposed to both the GeoMIP and the Chemistry-Climate Model Initiative (CCMI). To encourage more climate chemistry modeling groups to conduct this experiment, it uses RCP6.0 as the reference run since this is the standard reference run for CCMI, and most of the modeling groups have done this reference run already. Since RCP4.5 and RCP6.0 have a very similar anthropogenic forcing (see for example Tilmes et al., 2015, Figure 1), the baseline for the two experiments is very similar and, G3S can be used to understand how G4SSA-solar affects photosynthesis rate. Figure 1 shows the solar constant reduction of G3S which is ranging from 0.0 W/m$^2$ (2020) to 9.06 W/m$^2$ (2069). For G4SSA-solar, to simulation the radiative forcing of 8 Tg $SO_2$/yr, the solar constant needs to be reduced by 14.55 W/m$^2$ (1.1% dimming). The larger reduction is due to the difference between direct solar dimming and using aerosols to dim the sun. The basic principle, that solar dimming does not affect stratospheric ozone or produce diffuse radiation, is well illustrated by the G3S results.

We have added the following to Model and Experiment Design:

Page 6, Line 136-146

"The reason we used different reference runs (RCP4.5 and RCP6.0) for the two experiments (G3S and G4SSA) is that they come from different phases of GeoMIP. G3S was initiated before G4SSA when GeoMIP just started and the reference run for the first phase of GeoMIP was RCP4.5. G4SSA is participating in both GeoMIP and CCMI. Since RCP6.0 is the standard reference run for CCMI, to encourage more climate chemistry modeling groups to participate in G4SSA and generate robust understanding of how atmospheric chemistry responses to sulfate injection geoengineering, Tilmes et al. (2015) proposed that G4SSA be based on RCP6.0. Since the anthropogenic forcing is very similar between RCP4.5 and RCP6.0 between 2020 and 2070, we expect very little difference between the two experiments. The basic principle, that solar dimming does not affect stratospheric ozone or produce diffuse radiation like stratospheric aerosols do, is well illustrated by the G3S results."

And in the Results:

Page 9, Line 193-205

"Solar constant reduction climate intervention (G3S) efficiently cools the surface as well. Since there is less radiative forcing reduction due to the experiment design of G3S, the annual global averaged temperature reduction (gradually from 0°C to 0.8°C) is less than the reduction in G4SSA. Precipitation and surface evaporation also reduce under G3S. However, 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 slowly decreases because of decreasing emissions (the tropospheric aerosol removal effect, not shown). Although the two experiments have different radiative forcing reductions: 2.5 $W/m^2$ for G4SSA and 0-1.5 $W/m^2$ for G3S, we expect linear changes in temperature and precipitation corresponding to the radiative forcing change (Irvine et al., 2010; Kravitz et al., 2014). We focus on the diffuse radiation effect in this study, which is included in G4SSA and excluded in G3S due to the experiment design. Therefore, it is reasonable to compare the two experiments as to their diffuse radiation effect on photosynthesis."

We have also added references:

Irvine, P. J., Ridgwell, A., and Lunt, D. J.: Assessing the regional disparities in geoengineering impacts, Geophys. Res. Lett., 37, L18702, doi:10.1029/2010GL04447, 2010.

Kravitz, B., et al.: A multi-model assessment of regional climate disparities caused by solar geoengineering, Environ. Res. Lett., 9, 074013, doi:10.1088/1788-9326/7/074013, 2014.

We are doing to the G4SSA-solar experiment now, which is reducing the solar constant instead of using the specified sulfate aerosol distribution file. We are hoping to continue to work on this issue in the next manuscript.

And thanks for the suggestion of looking at other G4 runs. W are going to do it for the next paper after the Earth System Grid Federation is back.

*2. The influence of changes in ultraviolet (UV) radiation reaching the surface due to SSG on photosynthesis activity has not been investigated in the paper, as is mentioned in the article as well (page 25633, line 26-29). However, it is known that UV radiation has considerable impact on photosynthesis rates and thereby gross primary productivity (GPP).*

*Increasing amounts of UV radiation reaching the surface have profound negative impacts on photosynthetic activity of plants (Stapleton, 1992). One potential means for increasing amounts of UV radiation (especially UV-B) reaching the surface is by decreasing ozone concentrations in the stratosphere (Madronich et al., 1998).*
*While there is agreement on the fact that ozone concentrations near the poles will decrease as a consequence of SSG, contradicting findings exist with respect to the effect of SSG on*

*tropical ozone concentrations (Tilmes et al., 2009), (Heckendorn et al., 2009), and thereby its effect on photosynthesis rates in the tropics. As photosynthesis rates in the tropics are higher than near the poles, it is uncertain whether photosynthesis rates are forecast to increase or decrease based on the SSG-ozone-UV radiation link.*

*Given the importance and the uncertainty of (the global distribution of) changes in UV radiation reaching the surface due to SSG, we advise to implement UV-radiation and the effects of SSG thereon in the model used in the analysis.*

Thanks for this great comment! We are aware the potential impact of UV and ozone concentration change on the ecosystem and currently, we are writing a manuscript addressing how surface ozone concentration would change under G4SSA scenario compared with RCP6.0. And actually this is one of the primary goals of this experiment design – to understand the troposphere chemistry change during sulfate injection geoengineering. We are getting some interesting results in terms of surface ozone concentration change under G4SSA, and also we have run CLM-crop with the ozone damage module to evaluate this ozone concentration change impact on vegetation, including crops. UV radiation in the troposphere and the surface is another big issue regarding tropospheric chemistry and its impact on plant and human health. Unfortunately, CAM4-chem does not directly output UV. We are planning to use another NCAR radiation model offline to calculate how UV radiation change under G4SSA, and then further study how this UV radiation change would affect ecosystem and human being.

The suggestion of ozone and UV impact assessment under G4SSA is great, but it is beyond the scope of this study. We have mentioned the two potential impacts in our manuscript

Page 12, Line 268-273:

"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. Furthermore, changes in tropospheric chemistry and stratosphere troposphere exchange due to G4SSA could modify the surface ozone concentration regionally, which may be another potential impact on the photosynthesis rate. Further investigation of those issues is needed."

We are going to address the two issues in two future papers.

*3. The two experiments (G4SSA and G3S) use a limited number of ensemble members: three for G4SSA and one for G3S. The consensus in current literature is that a minimum of ten ensemble members is desired to capture the uncertainty within climate models (Buizza and Palmer, 1998; Bonavatia et al., 2011; Kumar et al., 2001).*

*A higher number of ensemble members would help to better define uncertainties. Opting to increase the number of observations for the G3S scenario would allow statistics to be calculated for that scenario, such as standard errors and confidence intervals. The large uncertainty found in climate model predictions due to the complexity of the system (Murphy et al., 2004) means that proper statistical descriptions of the errors are essential to put the results into perspective.*

*Within the article we could not find arguments for the decision to use three / one ensembles per scenario. We would invite the authors to carefully think about the consequences of their decision to use a limited number of ensemble members and assess the impact of this on their final results. In addition, we would like to see the authors include arguments for their decision on the number of ensembles used per experiment. In addition, the paper can be improved by including a jackknife analysis on the ensemble members to determine bias and variance per member (Berger and Skinner, 2005; Buishand and Beersma, 1993). This can help to give insight in the influence of different members on the spread and determine the direction to which new ensemble members can be explored.*

We agree that a larger number of ensemble members would better address the uncertainty. However, it would be very expensive and time consuming to run a GCM with chemistry with more than ten ensemble members for 70 simulation years. Based on the editor's suggestion ("The comment by Erik van Schaik also recommended that ten or more ensemble members be conducted. This is far too burdensome, and the authors are not required to do this."), we will not do more experiments at this time. However, as can be seen in Figs. 1 and 2, the global average values clearly are separate for the two experiments, and the differences between the ensemble members are much smaller.

Fig. 4 has been modified to indicate area with none statistically significant changes.

We have changed the text Page 11, Line 246-247

"Without explicit nutrient limitation, the increase of the photosynthesis rate is almost entirely over vegetated land during year 2030-2069 of G4SSA compared with RCP6.0 (Fig. 4a)"

Page 12, Line 274-276

"Without the diffuse radiation effect, the photosynthesis rate differences between G3S and RCP4.5 are not significant in more regions (Fig. 4b) compared with is the anomalies between G4SSA and RCP6.0."

And Fig. 4 caption has been changed to

"Fig. 4. (a) Photosynthesis rate differences between G4SSA and RCP6.0 during year 2030-2069 (sulfate injection period, exclude the first ten years) (b) Photosynthesis rate anomaly between G3S and RCP4.5 year 2030-2069 of solar reduction. Hatched regions are areas with p-value > 0.05 (where changes are not statistically significant based on paired T-test)."

*4. The photosynthesis rate is calculated under the assumption of no nutrient limitation. This is debatable, as nutrient-limitation is shown to have a significant impact on the terrestrial gross primary production (Elser et al., 2007). In addition, nutrient availability is shown to be dependent on soil temperatures, with lower N-mineralization rates associated with lower temperatures (Rustad et al., 2001; Davidson and Janssens, 2006). This is especially important as sulphate aerosols tend to have a cooling effect on the surface. Neglecting to include nutrient limitation can lead to wrong conclusions on the gross primary productivity. Within the article it remains unclear why the authors have opted to turn off the C-N cycle.*

*Lawrence et al. (2011) states the C-N module in CLM4 is biased (specifically in overestimation the leaf area) and therefore potentially unreliable, which is supported by Bonan et al. (2011). Such claims could be a valid reason not to include the C-N module. However, the real arguments why the authors decided not use this module remain unclear in the paper.*

We have added more explanation in text:

Page 5, Line 104-113

"Since the experiments are branched from the Climate Chemistry Model Initiative (CCMI) runs in which CAM4-chem participates, we used the same configuration as the reference run. Therefore we used the Community Land Model (CLM) version 4.0 with prescribed satellite phenology (CLM4SP) instead of the carbon-nitrogen cycle coupled with CAM4-chem. This model calculates vegetation photosynthesis under the assumption of prescribed phenology and no explicit nutrient limitations (Bonan et al., 2011). With the satellite phenology option, although nitrogen limitation is not explicitly included, there is some inherent nitrogen limitation because nitrogen availability limits the leaf area index in the satellite measurements used in CLM4SP, and the model has been validated with GPP observations. Dynamic vegetation is not turned on in this study."

Due to the experimental design (carbon-nitrogen cycle was not turned on), we cannot study the carbon fluxes and stores. We are planning the next experiment with the carbon-nitrogen cycle and dynamic vegetation turned on.

*5. In addition, we would like to see a more in-depth analysis of the effects of assuming no nutrient limitation on the results. A good starting point would be to compare the areas that show the largest increase in photosynthesis rates (e.g. the Amazon rainforest) and compare this to the nutrient status of these locations (Davidson et al., 2004). Such an analysis can help to put the estimate into perspective and help answer the question: how valid is the result of a 3.8±1.1 Gt C $yr^{-1}$ increase in global gross primary productivity under the assumption of no nutrient limitation?*

We have added text:

Page 12, Line 259-262:

"Since in reality, most Amazonian soils are highly weathered and relatively nutrient poor, this simulated increase might be overestimated (Davison et al., 2004). However, in our study, the prescribed plant phenology has some inherent nutrient limitation, and therefore the overestimation should not be substantial."

We have added discussion of the uncertainty:

Page 13, Line 296 – Page 14, Line 304:

"Our result of increasing of gross primary productivity due to enhanced stratospheric aerosols has uncertainties and needs to be further evaluated with new experiments using multiple Earth System Models. Since the carbon-nitrogen cycle in CLM4 is turned off, leaf area index (LAI) cannot be diagnosed by the climate changes due to G4SSA and hence the photosynthesis response may be biased. However, even if we use CLM4CN with the carbon-nitrogen cycle modeled, the photosynthesis response would still be imperfectly modeled, since there are a high bias in the LAI simulation and structural errors in the leaf photosynthesis process (Lawrence et al., 2011). Also, without dynamic vegetation, our study keeps a prescribed plant functional type during the whole simulation, and cannot simulate plant type change under a different climate."

We have added the reference.

Davidson, E. A. and Janssens, I. A.: Temperature sensitivity of soil carbon decomposition and feedbacks to climate change, Nature, 440, 165-173, doi:10.1038/nature04514, 2006.

*6. Please consider changes the title to something less definitive to account for the uncertainties and limitations within this study. Stating that stratospheric sulphate injection enhances gross primary productivity removes all debate, which is in my opinion not justified. An example for a more neutral title: "The impact of stratospheric sulphate geoengineering on terrestrial gross primary productivity: A model analysis".*

We have changed the title to "Stratospheric Sulfate Geoengineering Could Enhance the Terrestrial Photosynthesis Rate".

