We thank all referees for the helpful suggestions and comments which improved the manuscript. Our point by point answers to the comments are presented below. Referee comments are in bold and our replies in body text.

Referee #1 comments:

I recommend major revision or rejection of this paper for the reasons below. The fundamental premise of the paper is wrong, and the impacts of the different injection strategies on the resulting steady-state stratospheric aerosol cloud, including the size distribution of the particles, are not investigated. There are many missing details about the models used.

We strongly disagree with the referee that the premise of the paper would be somehow wrong, for the reasons outlined below. On the other hand, the referee's suggestion to include information on the particle size distribution is well taken and addressed below. We have also included more details about the models used.

The entire premise of this study is incorrect. The authors claim that overcooling of the Tropics is because of equatorial injection, but this does not account for two things. The first is the Brewer-Dobson circulation. If aerosols are created in the Tropics, they will be carried poleward by the stratospheric circulation, and the resulting steady-state aerosol distribution will be very smooth. The radiative forcing depends on the interaction of the aerosol cloud with insolation, not on where it was injected. And the latitudinal distribution of insolation varies much more than that of the aerosol cloud, and it is thin that determines the radiative forcing much more strongly.

The reason for the overcooling is two-fold, and this is now discussed more explicitly in the manuscript: Firstly, as the referee correctly points out, the tropics receive on average much more insolation than the mid and high latitudes. This would in itself lead to a maximum forcing in the equatorial region, assuming that the aerosol distribution were globally uniform. However (and secondly), localized or regional stratospheric injections do not lead to a globally uniform particle distribution, as has been shown by several earlier studies (English et al 2012, Niemeier et al 2011, Jones et al 2016). This also applies to the equatorial injections. While atmospheric circulation does transport some of the emitted sulfur away from the injection region, the particle burden still remains much higher close to the injection region than very far away from it. This is also clearly demonstrated in our Figures 4 a) and b) for injections in the tropics.

Therefore, the non-uniform radiative forcing pattern from equatorial injections is a result of both the uneven insolation pattern and the uneven aerosol distribution. While SRM cannot do anything about the former, it can have some control over the latter.

Thus, investigating the impacts of different injection strategies is a highly relevant question, as also highlighted by MacMartin et al. (2016) in their recent review article listing open research questions after a decade of investigation.

The second is atmospheric and oceanic circulation that spreads temperature anomalies out, and transports energy latitudinally. So the schemes they have modeled would not be expected to have much impact on the latitudinal distribution of aerosols.

Atmospheric and oceanic circulation does indeed spread temperature anomalies out, as was seen also in our study: the differences in radiative forcings between scenarios did not directly translate into differences in climate variables (e.g. temperature). This was also the motivation to use an Earth System Model in this study instead of concentrating only on the aerosol radiative effects. However, our results clearly show that in some areas different injection scenarios would lead to significant differences also in temperatures (Fig 8).

Overall, the results presented in the manuscript show that the radiative forcing and resulting climate effects are dependent on the injection scenario used. Our study shows that different injection strategies lead to a very different zonal forcing which is in contradiction to this referee claim. Hence, we disagree with the referee's claim that the premise of our study would be somehow incorrect.

On p. 3, line 27, you describe a scheme to allow time for the aerosols to form, but the gas does not stay in that location just waiting. It gets blown around by the stratospheric winds. You have to do a trajectory analysis to decide where to do the injection. And 4 and 6 months are much too long to wait. Most of the SO2 is converted to sulfate in less than a month.

We are a bit puzzled what the referee refers to here. The aerosol and gas phase chemistry schemes of this study are fully interactive with the ECHAM dynamical core, i.e. the aerosol particles and there precursor gases (both SO2 and its oxidation product H2SO4) are transported in the atmosphere according to ECHAM's advection scheme. The step-wise conversion of SO2 first to gas-phase H2SO4 and subsequently to particle-phase sulfate is calculated explicitly during the transport. Hence, the modelled SO_2 does not stay in any location "just waiting" nor does its conversion to sulfate take 4-6 months in our simulations.