*7. Figure 1d shows that global low cloud coverage reduces due to SSG. In the results on page 25631, line 20-22, the authors state that the low cloud cover decrease observed in the G4SSA model caused by SSG is consistent with literature. However, this is not mentioned in the referred article (Jones et al., 2013). Furthermore, the article of (Jones et al., 2013) is about solar constant reduction, and not about SSG. An article which also finds the decreased low cloud cover as a consequence of SSG is (Kalidindi et al., 2015). Therefore, it is recommended to replace the reference to (Jones et al., 2013) to (Kalidindi et al., 2015).*

Thanks very much. We have added the reference of Kalidindi et al. (2015). We still keep the reference of Jones et al., (2013) here, since that paper showed that a cooler environment reduces the hydrology cycle and therefore results in less precipitation. (Page 8, Line 171)

*8. The authors are not consistent in their use of the terms 'visible diffuse radiation' and 'broadband diffuse radiation'. It would be helpful for the readability of the paper to be consistent in the naming. For instance, on page 25631, line 22 the authors state "Diffuse radiation over land", which should be elaborated to "Visible diffuse radiation over land". On the other hand, on line 27 on the same page, the authors state that "diffuse radiation increased from 40 to 140 W/m2…", which should be changed into "broadband diffuse radiation increased from 40 to 140 W/m2", as this value refers to broadband diffuse radiation (Robock, 2005).*

We have added "visible"/"broadband" to clarify the diffuse radiation (Page 8, Line 178, 181). We have also clarified the definition of "visible" in the abstract "land-averaged downward visible (300-700 nm) diffuse radiation increased 3.2 W/m2 (11%)" (Page 1, Line 43)

*9. In the abstract on page 25628, line 9 the authors mention an increase in plant photosynthesis of 2.4% as a consequence of enhanced diffuse radiation and cooling of the atmosphere caused by SSG. This value is not mentioned the article itself, and it can only be inferred from Figure 2a. In the results themselves the number is mentioned, though, as a fixed increase in photosynthesis rate (on line 14 page 25634). Concerning the increase in plant photosynthesis mentioned in the abstract, it is misleading to state that there is a fixed relative increase in photosynthesis when the overall photosynthetic activity is increasing over time as well. At the start of the geoengineering period (in 2020), the relative increase in photosynthesis is larger than at the end of the geoengineering period (in 2070) given that the actual increase in photosynthesis activity due to SSG does not change (which can be concluded judging from Figure 2a). Therefore, we advise to change the number concerning the increase in photosynthesis rate in the abstract from 2.4% to 0.07 ± 0.02 μmol C m-2 s -1.*

Thanks. We have changed the abstract from 2.4% to 0.07 ± 0.02 μmol C $m^{-2}$ $s^{-1}$. (Page 1, Line 36)

*10. The discussion (p25636 l5-8) mentions the potential impact of stratospheric sulphate injection on the ocean carbon cycle. Whilst this is a valid statement it feels out of place within an article that does not assess ocean carbon biogeochemistry or use a model which includes it. The authors might want to consider removing this claim.*

We have changed the discussion. The ocean carbon cycle part has been put after the discussion of atmospheric $CO_2$ concentration change under sulfate injection geoengineering. The ocean carbon cycle discussion is to argue that the atmospheric $CO_2$ concentration will be determined by both terrestrial and ocean carbon reservoirs. And we think it is valuable to discuss the future experiment design (including ocean biogeochemical and carbon cycles) to fully address the question of how sulfate injection geoengineering impacts the global carbon cycle.

Page 15, Line 342 – Page 16, Line 358:

"In our simulations, the $CO_2$ concentration is prescribed in both G4SSA and RCP6.0, but we expect that the $CO_2$ concentration of G4SSA might be lower than the global warming scenario due to the diffuse radiation and the cooling effects. Because this $CO_2$ concentration change has been observed after volcanic eruptions due to enhanced land carbon sinks (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. However, the atmospheric $CO_2$ concentration is also highly impacted by another carbon reservoir, the ocean. 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 (Tjiputra et al., 2015). For example, an El Niño will cause the ocean to temporarily emit more $CO_2$ to the atmosphere. Although idealized geoengineering experiments have not shown any significant effect on El Niño (Gabriel and Robock, 2015), a longer period of geoengineering might impact on ocean circulation. The ocean model we used simulates dynamical and temperature responses, but does not include a biochemical and carbon cycle. Such responses will need to be included for an integrated assessment of the impacts of geoengineering on the global carbon budget."

*11. In the abstract (p25628 l14-16) the authors mention the potential risk of stratospheric sulphate injection geoengineering. This raises the expectation that this topic is described in further detail within the paper. However, as this is not the case we suggest to remove this from the abstract.*

At the end of the discussion, we have a short discussion on this issue.

Page 16, Line 359-362:

"Although there have been many reasons to be hesitant about the implementation of geoengineering (Robock, 2012; Robock, 2014), sulfate injection climate intervention may have 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. "

*12. In general, the paper makes good use of available literature and gives citations where required. On p25628 l19-20 two references are made (Crutzen, 2006; Wigley, 2006) which are not included in the references.*

We have added the two references.

"Crutzen, P.: Albedo enhancement by stratospheric sulfur injections: A contribution to resolve a policy dilemma?, Climatic Change, 77(3), 211-220, doi: 10.1007/s10584-006-9101-y, 2006.

Wigley, T. M. L.: A combined mitigation/geoengineering approach to climate stabilization, Science, 314, 452-454, doi:10.1126/science.1131728, 2006."

*13. Figure 2 mentions a photosynthesis rate in micromoles per m2 and second. However, neither photosynthesis rate refers to. It took some time for us to understand that the photosynthesis rate is in micromoles carbon per m2 and second. It is advisable to clarify this in both Figure 2 and in the body text on page 25633. The same applies for the calculation in the Results section on page 12-18, page 25634.*

We have changed the y-axis label in Fig. 2 as well as in the text to μmol C $m^{-2}$ $s^{-1}$.

*14. The results section contains some parts that could fit better in an introduction or discussion section. For example, one part of the results on page 25632 between line 13 and 25 starts with introducing why diffuse radiation is important for plant productivity. Thereafter, the link between stratospheric aerosols and photosynthesis rates via the partitioning between diffuse and total radiation is introduced. The real findings are presented at the end of this section. It would be advisable to critically review the results section and move parts to the introduction or discussion section where necessary to improve the readability of the paper.*

We have introduction of diffuse radiation and terrestrial carbon sink in the second paragraph of the Introduction. In the results section, we now mention diffuse radiation changes after volcano eruptions and the enhancement of the terrestrial carbon sink for comparison purposes.

*15. In addition, the results section might benefit from division into subsections. For example:*
*a. Radiation balance (p25631 l4)*
*b. Vegetation (p25632 l13)*
*c. Terrestrial carbon sink (p25634 l12)*

We have added three subtitles
a. Radiation Balance of G4SSA and G3S (Page 7, Line 149)
b. Diffuse radiation impact on vegetation photosynthesis rate (Page 9, Line 206)
c. Diffuse radiation and climate change impact on terrestrial carbon sink (Page 13, Line 285)

*16. P25632 l5-7: No reference to the estimate sulphate release of Pinatubo is given (see Bluth et al., 1992). In addition, the authors should reflect on the large uncertainty of this number by stating that the G4SSA scenario 'is roughly equivalent to one Pinatubo eruption every 2.5 years'.*

Thanks. We have added this reference and to address the uncertainty, we have added "which is equivalent to one Pinatubo eruption every 2.5 years (Bluth et al., 1992) with the assumption that all sulfate aerosol will reach the stratosphere," (Page 9, Line 186-187)

Bluth, G. J. S., Doiron, S. D., Schnetzler, C. C., Krueger, A. J., and Walter, L. S.: Global tracking of the SO2 clouds from the June, 1991 Mount Pinatubo eruptions, Geophys. Res. Lett., 19(2), 151-154, doi:10.1029/91GL02792, 1992.

*17. P25633 l23: 4.2±5.9% is not statistically significant (assuming the mean and standard error are given). Please replace this with 'could potentially' or something similar.*

We have changed it to "increasing its photosynthesis rate by 4.2 ± 5.9% would potentially help to bring more carbon out of the atmosphere" (Page 12, Line 258-259)

*18. P25643: Figure 1 has reversed line colours: G4SSA should be blue (not red), and vice versa for RCP6.0.*

Thanks. We have change it.

*19. P25643-25644: Figures 1 and 2 are not suitable for black / white printing. This can be improved by using dashed lines for the ensembles related to the baseline, or vice versa.*

Thanks, but it is not our responsibility to make sure all figures print in black and white. This is impossible for color shaded figures.

*20. p25644: In Figure 2 the y-axis should state that it is a photosynthesis rate, and not just photosynthesis.*

We have changed the Fig. 2 y-axis label to Photosynthesis Rate.

*21. p25631 l20, the authors state "the global cloud coverage, mainly low clouds is less". Figure 1d only takes low clouds into consideration, and therefore this sentence should become "the global low cloud coverage is less".*

We have changed it to "This cooling slows down the hydrology cycle with less average precipitation (-0.07 mm/day (2.5%)) (Fig. 1b), less ground evaporation (Fig. 1g) and less global low cloud coverage (Fig. 1c) which is consistent with previous studies (e.g., Niemeier et al., 2013; Tilmes et al., 2013; Jones et al., 2013; Kalidindi et al., 2015)." (Page 8, Line 168-171)

Figures

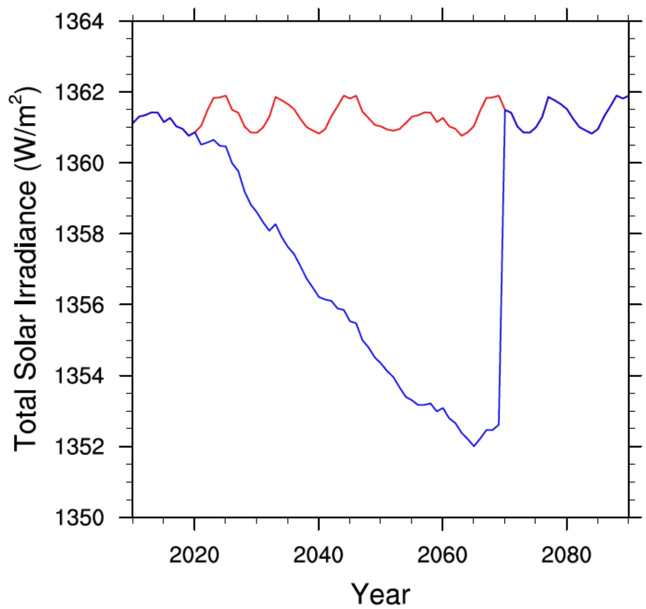



Figure1: Total solar irradiance (W/m$^2$) for G3S, baseline experiment (red), solar dimming experiment (blue).

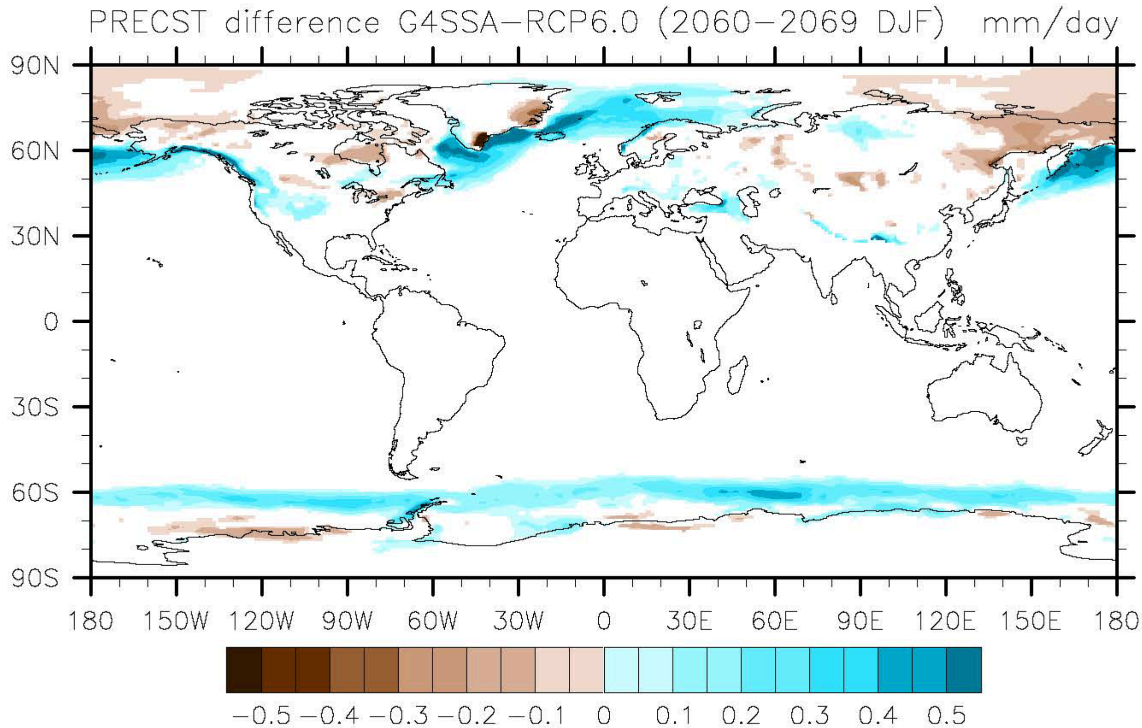



Figure 2. Convective/Large-scale snow rate difference (mm/day) between G4SSA and RCP6.0 in DJF (average of 2060-2069) (-0.05 – 0.05 mm/day is marked as white).

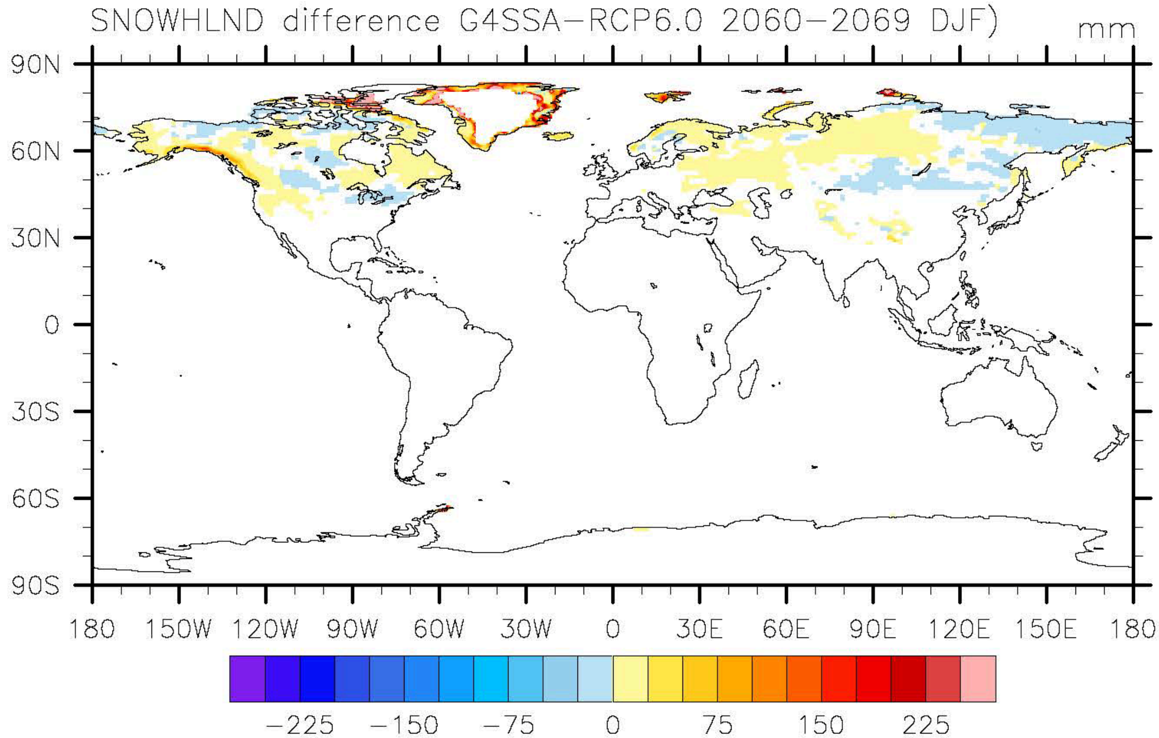



Figure 3. Water equivalent snow depth difference (mm) between G4SSA and RCP6.0 in DJF (average of 2060-2069) (-1 – 1 mm is marked as white).

References:


Jones, Andy, Jim M. Haywood, Kari Alterskjær, Olivier Boucher, Jason N. S. Cole, Charles L. Curry, Peter J. Irvine, Duoying Ji, Ben Kravitz, Jón Egill Kristjánsson, John C. Moore, Ulrike Niemeier, Alan Robock, Hauke Schmidt, Balwinder Singh, Simone Tilmes, Shingo Watanabe, and Jin-Ho Yoon, 2013: The impact of abrupt suspension of solar radiation management (termination effect) in experiment G2 of the Geoengineering Model Intercomparison Project (GeoMIP). *J. Geophys. Res. Atmos.*, **118**, 9743-9752, doi:10.1002/jgrd.50762.

Kravitz, B., Robock, A., Oman, L., Stenchikov, G., and Marquardt, A. B.: Sulfuric acid deposition from stratospheric geoengineering with sulfate aerosols, J. Geophysical Res., 114, D14109, doi:10.1029/2009JD011918, 2009.

Kravitz, B., Robock, A., Boucher, O., Schmidt, H., Taylor, K. E., Stenchikov, G., and Schulz, M.: The Geoengineering Model Intercomparison Project (GeoMIP), *Atmo. Sci. Lett.*, 12, 162-167, doi:10.1002/asl.316, 2011.

Niemeier, U., Schmidt, H., Alterskjaer, K., and Kristjánsson, J. E.: Solar irradiance reduction via climate engineering: Impact of different techniques on the energy balance and the hydrological cycle, J. Geophys. Res.-Atmos., 118, 11905–11917, doi:10.1002/2013JD020445, 2013.

Tilmes, S., R. R. Garcia, D. E. Kinnison, A. Gettelman, and P. J. Rasch, 2009: Impact of geoengineered aerosols on the troposphere and stratosphere. J. Geophysical Res., 114, D12305, doi:10.1029/2008JD011420.

Tilmes, S., M. J. Mills, U. Niemeier, H. Schmidt, A. Robock, B. Kravitz, J.-F. Lamarque, G. Pitari, and J. M. English, 2015b: A new Geoengineering Model Intercomparison Project (GeoMIP) experiment designed for climate and chemistry models. *Geosci. Model Dev.*, **8**, 43-49, doi:10.5194/gmd-8-43-2015.

**Stratospheric Sulfate Geoengineering ~~Enhances~~Could Enhance the Terrestrial ~~Gross Primary Productivity~~Photosynthesis Rate**

**Lili Xia[1], Alan Robock[1], Simone Tilmes[2] and Ryan R. Neely III[2,3]**

[1] Department~~[1]Department~~ of Environmental Sciences, Rutgers University, New Brunswick, NJ, USA

[2] National~~[2]National~~ Center for Atmospheric Research, Atmospheric Chemistry Division, Boulder, CO, USA

[3] National~~[3]National~~ Centre for Atmospheric Science and the Institute of Climate and Atmospheric Science, University of Leeds, Leeds, UK

*Correspondence to:* Lili Xia (lxia@envsci.rutgers.edu)

Submitted to *Atmospheric Chemistry and Physics*

August, 2015

Revised, January 2016

**Formatted:** Font: Times New Roman, 12 pt

**Formatted:** Left

**Formatted:** Font: Times New Roman, 12 pt

**Formatted:** Font: Times New Roman, 12 pt

**Formatted:** Font: Times New Roman

**Formatted:** Font: Italic

**Formatted:** Font: Italic

## Abstract

Stratospheric sulfate geoengineering could impact the terrestrial carbon cycle by enhancing the carbon sink. With an 8 Tg yr$^{-1}$ injection of $SO_2$ to ~~balance a~~produce a stratospheric aerosol cloud to balance anthropogenic radiative forcing from the 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 (300-700 nm) diffuse radiation increased 3.2 W/m$^2$ (11%). The enhanced diffuse radiation combined with the cooling increased plant photosynthesis by 0.07 ± 0.02 μmol C m$^{-2}$ ~~.4%,~~ s$^{-1}$, which could contribute to an additional 3.8~~±~~ ± 1.1 Gt C yr$^{-1}$ global gross primary productivity without explicit 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 potentially beneficial impact of stratospheric sulfate geoengineering would need to be balanced by a large number of potential risks in any future decisions about the implementation of geoengineering.

**Formatted:** Superscript

**Formatted:** Pattern: 15% (Auto Foreground, White Background)

**Keywords**: Geoengineering, Climate Engineering, Climate Intervention, Solar Radiation Management, GeoMIP, ~~Climate Intervention~~G4SSA, Diffuse Radiation, Photosynthesis Rate, Terrestrial Carbon Sink

## 1 Introduction

Stratospheric sulfate injection is one of the most discussed geoengineering ~~strategy to manipulate~~strategies for manipulating 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~~As explained in the initial design of the Geoengineering Model Intercomparison Project (GeoMIP) experiment (Kravitz et al., 2011), reducing the solar constant is another way to simulate sulfate injection geoengineering, and is easier to implement in a climate model. It was used in earlier geoengineering simulations (e.g., Govindasamy and Caldeira, 2000), and also can be thought of as a model of satellites in space blocking sunlight, as proposed ~~strategy~~by Angel (2006). Although the two methods could both potentially cool the surface, if they could ever be implemented, they would produce different climate responses, including stratospheric ozone depletion, troposphere ozone change ~~the climate system has~~, downward ultraviolet radiation, and downward diffuse radiation (e.g., Niemeier et al., 2013; Kalindidi et al., 2015; Nowack et al., 2015). Climate changes due to sunshade geoengineering and sulfate injection geoengineering have been extensively studied (Rasch et al., 2008b; Robock, 2008; Robock et al., 2009), ~~such as~~including 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~~couple~~ studies of~~on~~ its impact on the ecosystem – mainly focusing on the net primary productivity (Glienke et al., 2015; Kalidindi et al., 2015), the carbon

**Formatted:** Font: Times New Roman

**Formatted:** Font: Times New Roman, Bold cycle (Tjiputra et al., 2015), and 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 a few previous studies (e.g., Robock~~ (~~, 2008~~) and~~; Robock et al~~. (~~., 2009; Glienke et al., 2015), and ~~have not been~~need to be 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~~dramatically change the partitioning of downward direct and diffuse solar radiation (Robock, 2000~~; Robock~~, 2005). After the Mt. Pinatubo eruption in 1991 there was a sharp slowing of the $CO_2$ atmospheric concentration growth rate~~, which~~. This 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 a simultaneous El Niño and~~ the~~ increasing anthropogenic emission (Keeling et al., 1995; Ciais et al., 1995). Cooling due to ~~volcano~~volcanic eruptions (Robock, 2000) might be one ~~reason to explain~~explanation of 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; Gu et al., 2003; Farquhar and Roderick 2003; Mercado et al., 2009). In total, in 1992 and 1993, an additional 1.2-1.5 Gt C $yr^{-1}$ was captured by ~~the continents~~terrestrial vegetation (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~~promotes terrestrial vegetation growth (e.g~~.~~., Wild, 2009; Mercado et al., 2009). With the geographically varying changes in diffuse radiation fraction ~~(-20~~(0 to ~~-~~+30%) due to global dimming (1950-1980), the terrestrial carbon sink increased by 0.4 Gt C $yr^{-1}$ (Mercado et al., 2009). The most recent study also ~~shows~~showed that Amazon fires ~~that generate aerosols and enhance~~of 1998-2007 increased the annual mean diffuse radiation by 3.4-6.8% due to biomass burning aerosols, which would benefit the net primary productivity by 1.4-2.8% in the ~~Amazon~~Amazonian forests and balance 33-65% of the annual carbon emissions from biomass burning (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~~, would likely play an important role in the terrestrial carbon budget.