We added to the text the lines:

"*Based on the oxidation time of SO_2, p4 and p6 scenarios are expected lead to a smaller radiative forcing than p2. However, these scenarios are simulated to study how the phase of the changing injection area alters the radiative forcing.* "

The paper is full of acronyms that are never defined. Every one has to be defined the first time it is used.

Some of the acronyms, like model names, are actually better known than the full model names and thus quite often only short names are used. However, we have now included also the full names in the manuscript.

(Max Planck Institute's Earth System Model) - added to page 2

MAECHAM6.1-HAM2.2-SALSA, The middle atmosphere configuration of the European Centre Hamburg Model coupled with Hamburg Aerosol Model including a Sectional Aerosol module for Large Scale Applications
- added to page 4.

Aerosol Comparisons between Observations and Models - added to page 5
Coupled Model Intercomparison Project - added to page 5
Aerosol Chemistry Climate Model Intercomparison Project - added to page 5

GCM changed to *General circulation model* - at page 15

I don't understand the procedure used for the simulations. If the aerosol clouds are produced with a version of the climate model that responds to the radiative forcing from the stratospheric aerosol cloud, then why not use this model for the actual simulations. As was done, the aerosol cloud is prescribed externally and the resulting changes in stratospheric circulation do not affect the aerosol cloud.

There are two main reasons for the chosen model strategy. First, the configuration of the MPI-ESM that we used in our simulations does not include a prognostic calculation of aerosol properties, as was stated in the manuscript on page 4.

The second reason for using precalculated aerosol properties in the ESM simulations is that modelling of aerosol microphysics is computationally heavy and for the purpose of this study the benefits are expected to be small. It is therefore feasible to simulate aerosol microphysics only for a relatively short period of time (5 years) and then use these defined aerosol fields as prescribed fields in longer climate simulations (3 x 80 years) with MPI-ESM.

It is true that the changes in the atmospheric circulation due forcings given by RCP45 scenario are not taken account in the aerosol simulations and may affect the transport of aerosol so that they would differ from those simulated by ECHAM-HAMMOZ. However, it has to be noted that many of the GeoMIP simulations (Tilmes et al 2015, Xia et al., 2016) use methods similar to those presented here.

We added following text to end of section 2.2

"In addition, modelling aerosol microphysics is computationally heavy. Thus it was feasible to simulate aerosol microphysics only for a relatively short period (few years) and use the ECHAM-HAMMOZ simulated aerosol fields as prescribed fields in the longer simulations in MPI-ESM. Simulations with ECHAM-HAMMOZ were carried out using a free running setup to include the dynamical feedback resulting from the additional heating due to absorption radiation by the injected aerosols. However, stratospheric circulation could also be altered by changes in the atmospheric GHG concentration (in our case following the RCP4.5 scenario) and its impacts on the tropospheric climate; however, these impacts were not taken into account when the aerosol fields were calculated in ECHAM-HAMMOZ."

How was ozone chemistry addressed? Did the aerosols affect ozone, and did the radiative forcing from ozone depletion affect the climate? Of course, these impacts will vary depending on what years were simulated and what the assumed ODP concentrations were.

Ozone chemistry is not included in our model configuration. The following text was added to section 2.2.1: "The *hydroxyl radical (OH) and ozone concentrations are accounted for through prescribed monthly mean fields. Thus, the effect of sulfur injections on the ozone layer is not simulated in our model*.".