## 2 Model ~~Simulation~~and Experiment Design

Formatted: Font: Times New Roman

Formatted: Font: Times New Roman, Bold

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° x 1.25° lat-lon and 26 levels from the surface to about 40 km (3.5 hPa~~mb~~) (Lamarque et al., 2012; Tilmes et al., 2015a, 2016) to simulate two solar radiation ~~managements~~management schemes: a specific sulfate injection scenario and a solar constant reduction scenario. ~~The~~Since the experiments are branched from the Climate Chemistry Model Initiative (CCMI) runs in which CAM4-chem participates, we used the same configuration as the reference run. Therefore we used the Community Land Model (CLM) version 4.0 ~~is coupled with CAM4-chem, and~~ with prescribed satellite phenology (CLM4SP) instead of the version of CLM with ~~the~~a carbon-nitrogen cycle ~~turned off, it~~, coupled with CAM4-chem. This model calculates vegetation photosynthesis under the assumption of ~~no~~prescribed phenology and no explicit nutrient limitations (Bonan et al., 2011). With the satellite phenology option, although nitrogen limitation is not explicitly included, there is some inherent nitrogen limitation because nitrogen availability limits the leaf area index in the satellite measurements used in CLM4SP, and the model has been validated with gross primary productivity (GPP) observations. Dynamic vegetation is not turned on in this study. The ocean model does not include any ~~bio-geo-chemical~~biogeochemical 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 (at 60 ~~hPa~~mb) of 8 Tg $SO_2$ $yr^{-1}$ from 2020 to 2070, which produces a radiative forcing of about -2.5 $W/m^2$. 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~~mb and gradually decreases to 10-12 $\mu m^2$ $cm^{-3}$ at the poles (Tilmes et al., 2015b). Starting on January 1, 2070 the sulfate injection reduces gradually to zero on December 31, 2071 (Tilmes et al., 2015b). The G4SSA simulation continues after the end of sulfate injection from 2072 to 2089 to study the termination effect. Using specified stratospheric aerosols, tropospheric aerosols are not changed, and therefore we cannot evaluate how the geoengineered stratospheric sulfate aerosols would be transported into the troposphere and affect tropospheric chemistry. Using a fixed stratospheric aerosol distribution to compare the effect of geoengineered stratospheric aerosols in different models is similar to what has been done to investigate the impact of volcanic eruptions in chemistry climate model comparison projects in the past. For more details on the prescription of stratospheric aerosols in CAM4-chem see Neely et al. (2015). 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

**Formatted:** Indent: First line: 0.5"

2004 to 2089. ~~Both G3S and RCP4.5 have only one ensemble member each.~~ The reason we used different reference runs (RCP4.5 and RCP6.0) for the two experiments (G3S and G4SSA) is that they come from different phases of GeoMIP. G3S was initiated before G4SSA when GeoMIP just started and the reference run for the first phase of GeoMIP was RCP4.5. G4SSA is participating in both GeoMIP and CCMI. Since RCP6.0 is the standard reference run for CCMI, to encourage more climate chemistry modeling groups to participate in G4SSA and generate robust understanding of how atmospheric chemistry responses to sulfate injection geoengineering, Tilmes et al. (2015) proposed that G4SSA be based on RCP6.0. Since the anthropogenic forcing is very similar for RCP4.5 and RCP6.0 between 2020 and 2070, we expect very little difference between the two experiments. The basic principle, that solar dimming does not affect stratospheric ozone or produce diffuse radiation like stratospheric aerosols do, is well illustrated by the G3S results. Both G3S and RCP4.5 have only one ensemble member each.

## 3 Results

### 3.1 Climate and radiation response

Formatted: Font: Times New Roman

Formatted: Font: Times New Roman, Bold

Under the RCP6.0 scenario, the anthropogenic greenhouse gas radiative forcing increases global average surface air temperature from 288.5 K 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).~~as well as land average evaporation (Figs. 1b, 1g) increase. Global soil water content (10 cm, including liquid water and ice) slightly increase with global warming (Fig. 1i). The global surface downward solar radiation gradually decreases by about 1 W/m$^2$ during the period 2004-2089 (Fig. ~~1c~~1d) as the total cloud coverage increases, ~~especially~~particularly low clouds~~cloud coverage~~, which increase~~increases~~ by 0.7% (Fig. ~~1d~~1c).

However, the ~~terrestrial~~land-average visible direct solar radiation shows an upward trend (Fig. 1e) due to the effects of gradual tropospheric aerosol reductions under RCP6.0. The ~~terrestrial~~downward total solar radiation averaged over land (not shown) also has a slight increasing trend from 2004 to 2089, which is opposite ~~with~~to the ~~global~~globally-averaged surface solar radiation trend. There are two reasons~~: first,~~ for this: the reduction in aerosol emissions mainly affects the continents~~;~~ and ~~second,~~ the ~~increasing~~increase of cloud coverage is mainly over the ocean. ~~Land average~~Averaged visible diffuse radiation (300-700 nm) over land decreases in RCP6.0 (Fig. 1f) due to the decreasing of aerosol emission in the RCP6.0 scenario (Meinshausen et al., 2011). Under this global warming scenario, vegetated-land averaged canopy transpiration decreases mainly due to increasing $CO_2$ (Fig. 1h) (Reddy et al., 1995).

With ~~the negative radiative forcing of stratospheric sulfate aerosol (–~~1.6 W/m$^2$~~)~~ less total surface solar radiation (Fig. ~~1c~~1d), G4SSA successfully cools the surface by ~~1~~0.8 ± 0.2 K as compared to RCP6.0 (Fig. 1a). ~~In this model, the global cloud coverage (mainly low clouds) is less (Fig. 1d) and the~~This cooling slows down the hydrology cycle with less average precipitation ~~reduces by (–~~0.07 mm/day ~~(~~((–2.5~~%)~~%)) (Fig. 1b), less ground evaporation (Fig. 1g) and less global low cloud coverage (Fig. 1c), which is consistent with previous studies (e.g~~.,~~., Niemeier et al., 2013; Tilmes et al., 2013; Jones et al., 2013~~). Diffuse~~; Kalidindi et al., 2015). And there is no change in the soil water content under G4SSA and RCP6.0 scenarios (Fig. 1i). Visible diffuse radiation over the land increases significantly (Fig. 1f) as the sulfate aerosols in the stratosphere (~~2~~3.0 Tg S equilibrium loading~~)~~ (Tilmes et al., 2015b)) scatter solar radiation. Therefore~~ although~~, while the total surface 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.~~-~~ Kalidindi et al. (2015) showed that with a 20 Tg sulfate aerosol ($SO_4$) stratospheric loading to balance the

**Formatted:** Indent: First line: 0.5"

**Formatted:** Font color: Blue

radiative forcing of $2xCO_2$, broadband diffuse radiation would increase by 11.2 $W/m^2$ compared with the reference run. However they used a very unrealistic stratospheric aerosol distribution, with very small effective radius of 0.17 μm and uniform geographical distribution. Three months after the eruption of Mt. Pinatubo in 1991, broadband diffuse radiation increased from 40 $W/m^2$ 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 largergreater. The photosynthesis rate of a northern hardwood forest (Harvard Forest) 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 1991 Pinatubo eruption every 2.5 years (Bluth et al., 1992) with the assumption that all sulfate aerosol will reach the stratosphere, diffuse radiation enhancement is expected to enhance the terrestrial photosynthesis rate and potentially increase the land carbon sink. Furthermore, the drier, cooler, and more diffuse radiation environment under G4SSA reduces the canopy transpiration comparing with RCP6.0 (Fig. 1h) (Kanniah et al., 2012), which may indicate that less $CO_2$ is released back to the atmosphere by plant respiration.

Solar constant reduction climate intervention (G3S) efficiently cools the surface as well. Since there is less radiative forcing reduction due to the experiment design, the annual global averaged temperature reduction (gradually from 0°C to 0.8°C) is less than the reduction in G4SSA. Precipitation and ground evaporation also reduce under G3S. However, G3S has no effect on diffuse radiation compared with RCP4.5 since there ~~is~~are no additional ~~aerosol~~aerosols injected into the atmosphere. The overall trend of surface visible diffuse radiation in both G3S and RCP4.5 ~~is decreasing~~slowly decreases because of decreasing emissions (the tropospheric aerosol removal effect in RCP4.5, not shown). Although the two experiments have different radiative forcing reductions: 2.5 W/m$^2$ for G4SSA and 0-1.5 W/m$^2$ for G3S, we expect linear changes in temperature and precipitation corresponding to the radiative forcing change (Irvine et al., 2010; Kravitz et al., 2014). We focus on the diffuse radiation effect in this study, which is included in G4SSA and excluded in G3S due to the experiment design. Therefore, it is reasonable to compare the two experiments as to their diffuse radiation effect on photosynthesis.

### 3.2 Diffuse radiation and climate change impacts on vegetation photosynthesis rate

Formatted: Font: Bold

Diffuse radiation is more advantageous for plant productivity than direct radiation (e.g~~.~~., Gu et al., 2002~~), since~~) because diffuse radiation ~~is~~provides more homogeneous distribution of radiation within the canopy and more light can be absorbed by ~~plants more homogeneously and also more efficiently~~ shaded leaves without exceeding ~~photosynthesis~~the photosynthetic 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~~this 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~~. Therefore the increase of diffuse radiation in our study would have a positive impact on plant photosynthesis.

Formatted: Indent: First line: 0.5"

Without explicit 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 model-simulated increase may not be realistic, since the actual photosynthesis rate is limited by the amount of soil nutrients~~,~~ such as nitrogen and phosphorus (e.g~~.~~., Vitousek and Howarth, 1991; Davidson et al., 2004; Elser et al., 2007). Under the G4SSA scenario, global averaged photosynthesis increases 0.07±0.02 µmol C $m^{-2}$ $s^{-1}$ compared with that in the RCP6.0 scenario (Fig. 2a). This enhancement is due to the combination of the climate changes, such as cooling, and diffuse radiation ~~effects. Photosynthesis reaches its~~enhancement. Different types of plants show maximum photosynthesis rates at ~~an~~certain optimal temperature ~~for different plants under different~~depending on $CO_2$ concentrations (e.g~~.~~., Sage and Kubien, 2007). Fig. 3 shows that the photosynthesis rate in different regions responds to G4SSA differently and temperature plays an important role. In general, the cooling effect from solar radiation management would increase photosynthesis in tropical regions where there ~~might~~is likely to 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. In the Tropics, the photosynthesis rate change has an increasing trend (Fig. 3), because the cooling effect of G4SSA benefits photosynthesis more when global warming gets severe. And the large variation of the photosynthesis rate change in the Tropics (Fig. 3) might be related to the strong sensitivity of tropical forest to precipitation change (Phillips et al., 2009; Tjiputra et al., 2015).

Fig. 2b shows the photosynthesis ~~rate~~rates 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~~.~~ (Fig. 4b). Therefore, the increase of the photosynthesis rate in Fig. 2a under the G4SSA scenario is ~~mostly~~primarily caused by the enhancement of diffuse radiation.

Without explicit nutrient limitation, the increase of the photosynthesis rate is almost ~~all~~entirely over vegetated land during year 2030-2069 of G4SSA compared with RCP6.0 (Fig. ~~3a~~4a) as a combination impact of climate factors controlling plant photosynthesis (Fig. 5). The strongest increase is in the Amazon rainforest with a value of 1.42 μmol C $m^{-2}$ $s^{-1}$ (26.3~~%),~~%) (Fig. 4a), where multiple layers of the canopy, especially the tallest canopy, would receive more diffuse radiation, and the cooling helps plant growth during the entire year. Those two positive impacts of diffuse radiation and surface temperature changes from G4SSA are countered by the negative impacts from the regional reductions of soil water content (not shown here) and the global reduction of total solar radiation (Figs. 5b and 5c). In a previous study, precipitation was found to be the largest climate factor controlling GPP during 1998-2005 (Beer et al., 2010). 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~~would potentially help to bring more carbon out of the atmosphere. Since in reality, most Amazonian soils are highly weathered and relatively nutrient poor, this simulated increase might be overestimated (Davison et al., 2004). However, in our study, the prescribed plant phenology has some inherent nutrient limitation, and therefore the overestimation should not be substantial. In high latitude and high altitude regions, although increasing diffuse radiation ~~is not the dominant factor controlling~~still increases the photosynthesis rate, ~~and the colder environment under G4SSA~~ temperature reduction has a negative impact on photosynthesis (Fig. 5a), which is consistent with a previous study (Glienke et al., 2015), and the stronger temperature reduction in high latitude regions would reduce the photosynthesis rate (Fig. ~~3a).~~4a). Over high altitude regions, such as the Rocky Mountains and the Himalayas, increased snow cover (not shown here) contributes to the reduction of photosynthesis under G4SSA as well. 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. Furthermore, changes in tropospheric chemistry and stratosphere troposphere exchange due to G4SSA could modify the surface ozone concentration regionally, which may be another potential impact on photosynthesis rate. Further investigation of those issues is needed.

Without the diffuse radiation effect, the photosynthesis rate ~~difference~~differences between G3S and RCP4.5 ~~is mainly due to the cooling effect~~are not significant in more regions (Fig. ~~3b).~~4b) than for the differences between G4SSA and RCP6.0. The Amazon rainforest still has the largest photosynthesis increase, with a maximum value of 1.24 μmol C $m^{-2}$ $s^{-1}$, but the average photosynthesis change in the Amazon region is only 0.7±5.7%. ~~Since the~~The two climate interventions (G4SSA and G3S) ~~are under~~have 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~~. We cannot, therefore, evaluate ~~the exact fraction of~~how much the enhancement of diffuse radiation ~~contribution~~contributes to the ~~increasing~~increase of photosynthesis. ~~But from~~When comparing 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.