What is missing in this paper is an analysis of the sulfate clouds simulated by the different injection schemes. What we need to see is the resulting mean distributions of aerosol amount and size distributions as a function of latitude and altitude. This is what is forcing the model, and how the different injection schemes affect these distributions is fundamental to the rest of the paper. For example, how do microphysics and transport interact with each other? When varying the latitude as a function of season, does the new SO2 encounter a pristine atmosphere, or are the residual aerosols still there? How does the time to create the aerosols vary for the different schemes? Part of the goal should be to produce smaller particles so as to get more radiative forcing for the

same S injection, which would be accomplished by creating new particles rather than making existing particles larger. Did this really happen? It is important to show this. And then, how does this affect the radiative forcing? Without these details, we cannot evaluate whether it makes a difference or not how the injections are done

The question of size distributions was raised by several referees, and hence we added two more figures (Fig. 3 and 6) to the manuscript as well as a new section 3.1.2 to discuss this topic. Figure 3 now shows the zonal mean effective radius in most of the studied scenarios for different seasons. Note that we use the effective radius to describe the aerosol size instead of showing the full size distribution. For example in English et al 2012 the aerosol size distribution was presented at the Equator. However, here the injection areas vary between different scenarios, and thus the objective evaluation of differences would be extremely complicated. With effective radii, the size distribution can be described by a single value and differences between regions and time can be evaluated more easily. The differences in the altitude where the particles are located are small and thus only zonal mean of effective radii is included.

In addition, Figure 6 shows the time dependent zonal mean of AOD at 533nm and together with the new figure 3, these figures answer most of the questions raised by the referee. The average time for the oxidation of SO2 can be seen in the table 1. Separating a contribution of microphysics from all the other factors which are affecting the radiative forcing is challenging. However, some qualitative evaluation can be done based on the AOD and figure 6.

In addition to the completely new section 3.1.2, the following pieces of text were added to section 3.1.1 :

"*Thus the particle effective radius is clearly smaller in scenario NHSH than in scenario NH, especially in the northern hemisphere (Fig 3).* "

"As a result, the number concentration of smaller particles increases. Figure 3 shows that the particle effective radius is on average smaller in scenario p2 than in EQ."

"*Figure 3 shows that in scenario p2w particles are consistently smaller than in p2. However, due to the atmospheric circulation, which transports particles mainly towards poles, in scenario p2w particles are removed more quickly from the atmosphere because sulfur is injected at a larger distance from the equator. Thus there is no difference in stratospheric sulfur burden between p2 and p2w scenarios (Table1).* "

How good is the aerosol model anyway? Does it produce the correct spatial and size distributions? It at least needs to be tested on the 1991 Pinatubo eruption.

The model version used in this study has been evaluated against observations of the Mt Pinatubo eruption as well as against other modelling studies, and has been shown to reproduce realistic aerosol loads and properties (Laakso et al 2016). Furthermore, previous studies with a simpler modal aerosol scheme (M7) have also shown that ECHAM-HAM is capable of capturing the main mechanisms and features of stratospheric aerosol evolution (Niemeier et al. 2009, Toohey et al 2011). Kokkola et al. (2009) showed that the sectional aerosol module (SALSA), which is used in this study, outperforms M7 in conditions where both high and low SO2 concentration conditions are present simultaneously.

We added text "*The model has been shown to simulate the stratospheric aerosol loads and radiative properties consistently compared to observations of the Mt Pinatubo 1991 eruption as well as other models (Laakso et al., 2016).*" to section 2.2.1.

You should use a different projection for figs. 6 and 8. The one used (Mercator?) makes the poles too large. At least use equal spacing with latitude.

Map projections of the figures have been changed from Miller to Robinson. The hatching now shows areas which are not statistically significant (instead of significant differences)

The paper is missing statistical significance testing in parts. For example, are the differences shown in Table 1 significantly different or not?

We added variances for the temperature and precipitation values and warming rates. All the results in Table 1 are statistically significant.

There are many missing articles (the, a) and the wrong use of prepositions (at, in, for, to). I tried to correct as many as I could, but a native speaker of English should go through and edit the entire paper. I know the article problem exists for native speakers of Russian, Chinese and Japanese. I guess there are no articles in Finnish either.

We thank the reviewer for these corrections. We have done our best to correct this issue. The final text will be polished off by the ACP copy-editing team.

In addition to comments presented here, supplement comments are taken into account in the revised manuscript.