### 3.3 Diffuse radiation and climate change impacts on the terrestrial carbon sink

We have ~~briefly~~ calculated the additional carbon sink due to the increase of photosynthesis. ~~Based on our simulations, without nutrient limitation~~Using the land area

**Formatted:** Indent: First line: 0.5"

($1.5\times10^{8}$ km$^{2}$) in CLM, for G4SSA, the global land average photosynthesis rate increases 0.07±0.02 μmol C m$^{-2}$ s$^{-1}$ ~~under the G4SSA sulfate injection climate intervention scenario, and the land area used for photosynthesis calculation in CLM is $1.5\times10^{8}$ km$^{2}$.~~compared with RCP6.0. Therefore the increase of the photosynthesis rate without explicit nutrient limitation would increase ~~gross primary productivity of~~GPP by 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~~was the result of 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.,~~significant in 1993 (0.04 Gt C yr$^{-1}$).~~ 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.~~

Formatted: Not Superscript/ Subscript

## 4 Discussion

Formatted: Font: Times New Roman

Formatted: Font: Times New Roman, Bold

Formatted: Keep with next

~~Although~~Our result of increasing of gross primary productivity due to enhanced stratospheric aerosols has uncertainties and needs to be further evaluated with new experiments using multiple Earth System Models. Since the ~~calculation here~~carbon-nitrogen cycle in CLM4 is ~~based on an assumption of no nutrient limitation~~turned off, leaf area index (LAI) cannot be diagnosed by the climate changes due to G4SSA and hence the photosynthesis response may be biased. However, even if we use CLM4CN with the carbon-nitrogen cycle modeled, the photosynthesis response would still be imperfectly modeled, since there are a high bias in the LAI simulation and structural errors in the leaf photosynthesis process (Lawrence et al., 2012). Also, without dynamic vegetation, our study keeps a prescribed plant functional type during the whole simulation, and cannot simulate plant type change under a different climate.

Another source of uncertainty is the use of only one climate model. Jones et al. (2013) and Glienke et al. (2015) showed that there is a large range of simulated net primary productivity (NPP) changes as the $CO_2$ concentration increases or under solar reduction geoengineering using different land models, which ~~could overestimate the benefits from~~ is mainly due to the availability of a nitrogen cycle. With a nitrogen cycle, there is a much smaller $CO_2$ fertilization effect on plant growth. We expect that with the carbon-nitrogen cycle turned on, the upward trend of the photosynthesis rate under both G4SSA and RCP6.0 in Fig. 2a will be reduced. Furthermore, models respond to different climates at the same atmospheric $CO_2$ concentration differently. Eight models participating in the GeoMIP G1 (instantaneously quadrupling of the $CO_2$ concentration (abrupt4xCO2) while simultaneously reducing the solar constant to balance the forcing) (Kravitz et al., 2011) showed different and even opposite trends of NPP changes between abrupt4xCO2 and G1 because of different behaviors in GPP and respiration (Glienke et al., 2015). In G1, GPP as well as NPP reduced under G1 compared with abrupt4xCO2 using CCSM4 (CAM4 coupled with CLM4CN). However, G1 has a much stronger temperature reduction and no diffuse radiation ~~in terms of~~ change. Considering the inconsistent responses of models to geoengineering induced climate changes even with the same $CO_2$ concentration, multiple model study is necessary to better understand how photosynthesis and NPP would change under sulfate injection geoengineering.

Sulfate injection geoengineering could potentially change the terrestrial carbon sink~~,~~ ~~there are~~ since it might increase GPP compared with a global warming scenario due to the diffuse radiation and other climate changes. However, to further investigate this issue, we need to consider other mechanisms that sulfate injection geoengineering ~~might~~would trigger. The cooling effect would also 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~~ in 1992, since the cooling effect ~~also~~ suppresses soil respiration~~, which~~ and reduces carbon emissions ~~as much as increasing of~~. In 1993, the cooling effect actually enhances the land carbon sink~~. Moreover~~ more than the diffuse radiation. Furthermore, respiration of terrestrial ecosystems, ~~including~~such as the decomposition of soil organic carbon~~,~~ is not included in our study, which might be more sensitive to temperature change than ~~the gross primary productivity~~to GPP (Jenkinson et al., 1991) and add another additional terrestrial carbon sink under sulfate injection geoengineering (Tjiputra et al., 2015). 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).

In our simulations, the $CO_2$ concentration is prescribed in both G4SSA and RCP6.0, but we expect that the $CO_2$ concentration of G4SSA might be lower than the global warming

**Formatted:** Indent: First line: 0.5"

scenario due to the diffuse radiation and the cooling effects because this $CO_2$ concentration change has been observed after volcanic eruptions due to enhanced land carbon sinks (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. However, the atmospheric $CO_2$ concentration is also highly impacted by another carbon reservoir, the ocean. 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~~.~~ (Tjiputra et al., 2015). For example, an El Niño will cause the ocean to temporarily emit more $CO_2$ to the atmosphere. ~~However,~~Although idealized geoengineering experiments have not shown any significant effect on El Niño (Gabriel and Robock, 2015~~).~~), a longer period of geoengineering might impact ocean circulation. The ocean model we used ~~does simulate~~simulates dynamical and temperature responses, but does not include a biochemical and 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~~Although there have been many reasons to be hesitant about the implementation of geoengineering (Robock, 2012; Robock, 2014), sulfate injection climate intervention ~~has~~may have a great potential to increase ~~the~~ land ~~gross primary productivity~~GPP, 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; Robock, 2014).~~

## 5 Conclusions

With our experimental design, simulated stratospheric sulfate geoengineering with 8 Tg $yr^{-1}$ injection of $SO_2$ would change the partitioning of solar radiation with an increase of surface diffuse radiation about 3.2 $W/m^2$ in visible wavelengths over land. This enhanced diffuse radiation combining with other climate changes, such as cooling, soil water content change, and total solar radiation reduction increase plant photosynthesis rates significantly in temperate and tropical regions, and reduce the photosynthesis rate in high latitude and mountain regions. Overall, the increase of the land-averaged photosynthesis rate is $0.07 \pm 0.02$ μmol C $m^{-2}$ $s^{-1}$, which could contribute to an additional $3.8 \pm 1.1$ Gt C $yr^{-1}$ global carbon sink. These results are affected by the experimental design, since the carbon-nitrogen cycle and dynamic vegetation are not included. Further investigation is needed to fully understand the contribution of enhanced diffuse radiation due to sulfate geoengineering on the terrestrial carbon sink.

## Acknowledgments

This work is supported by NSF grants AGS-1157525 and GEO-1240507. Computer simulations were conducted on the National Center for Atmospheric Research Yellowstone supercomputer. The National Center for Atmospheric Research is funded by the National Science Foundation. The climate model used in this study (CESM CAM4-chem) is developed under the Climate Simulation Laboratory. We thank Jean-Francois Lamarque, Daniel Marsh, Andrew Conley, and Douglas E. Kinnison for the CAM4-Chem development. We thank Peter Lawrence and Danica Lombardozzi for helping us understanding how CLM4 calculates photosynthesis. Neely was supported by ~~the~~ NSF via NCAR's Advanced Study Program. We thank the reviewers, who helped to substantially improve this work.

## References


Allen Jr~~,~~., L. H., Boote, K. J., Jones, J. W., Jones, P. H., Valle, R. R., Acock, B., Rogers, H. H., and Dahlman, R. C.: Response of vegetation to rising carbon dioxide: Photosynthesis, biomass, and seed yield of soybean, Global Biogeochemical Cycles, 1(1), 1-14, doi:10.1029/GB001i001p00001, 1987.

Angel, R.: Feasibility of cooling the Earth with a cloud of small spacecraft near the inner Lagrange point (L1), Proc. Natl. Acad. Sci. U.S.A., 103, 17,184–17,189, doi:10.1073/pnas.0608163103, 2006.

Bala, G., Duffy, P. B., and Taylor, K. E.: Impact of geoengineering schemes on the global hydrological cycle, Proc. Natl. Acad. Sci., 105(22), 7664-7669, doi:10.1073/pnas.0711648105, 2008.

Berdahl, M., Robock, A., Ji, D., Moore, J. C., Jones, A., Kravitz, B., and Watanabe, S.: Arctic cryosphere response in the Geoengineering Model Intercomparison Project (GeoMIP) G3 and G4 scenarios, J. Geophys. Res. Atmos., 119, 1308-1321, doi:10.1002/2013JD020627, 2014.

Bluth, G. J. S., Doiron, S. D., Schnetzler, C. C., Krueger, A. J., and Walter, L. S.: Global tracking of the $SO_2$ clouds from the June, 1991 Mount Pinatubo eruptions, Geophys. Res. Lett., 19(2), 151-154, doi:10.1029/91GL02792, 1992.

Bonan, G. B., Lawrence, P. J., Oleson, K. W., Levis, S., Jung, M., Reichstein, M., Lawrence, D. M., and Swenson, S. C.: Improving canopy processes in the Community Land Model version 4 (CLM4) using global flux fields empirically inferred from FLUXNET data, J. Geophys. Res., 116, G02014, doi:10.1029/2010JG001593, 2011.


**Formatted:** Pattern: Clear

**Formatted:** Pattern: Clear

**Formatted:** Pattern: Clear

Chameides, W. L., Yu, H., Liu, S. C., Bergin, M., Zhou, X., Mearns, L., Wang, G., and Kiang, C. S.: Cases study of the effects of atmospheric aerosols and regional haze on agriculture: An opportunity to enhance crop yields in China through emission controls?, Proc. Natl. Acad. Sci., 96, 13,626-13,633, doi:10.1073/pnas.96.24.13626, 1999.

Formatted: Pattern: Clear

Ciais, P., Tans, P. P., Trolier, M., White, J. W. C., and Francey, R. J.: A large Northern Hemisphere terrestrial $CO_2$ sink indicated by the 13C/12C ratio of atmospheric $CO_2$, Science, 269(25), 1098-1102, doi:10.1126/science.269.5227.1098, 1995.

Cohan, D. S., Xu, J., Greenwald, R., Bergin, M. H.,  and Chameides, W. L.: Impact of atmospheric aerosol light scattering and absorption on terrestrial net primary productivity, Global Biogeochemical Cycles, 16(4), 1090, doi:10.1029/2001GB001441, 2002.

Crutzen, P.: Albedo enhancement by stratospheric sulfur injections: A contribution to resolve a policy dilemma?, Climatic Change, 77(3), 211-220, doi: 10.1007/s10584-006-9101-y, 2006.

Davidson, E. A., et al.: Nitrogen and phosphorus limitation of biomass growth in a tropical secondary forest, Ecological Applications, 14 (4), S150-S163, doi:10.1890/01-6006, 2004.

Davidson, E. A. and Janssens, I. A.: Temperature sensitivity of soil carbon decomposition and feedbacks to climate change, Nature, 440, 165-173, doi:10.1038/nature04514, 2006.

Elser, J. J., et al.: Global analysis of nitrogen and phosphorus limitation of primary producers in freshwater, marine and terrestrial ecosystems, Ecology Lett., 10 (12), 1135-1142, doi:10.1111/j.1461-0248.2007.01113.x, 2007.

Farquhar, G. D. and Roderick, M. L.: Pinatubo, diffuse light, and the carbon cycle, Science, 299(5615), 1997-1998, doi:10.1126/science.1080681, 2003.

Gabriel, C. J. and Robock, A.: Stratospheric geoengineering impacts on El Niño/Southern Oscillation, Atmos. Chem. Phys. Discuss., 15, 9173-9202, doi:10.5194/acpd-15-9173-2015, 2015.

**Formatted:** Pattern: Clear

Glienke, S., Irvine, P. J. and Lawrence, M. G.: The impact of geoengineering on vegetation in experiment G1 of the GeoMIP, J. Geophys. Res. Atmos., 120, 10,196–10,213, doi:10.1002/2015JD024202, 2015.

Govindasamy, B., and Caldeira, K., Geoengineering Earth's radiation balance to mitigate $CO_2$-induced climate change, Geophys. Res. Lett., 27, 2141-2144, doi:10.1029/1999GL006086, 2000.

Gu, L., Fuentes, J. D., Shugart, H. H., Staebler, R. M., and Black, T. A.: Responses of net ecosystem exchanges of carbon dioxide to changes in cloudiness: Results from two North American deciduous forests, J. Geophys. Res., 104, 31,421-31,434, doi:10.1029/1999JD901068, 1999.

Gu, L., Baldocchi, D., Verma, S. B., Black, T. A., Vesala, T., Falge, E. M., and Dowty, P. R.: Advantages of diffuse radiation for terrestrial ecosystem productivity, J. Geophys. Res. Atmos., 107(D6), ACL 2-1-ACL 2-23, doi:10.1029/2001JD001242, 2002.

Gu, L., Baldocchi, D., Wofsy, S. C., Munger, J. W., Michalsky, J. J., Urbanski, S. P., and Boden, T. As.: Response of a deciduous forest to the Mount Pinatubo eruption: Enhanced photosynthesis, Science, 299, 2035-2038, doi:10.1126/science.1078366, 2003.

**Formatted:** Pattern: Clear

Heckendorn, P., Weisenstein, D., Fueglistaler, S., Luo, B. P., Rozanov, E., Schraner, M., Thomason, L. W., and Peter, T.: The impact of geoengineering aerosols on stratospheric temperature and ozone, Environ. Res. Lett., 4, 045108, doi:10.1088/1748-9326/4/4/045108, 2009.

**Formatted:** Pattern: Clear

**Formatted:** Pattern: Clear

Irvine, P. J., Ridgwell, A., and Lunt, D. J.: Assessing the regional disparities in geoengineering impacts, Geophys. Res. Lett., 37, L18702, doi:10.1029/2010GL04447, 2010.

Jenkinson, D. S., Adams, D. E., and Wild, A.: Model estimates of $CO_2$ emissions from soil in response to global warming, Nature, 351, 304-306, doi:10.1038/351304a0, 1991.

Jones, A., Haywood, J., Boucher, O., Kravitz, B., and Robock, A.: Geoengineering by stratospheric $SO_2$ injection: Results from the Met Office HadGEM2 climate model and comparison with the Goddard Institute for Space Studies ModelE, Atmos. Chem. Phys., 10, 5999-6006, doi:10.5194/acp-10-5999-2010, 2010.

Jones, A., et al.: The impact of abrupt suspension of solar radiation management (termination effect) in experiment G2 of the Geoengineering Model Intercomparison Project (GeoMIP), J. Geophys. Res. Atmos., 118, 9743-9752, doi:10.1002/jgrd.50762, 2013.

Jones, C. D. and Cox, P. M.: Modeling the volcanic signal in the atmospheric $CO_2$ record, Global Biogeochemical Cycles, 15(2), 453-465, doi:10.1029/2000GB001281, 2001.

Kalidindi, S., Govindasamy, B., Angshuman, M., and Caldeira, K.: Modeling the solar radiation management: A comparison of simulations using reduced solar constant and stratospheric sulphate aerosols, Climate Dynamics, 44 (9-10), 2909-2925, doi:10.1007/s00382-014-2240-3, 2015.

Kanniah, K. D., Beringer, J., North, P., and Hutley, L.:Control of atmospheric particles on diffuse radiation and terrestrial plant productivity: A review, Progress in Physical Geography, 36 (2), 209-237, doi:10.1177/0309133311434244, 2012.

**Formatted:** Pattern: Clear

Keeling, C. D., Whorf, T. P., Wahlen, M., and van der Plichtt, J~~. van. der:~~.: Interannual extremes in the rate of rise of atmospheric carbon dioxide since 1980, Nature, 375(6533), 666-670, doi:10.1038/375666a0, 1995.

Knohl A~~.~~., and Baldocchi, D. D.: Effects of diffuse radiation on canopy gas exchange processes in a forest ecosystem, J. Geophys. Res., 113, doi:10.1029/2007JG000663, 2008.

Kravitz, B., Robock, A., Boucher. O., Schmidt, H., Taylor, K. Stenchikov, G., and Schulz, M.,: The Geoengineering Model Intercomparison Project (GeoMIP). Atmos. Sci. Lett., 12, 162-167, doi:10.1002/asl.316, 2011.

Kravitz, B., et al.: A multi-model assessment of regional climate disparities caused by solar geoengineering, Environ. Res. Lett., 9, 074013, doi: 10.1088/1748-9326/9/7/074013, 2014.

Lamarque, J.-F., Emmons, L. K., Hess, P. G., Kinnison, D. E., Tilmes, S., Vitt, F., Heald, C. L., Holland, E. A., Lauritzen, P. H., Neu, J., Orlando, J. J., Rasch, P. J., and Tyndall, G. K.: CAM-Chem: Description and evaluation of interactive atmospheric chemistry in the Community Earth System Model, Geosci. Model Dev., 5, 369-411, doi:10.5194/gmd-5-369-2012, 2012.

Lawrence, D. M., et al.: The CCSM4 Land Simulation, 1850-2005: Assessment of surface climate and new capabilities, J. Climate, 25, 2240-2260, doi:http://dx.doi.org/10.1175/JCLI-D-11-00103.1,2012.

Leakey, A. D. B., Ainsworth, E. A., Bernacchi, C. J., Rogers, A., Long, S. P., and Ort, D. R.: Elevated $CO_2$ effects on plant carbon, nitrogen, and water relations: Six important lessons from FACE, J. Exp. Bot., 60(10), 2859-2876, doi:10.1093/jxb/erp096, 2009.

Lucht, W., Pretice, I. C., Myneni, R. B., Sitch, S., Friedlingstein, P., Cramer, W., Bousquet, P., Buermann, W., and Smith, B.: Climatic control of the high-latitude vegetation greening trend and Pinatubo effect, Science, 296(5573), 1687-1689, doi:10.1126/science.1071828, 2002.

Misson, L., Lunden, M., McKay, M., and Goldstein, A. H.: Atmospheric aerosol light scattering and surface wetness influence the diurnal pattern of net ecosystem exchange in a semi-arid ponderosa pine plantation, Agric. Forest Meteor., 129, 69-83, doi:10.1016/j.agrformet.2004.11.008, 2005.

Meinshausen, M., et al.: The RCP greenhouse gas concentrations and their extension from 1765 to 2300, Climatic Change, 109, 213-241, doi:10.1007/s10584-011-0156-z, 2011.

Mercado, L. M., Bellouin, N., Sitch, S., Boucher, O., Huntingford, C., Wild, M., and Cox, P. M.: Impact of changes in diffuse radiation on the global land carbon sink, Nature, 458(7241), 1014-1017, doi:10.1038/nature07949, 2009.

Neely III, R. R., Conley, A., Vitt, F., and Lamarque, J. F.: A consistent prescription of stratospheric aerosol for both radiation and chemistry in the Community Earth Esystem Model (CESM1), Geosci. Model Dev. Discuss., 8, 10711-10734, doi:10.5194/gmdd-8-10711-2015, 2015.

Nemani, R. R., Keeling, C. D., Hashimoto, H., Jolly, W. M., Piper, S. C., Tucker, C. J., Myneni, R. B., and Running, S. W.: Climate-driven increases in global terrestrial net primary production from 1982 to 1999, Science, 300(5625), 1560-1563, doi:10.1126/science.1082750, 2003.

Niemeier, U., Schmidt, H., and Timmreck, C.: The dependency of geoengineered sulfate aerosol on the emission strategy, Atmos. Sci. Let., 12, 189-194, doi:10.1002/asl.304, 2010.

**Formatted:** Pattern: Clear

**Formatted:** Pattern: Clear

Niemeier, U., Schmidt, H., Alterskjær, K., and Kristjánsson, J. E.: Solar irradiance reduction via climate engineering: Impact of different techniques on the energy balance and the hydrological cycle, J. Geophys. Res. Atm., 118(21), 11,905-11,917, doi:10.1002/2013JF020445, 2013.

Niyogi D., et al.: Direct observations of the effect of aerosol loading on net ecosystem $CO_2$ exchanges over different landscapes, Geophy. Res. Lett., 31, L20506, doi:10.1029/2004GL020915, 2004.

Nowack, P. J., Abraham, N. L., Braesicke, P., and Pyle, J. A.: Ozone changes under solar geoengineering: implications for UV exposure and air quality, Atmos. Chem. Phys. Discuss., 15, 31,973-32,004, doi:10.5194/acpd-15-31973-2015, 2015.

~~Meinshausen, M., et al.: The RCP greenhouse gas concentrations and their extension from 1765 to 2300, Climatic Change, 109, 213-241, doi:10.1007/s10584-011-0156-z, 2011.~~

~~Mercado, L. M., Bellouin, N., Sitch, S., Boucher, O., Huntingford, C., Wild, M., and Cox, P. M.: Impact of changes in diffuse radiation on the global land carbon sink, Nature, 458(7241), 1014-1017, doi:10.1038/nature07949, 2009.~~

Oliveira, P. H. F., Artaxo, P., Pires, C., Lucca, S. D., Procopio, A., Holben, B., Schafer, J., Cardoso, L. F., Wofsy, S. C., and Rocha, H. R.: The effects of biomass burning aerosols and clouds on the $CO_2$ flux in Amazonia, Tellus, Ser. B., 59(3), 338-349, doi:10.1111/j.1600-0889.2007.00270.x, 2007.

Pan Y., et al.: A large and persistent carbon sink in the world's forest, Science, 333, 988-993, doi:10.1126/science.1201609, 2011.

Formatted: Pattern: Clear

Formatted: Pattern: Clear

Parkes, B., Challinor, A., and Nicklin, K.: Crop: failure rates in a geoengineered climate: impact of climate change and marine cloud brightening, Environ. Res. Lett., 10, 084003, doi:10.1088/1748-9326/10/8/084003, 2015.

Pitari, G., et al.: Stratospheric ozone response to sulfate geoengineering: Results from the Geoengineering Model Intercomparison Project (GeoMIP), J. Geophys. Res. Atmos., 119, 2629–2653, doi:10.1002/2013JD020566, 2012.

Pongratz, J., Lobell, D. B., Cao, L., and Caldeira, K.: Crop yields in a geoengineered climate, Nature Clim. Change, 2(2), 101-105, doi:10.1038/nclimate1373, 2012.

Rap, A., et al.: Fires increase Amazon forest productivity through increases in diffuse radiation, Geophys. Res. Lett., 42(11), 4654-4662, doi:10.1002/2015GL063719, 2015.

Rasch, P. J., Crutzen, P. J., and Coleman, D. B.: Exploring the geoengineering of climate using stratospheric sulfate aerosols: the role of particle size, Geophys. Res. Lett., 35, L02809, doi:10. 1029/2007GL032179, 2008a.

Rasch, P. J., Tilmes, S., Turco, R. P., Robock, A., Oman, L., Chen, C-C. (Jack), Stenchikov, G. L., and Garcia, R. R.: An overview of geoengineering of climate using stratospheric sulfate aerosols, Phil. Trans. Royal Soc. A., 366, 4007-4037, doi:10.1098/rsta.2008.0131, 2008b.

Reddy, V. R., Reddy, K. R., and Hodges, H. F.: Carbon dioxide enrichment and temperature effects on cotton canopy photosynthesis, transpiration, and water-use efficiency, Field Crops Research, 41 (1), 13-23, doi:10.1016/0378-4290(94)00104-K, 1995.

Robock, A.: Volcanic eruptions and climate, Rev. Geophys., 38, 191-219, 2000.

Robock, A.: Cooling following large volcanic eruptions corrected for the effect of diffuse radiation on tree rings, Geophys. Res. Lett., 32, L06702, doi:10.1029/2004GL022116, 2005.



Formatted: Pattern: Clear

Formatted: Pattern: Clear

Formatted: Pattern: Clear

Formatted: Pattern: Clear

Formatted: Pattern: Clear

Robock, A.: 20 reasons why geoengineering may be a bad idea. Bull. Atomic Scientists, 64(2), 14-18, doi:10.2968/064002006, 2008.

Robock, A.: Will geoengineering with solar radiation management ever be used? Ethics, Policy & Environment, 15, 202-205, 2012.

Robock, A.: Stratospheric aerosol geoengineering, Issues Env. Sci. Tech. (special issue “Geoengineering of the Climate System”), 38, 162-185, 2014.

Robock, A., Oman, L., and Stenchikov, G.: Regional climate responses to geoengineering with tropical and Arctic $SO_2$ injections, J. Geophys. Res., 113, D16101, doi:10.1029/2008JD010050, 2008.

Robock, A., Marquardt, A. B., Kravitz, B., and Stenchikov, G.: The benefits, risks, and costs of stratospheric geoengineering, Geophys. Res. Lett., 36, L19703, doi:10.1029/2009GL039209, 2009.

Roderick, M., Farquhar, G. D., Berry, S. L., and Noble, I. R.: On the direct effect of clouds and atmospheric particles on the productivity and structure of vegetation, Oecologia, 129(1), 21-30, 2001.

Sage, R. F. and Kubien, D. S.: The temperature response of C3 and C4 photosynthesis, Plant, Cell and Environment, 30, 1086-1106, doi:10.1111/j.1365-3040.2007.01682.x, 2007.

Tilmes, S., Müller, R., and Salawitch, R.: The sensitivity of polar ozone depletion to proposed geoengineering schemes, Science, 320(5880), 1201-1204, doi:10.1126/science.1153966, 2008.

**Formatted:** Pattern: Clear

**Formatted:** Pattern: Clear

Tilmes, S., et al.: The hydrological impact of geoengineering in the Geoengineering Model Intercomparison Project (GeoMIP), J. Geophys. Res. Atmos., 118, 11,036-11,058, doi 10.1002/jgrd.50868, 2013.