Note to authors: Three things in your formatting annoy me, and it is not a good idea to annoy reviewers. First of all, use 12 pt font. Such a tiny font is hard to read. Second,

separate the references by using hanging indent or extra spacing between each reference. It is very hard to find specific references the way you have it formatted. Third, number the lines sequentially from the beginning and do not start over on each page. If I want to refer to the line number in my comments, I have to first also search for the page number each time. Why make me do that?

We hope that Copernicus Publications takes note of this comment. The manuscript was prepared using the Copernicus Publications Word template (docx) (http://www.atmospheric-chemistry-and-physics.net/Copernicus_Word_template.docx) as advised by the journal. It defines the font size, style of references and also numbering of lines.

References:

Jones, A. C., Haywood, J. M., and Jones, A.: Climatic impacts of stratospheric geoengineering with sulfate, black carbon and titania injection, Atmos. Chem. Phys., 16, 2843-2862, doi:10.5194/acp-16-2843-2016, 2016.

Kokkola, H., Hommel, R., Kazil, J., Niemeier, U., Partanen, A.-I., Feichter, J., and Timmreck, C.: Aerosol microphysics modules in the framework of the ECHAM5 climate model intercomparison under stratospheric conditions, Geosci. Model Dev., 2, 97-112, doi:10.5194/gmd-2-97-2009, 2009.

Laakso, A., Kokkola, H., Partanen, A.-I., Niemeier, U., Timmreck, C., Lehtinen, K. E. J., Hakkarainen, H., and Korhonen, H.: Radiative and climate impacts of a large volcanic eruption during stratospheric sulfur geoengineering, Atmos. Chem. Phys., 16, 305-323, doi:10.5194/acp-16-305-2016, 2016.

MacMartin D. G., B. Kravitz, J. C. S. Long, and P. J. Rasch, Geoengineering with stratospheric aerosols: What do we not know after a decade of research?, Earth’s Future, 4, 543–548, doi:10.1002/2016EF000418, 2016.

Pierce, J. R.; Weisenstein, D. K.; Heckendorn, P.; Peter, T.; Keith, D. W.: Efficient formation of stratospheric aerosol for climate engineering by emission of condensable vapor from aircraft, Geophysical Research Letters, 37, doi:10.1029/2010GL043975, 2010.

Tilmes, S., Mills, M. J., Niemeier, U., Schmidt, H., Robock, A., Kravitz, B., Lamarque, J.-F., Pitari, G., and English, J. M.: 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, 2015.

Toohey, M., Krüger, K., Niemeier, U., and Timmreck, C.: The influence of eruption season on the global aerosol evolution and radiative impact of tropical volcanic eruptions, Atmos. Chem. Phys., 11, 12351–12367, doi:10.5194/acp-11-12351-2011, 2011.

Xia, L., Robock, A., Tilmes, S., and Neely III, R. R.: Stratospheric sulfate geoengineering could enhance the terrestrial photosynthesis rate, Atmos. Chem. Phys., 16, 1479-1489, doi:10.5194/acp-16-1479-2016, 2016.

Referee #2 comments:

The broad objective of this paper is exactly the type of research that geoengineering needs. However, there are a number of clarifications needed. Furthermore, the primary motivation for the specific seasonally-dependent scenarios considered is based on tracking the latitude at which the insolation is strongest, but the actual situation is somewhat more complicated and not as well described in the paper as it could be. Because of the stratospheric circulation, the peak aerosol concentrations will not occur at the latitude of injection (other than for the equatorial case). Thus, if the only thing you cared about was being "efficient" in the sense of trying to best align the peak aerosol concentration with the peak of insolation, you'd have to do some complicated estimation of where to inject as a function of time of year, taking account of the seasonally varying Brewer-Dobson Circulation. So what you picked is a reasonable first guess just to see whether the seasonal-variation idea has any merit at all, but should simply be described as an initial step towards coming up with better strategies, acknowledging that much more work would be needed to understand the options. Figure 4a,b should be given somewhat more prominence in the discussion, that is, the aerosols are widely dispersed relative to the insolation even with the seasonal strategies.