Tilmes, S., et al.: Description and evaluation of tropospheric chemistry and aerosols in the Community Earth System Model (CESM1.2), Geosci. Model Dev., 8, 1395-1426, doi:10.5194/gmd-8-1395-2015, 2015a.

Tilmes, S., et al.: A new Geoengineering Model Intercomparison Project (GeoMIP) experiment designed for climate and chemistry models, Geosci. Model Dev., 8, 43-49, doi:10.5194/gmd-8-43-2015, 2015b.

Tilmes, S., et al.: Representation of the Community Earth System Model (CESM1) CAM4-chem within the Chemistry-Climate Model Initiative (CCMI), Geosci. Model Dev. Discuss., doi:10.5194/gmd-2015-237, 2016.

Tjiputra, J. F., Grini, A. and Lee, H.: Impact of idealized future stratospheric aerosol injection on the large scale ocean and land carbon cycles, J. Geophys. Res. Biogeo., 120, doi:10.1002/2015JG003045, 2015.

Vitousek, P. M. and Howarth, R. W.: Nitrogen limitation on land and in the sea: How can it occur? Biogeochemistry, 13(2), 87-115, 1991.

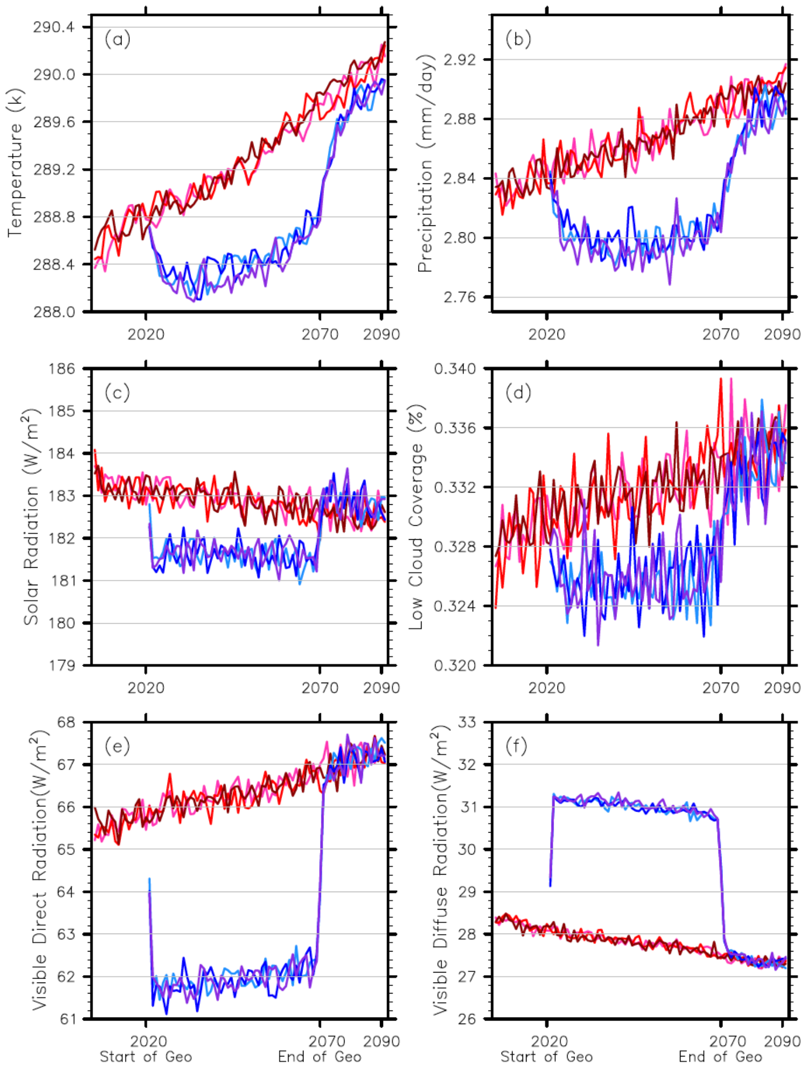
Wigley, T. M. L.: A combined mitigation/geoengineering approach to climate stabilization, Science, 314, 452-454, doi:10.1126/science.1131728, 2006.

Wild, M.: Global dimming and brightening: A review, J. Geophys. Res. Atmos., 114, D00D16, doi:10.1029/2008JD011470, 2009.

Formatted: Pattern: Clear

Formatted: Pattern: Clear

Xia, L., et al.: Solar radiation management impacts on agriculture in China: A case study in the Geoengineering Model Intercomparison Project (GeoMIP), J. Geophys. Res. Atmos., 119, 8695-8711, doi:10.1002/2013JD020630, 2014.



(a)
Temperature (k)
290.4
290.0
289.6
289.2
288.8
288.4
288.0
(b)
Precipitation (mm/day)
2.92
2.88
2.84
2.80
2.76
(c)
Solar Radiation (W/m²)
186
185
184
183
182
181
180
179
(d)
Low Cloud Coverage (%)
0.340
0.336
0.332
0.328
0.324
0.320
(e)
Visible Direct Radiation(W/m²)
68
67
66
65
64
63
62
61
(f)
Visible Diffuse Radiation(W/m²)
33
32
31
30
29
28
27
26
2020
2070
2090
Start of Geo
End of Geo

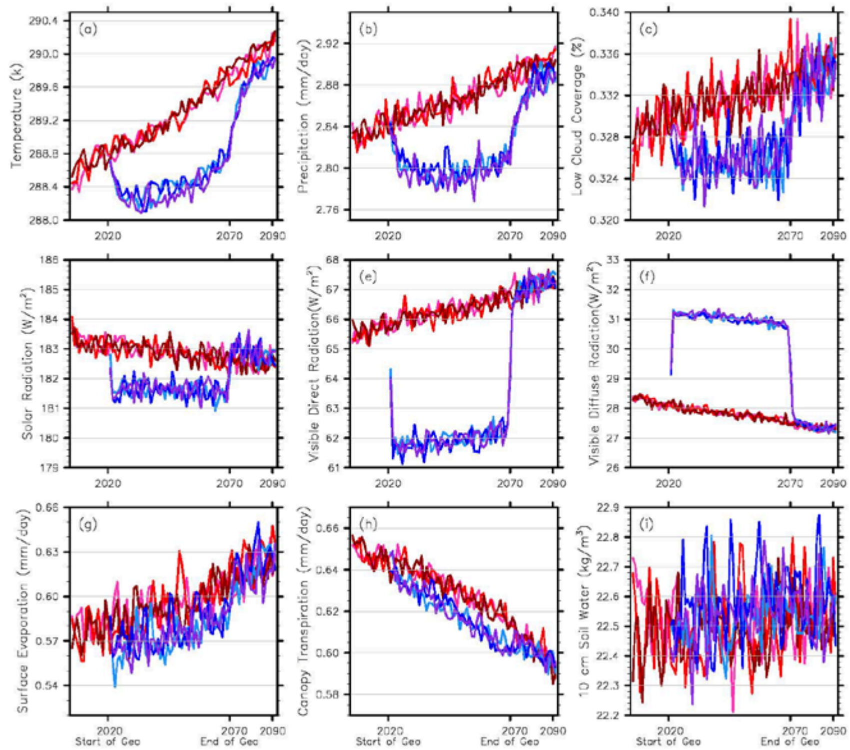
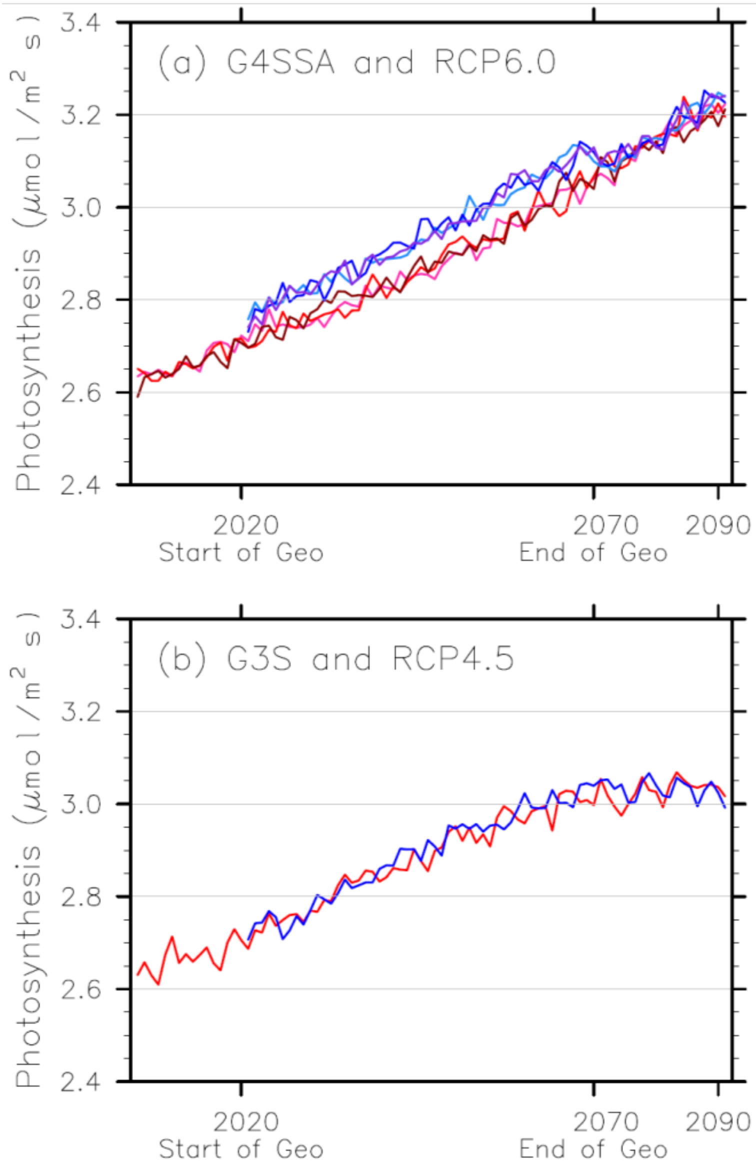



**Fig. 1.** Global~~-~~-average (a) temperature~~ (a),~~, (b) precipitation~~ (b), ~~, (c) low cloud coverage, and (d) surface downward solar radiation ~~(c) and low cloud coverage (d) ~~under G4SSA sulfate injection geoengineering ~~— G4SSA (red~~(blue lines) and under RCP6.0 (~~blue~~red lines). Land~~-~~-average (e) surface downward visible direct radiation~~ (e) and~~, (f) diffuse radiation~~ (f) ~~, (g) surface evaporation, (h) canopy transpiration and (i) vegetated land top 10 cm soil water (liquid water and ice) content under G4SSA (~~red~~blue lines) and RCP 6.0 (~~blue~~red lines). The three red lines and blue lines indicate three ensemble members of RCP6.0 and G4SSA~~ and RCP6.0~~. Sulfate injection starts at 2020 and ends at ~~2069~~2070.