We agree with this comment, and have added the following text in the revised manuscript: *"This study should be taken as a first step in evaluating optimal injection strategies in terms of geographically more uniform aerosol fields/radiative forcing/climate impacts without losing the effectiveness of geoengineering compared to continuous equatorial injections. In order to fully optimize the injection strategy, one should try to also account for the effect of stratospheric circulation on aerosol transport, together with existing planetary reflectivity and a detailed analysis of aerosol microphysics. These aspects are out of the scope of this study. "*

We also added a new section (3.1.2) to the manuscript which helps to highlight this issue. New figure 6 shows the zonal mean aerosol optical depth at different times of the year together with the injection area and latitudes with the strongest solar intensity. In addition, we added figure 6f which shows the seasonal atmospheric circulation at the height level of the sulfur field. This section and the figure provide more information about why the seasonally changed injection area leads to a slightly larger global mean radiative forcing and a larger midlatitude forcing than the equatorial injection scenario. It also shows where and when the sulfur field was not optimally located and thus helps in estimating the effects of sulfur injection strategies which are aiming for either a maximum global mean radiative forcing response or an increasing radiative effect in the midlatitudes .

Also, I'm unclear whether the objective is to be more efficient by aligning aerosols with peak of solar radiation, or whether the objective is to do a better job of compensating for the spatial pattern of warming due to CO2 (as described in a few papers using patterns of solar reduction). These are different objectives, and the "right" strategy for each will be different (this is why I raise questions with your use of terms like "optimal" and "efficacy" below). You mix these objectives in your motivation; the introduction talks more about the latter objective, but the choice of seasonally varying injection is motivated by the former. In principle its ok to say that both of these are issues with the usual equatorial injection and that you're exploring how alternate strategies affect things, but you should be clear that you simply picked something that was somewhat physically motivated to see how it would affect the climate, and that there's no attempt to optimally solve either of these two problems.

Seasonally varying injections are motivated both by better compensating for the spatial forcing pattern due to greenhouse gases while simultaneously trying to maximize the cooling effect at the time when solar radiation is at its peak over the subtropics. However as was replied in the previous comment, the aim of the study is not to fully optimize the global radiative forcing or optimal temperature pattern. We will clarify this in the revised manuscript.

Our aim of the study is clarified in the introduction in the following chapter:
"In this study, we have investigated injection scenarios that aim to produce a geographically more even radiative forcing pattern than equatorial sulfur injections, while still maintaining a high global mean forcing. Such scenarios are sought via seasonally varying injection areas in which the target injection area follows the maximum solar intensity with different time lags. These scenarios are compared to more commonly used strategies with fixed injection areas. This study should be taken as a first step in evaluating optimal injection strategies in terms of geographically more uniform aerosol fields/radiative forcing/climate impacts without losing the effectiveness of geoengineering compared to continuous equatorial injections. In order to fully optimize the injection strategy, one should try to account for also the effect of stratospheric circulation on aerosol transport, together with existing planetary reflectivity and a detailed analysis of aerosol microphysics. These aspects are out of the scope of this study."

Text is also modified in relevant parts and we avoid using word "optimal scenarios" when talking about scenarios studied here.

1. L11-13, the actual issues here are a bit more subtle. Equatorial injection is often picked because the aerosols will disperse globally, so to know that the radiative forcing from equatorial injection is highest at the equator, one needs to also know that the aerosol concentrations from equatorial injection are at best uniformly distributed spatially (and in fact they'll be concentrated equatorially, as shown in your Figure 4). Not sure how to convey this concisely, but the second sentence isn't quite right.

These lines now read:

"In geoengineering studies, these injections are commonly targeted to the Equator, where the yearly mean intensity of the solar radiation is highest and from where the aerosols disperse globally due to the Brewer Dobson Circulation. However, compensating the greenhouse gas induced zonal warming by reducing the solar radiation would require a relatively larger radiative forcing to the mid and high latitudes and a lower forcing to the low latitudes than what is achieved by continuous equatorial injections."

2. L12, "optimal" in what sense?

We now avoid using the word 'optimal'. See also reply to the earlier referee comment.

3. L15, what do you mean by "efficacy"?

Efficacy was changed to "*the mean radiative forcing of stratospheric sulfur* "

4. L23, I would be careful using the word "significant" unless you mean it in the narrow sense of "statistically significant" (which will of course depend on the magnitude of forcing). More to the point, the last sentence of the abstract does seem like a rather important result, and quite "significant" in the non-narrow sense of the word.

"Very significant" changed to "*as large*"

5. L31, not sure what "efficiently" means in this context. Ditto page 2 line 2.

Word "efficiently" was removed from the sentence. The second sentence in Page 2 was changed to: *"Because of the stability of the stratosphere and the lack of efficient removal mechanisms which are prevalent in the troposphere, the stratospheric lifetime of..."*

6. P2, L17, I've cited that paper; I think the year is 2013 not 2012. (The same authors

also have a more recent study from 2016 in ESD that would be appropriate to also cite.)

This is correct, and the year was changed to 2013. We also added Kravitz et al. 2016 to the reference list and cited it here and section 3.1.2

7. P2, L24, "this kind" means which kind? Specifically studies looking at how injection at different latitudes affects the climate differently? (Didn't Tilmes do a study on that in the last few years too?)

"This study" was rewritten as follows: "*where other than equatorial injection was studied by global aerosol-climate* model"

Tilmes has done several good geoengineering studies, but none of those (to our knowledge) study injections to various latitudes.

8. P2, L30, what do you mean by "target area"?

"Target" changed to *"the injection"*

9. P2, last two sentences, I know why you use two models, but you might want to say that explicitly. (And be explicit about what you're giving up by not having a single model that includes everything.)

Text "*(MPI-ESM) does not include a prognostic calculation of aerosol processes in its current configuration*" was added to the end of the line

In section 2.2 Model description now reads:

"The two-step approach was selected because the currently available middle atmosphere configuration of MPI-ESM does not include a prognostic calculation of aerosol properties. In addition, modelling aerosol microphysics is computationally heavy. Thus it was feasible to simulate aerosol microphysics only for a relatively short period (few years) and use the ECHAM-HAMMOZ simulated aerosol fields as prescribed fields in the longer simulations in MPI-ESM. Simulations with ECHAM-HAMMOZ were carried out using a free running setup to include the dynamical feedback resulting from the additional heating due to absorption radiation by the injected aerosols. However, stratospheric circulation could also be altered by changes in the atmospheric GHG concentration (in our case following the RCP4.5 scenario) and its impacts on the tropospheric climate; however, these impacts were not taken into account when the aerosol fields were calculated in ECHAM-HAMMOZ. . ."

10. P3, L4, note that keeping the height constant while varying latitude might matter because the tropopause height varies with latitude, at higher latitudes you're putting

material higher into the upper branch of the circulation.

This is true and will definitely have an impact if the injection area varies over a wider area and reaches higher latitudes. Most of the scenarios studied here included injection between 30 N and 30 S latitudes, where the tropopause height varies only a little. However in the p2w scenario, it might have some effect. We will mention this in the revised manuscript.

"*In addition, the tropopause height varies with latitude and when injecting sulfur to higher latitudes in p2w scenario, some of the sulfur is injected into the upper branch of the stratospheric circulation*."

11. Section 2.2.1, I haven't read all of the references, but is there any validation against, for example Pinatubo observations, to suggest that the aerosol processes are correctly captured? Might want to mention that explicitly. Did aerosol simulations involved stratospheric chemistry also? (Interactions with ozone concentrations could matter.) How does your aerosol spatial distribution and amplitude compare with previous simulations for the equatorial case?