644 

(a) G4SSA and RCP6.0
Photosynthesis (μmol/m² s)
3.4
3.2
3.0
2.8
2.6
2.4
2020
Start of Geo
2070
End of Geo
2090
(b) G3S and RCP4.5
Photosynthesis (μmol/m² s)
3.4
3.2
3.0
2.8
2.6
2.4
2020
Start of Geo
2070
End of Geo
2090

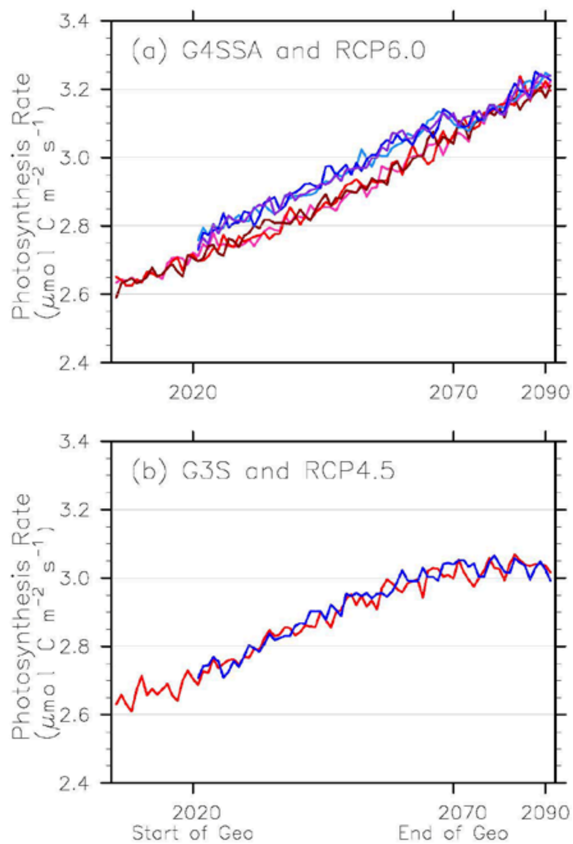
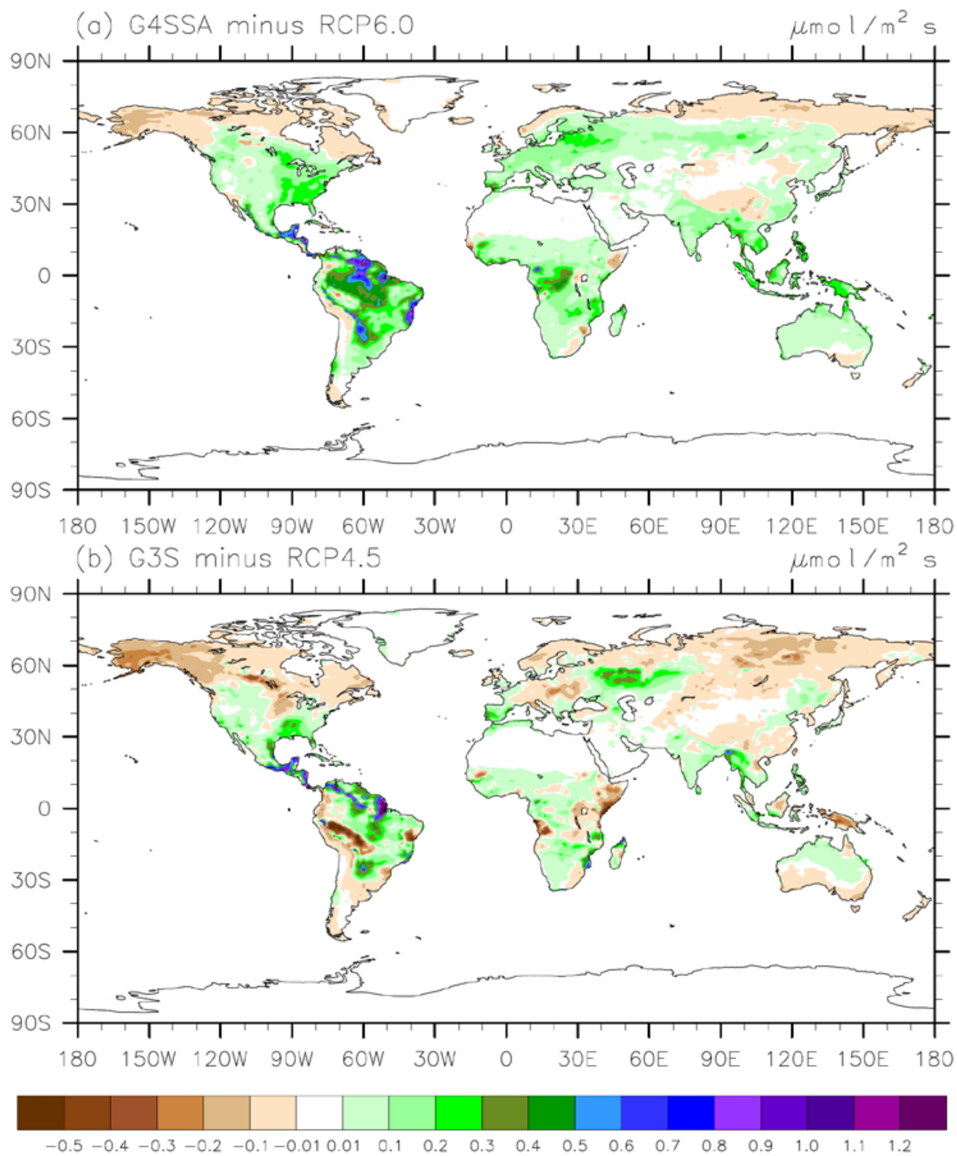



**Fig. 2.** Land average photosynthesis rate without explicit nutrient limitation (a) under sulfate injection geoengineering (G4SSA) (blue lines) and RCP6.0 (red lines) ~~(a)~~ and (b) under solar constant reduction geoengineering (G3S) (blue line) and RCP4.5 (red line~~) (b).~~

).



(a) G4SSA minus RCP6.0
μmol/m² s
90N
60N
30N
0
30S
60S
90S
180 150W 120W 90W 60W 30W 0 30E 60E 90E 120E 150E 180
(b) G3S minus RCP4.5
μmol/m² s
90N
60N
30N
0
30S
60S
90S
180 150W 120W 90W 60W 30W 0 30E 60E 90E 120E 150E 180
−0.5 −0.4 −0.3 −0.2 −0.1 −0.01 0.01 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2

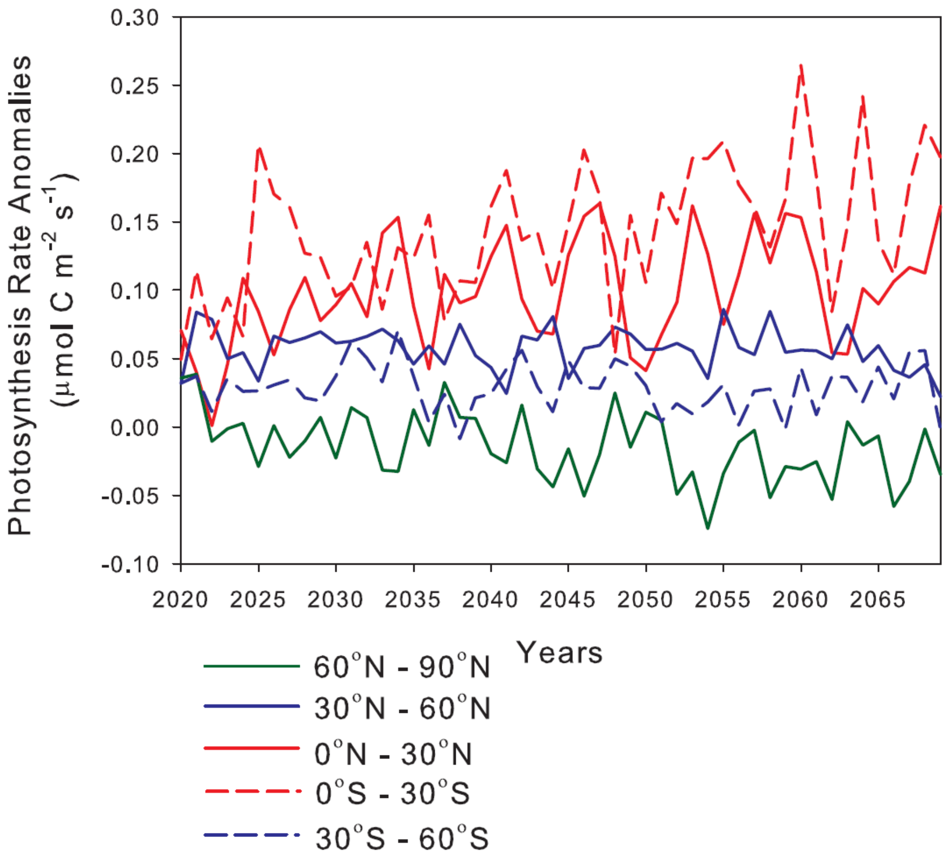



**Fig. 3.** Regional averaged annual photosynthesis rate difference of G4SSA minus RCP6.0 from 2020 to 2069 when sulfate injection geoengineering applied.

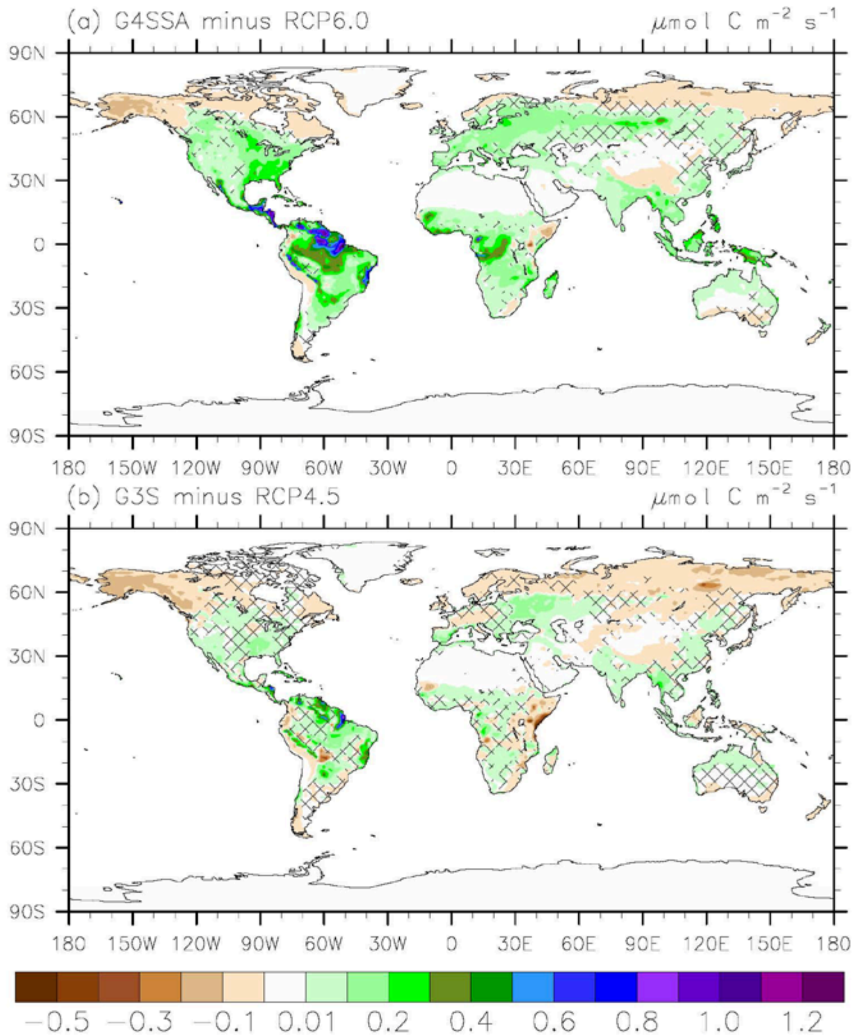



**Fig. 4.** (a) Photosynthesis rate differences between G4SSA and RCP6.0 during ~~the last 10~~ years ~~of sulfate injection (2060~~2030-2069~~).~~ (sulfate injection period, excluding the first 10 years). (b) Photosynthesis rate anomaly between G3S and RCP4.5 ~~during the last 10 years~~year 2030-2069 of solar ~~constant~~ reduction~~ (2060-2069).~~. Hatched regions are areas with $p > 0.05$ (where changes are not statistically significant based on a paired t-test).

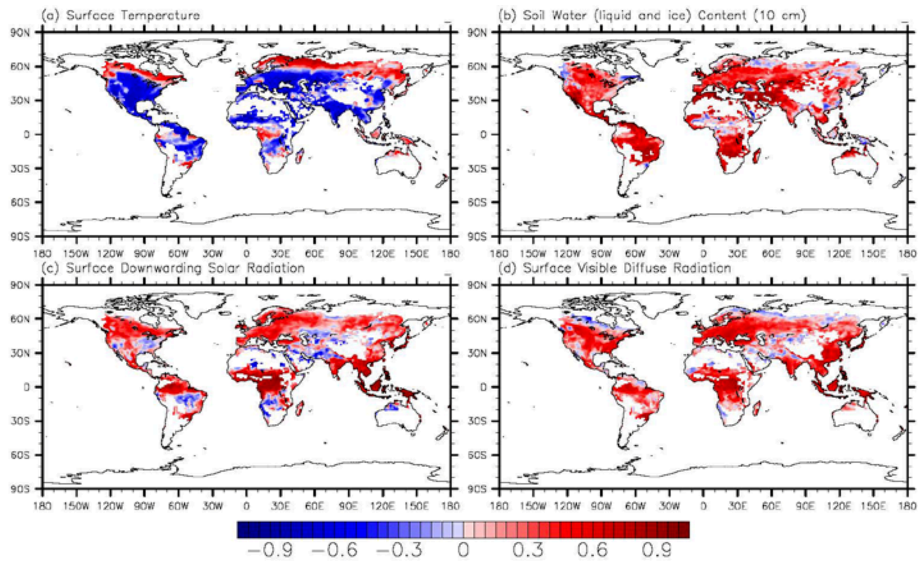



**Fig. 5.** Correlation coefficient of the monthly photosynthesis rate anomalies in JJA during year 2030-2069 (G4SSA minus RCP6.0, Fig. 3a) and (a) surface temperature anomalies, (b) top 10 cm soil water (including liquid water and ice) anomalies, (c) surface downward solar radiation anomalies, and (d) surface visible diffuse radiation anomalies during year 2030-2069.