Our model has been evaluated against the observations of the Mt Pinatubo eruption in Laakso et al 2016.

We added the following text "*The model has been shown to simulate the stratospheric aerosol loads and radiative properties consistently compared to the observations of Mt Pinatubo eruption as well as other models (Laakso et al., 2016).*" to section 2.2.1.

Our simulations used prescribed ozone fields, and therefore the injected aerosol did not impact the ozone concentrations. This is now explicitly stated in the manuscript.

"The hydroxyl radical (OH) and ozone concentrations are accounted for through prescribed monthly mean fields. Thus, the effect of sulfur injections on the ozone layer is not simulated in our model"

We added the following lines to the manuscript to point out that our results are consistent with earlier studies:

"However, outside the tropics the forcing declines fast (EQ)) as seen also in the case of equatorial injection in Niemeier et al. (2011)."

*"In scenario **EQ**, sulfate is concentrated near the injection area in Equator and near the 50° N and 50° S latitudes as shown in earlier studies (English et al., 2012; Jones et al., 2016; Niemeier et al., 2011)"*

"In the case of equatorial injections, AOD is clearly larger close to the Equator and in high latitudes than in mid latitudes. This is consistent with earlier studies (English et al., 2012; Jones et al., 2016; Niemeier et al., 2011)."

12. Page 6, what do you mean by saying they were based on GeoMIP G4?

"Were based" changed to "*our setup of scenarios was similar to* ".

Here we mean that the baseline scenario (RCP45) as well as the start and end years of SRM were chosen based on GeoMIP G4. In addition, SRM was started (and suspended) at full force similar to G4. However the amount of injected sulfur was double compared to GeoMIP G4.

13. Section 3.1 has lots of good insights and observations, but one thing missing is any discussion of aerosol size distribution – is it the same for the different injection scenarios? This could have a big impact on the radiative forcing.

We added two more figures to the manuscript and a new section 3.1.2 with discussion on this topic. Figure 3 shows the zonal mean effective radius in the most of the studied scenarios in different seasons. Figure 6 shows the time dependent zonal mean of AOD for 533nm.

In addition to the completely new section 3.1.2, where we discuss resulted zonal AOD at the different time of the year, the following texts were added to section 3.1.1 :

"*Thus the particle effective radius is clearly smaller in scenario NHSH than in scenario NH, especially in the northern hemisphere (Fig 3).* "

"As a result, the amount of smaller particles increases. Figure 3 shows that the particle effective radius is on average smaller in scenario p2 than in EQ."

"*Figure 3 shows that in scenario p2w particles are consistently smaller than in p2. However, due to the atmospheric circulation, in p2w particles are removed more quickly from the atmosphere because sulfur is injected at a larger distance from the equator. Thus there is no difference in stratospheric sulfur burden between p2 and p2w scenarios (Table1).* "

14. P10 (P9)**, L17&18, what is the standard error in the temperature changes due to natural variability? (Are the differences between scenarios statistically significant?) Ditto for the rates of warming on L28, and for precipitation changes on next page.**

Lines 17-18 now read: *"Compared to RCP45, the global mean temperature is -1.27 (± 0.18), -1.13 (± 0.13), -1.21(± 0.19), -1.34 (± 0.14) and -1.29 (± 0.15) K cooler in scenarios EQ, NH, NHSH, p2, and p2w (not shown in the figure 5) between 2060-2070"*

L28:

”Between the years from 2030 to 2070 the warming rate is 1.95 (± 0.68) K / 100 yr in RCP45 scenario, but in scenario EQ the warming rate is reduced to 1.25 (± 0.55) K / 100 yr”

For precipitation changes:

“Compared to the years 2010 - 2020 the global mean precipitation has been changed by +0.044 (± 0.013), -0.051 (± 0.013), -0.036 (± 0.013), -0.043 (± 0.015), and -0.054 (± 0.011) and -0.05 (± 0.014) mm/day in RCP45, EQ, NH, NHSH, and p2 and p2w”

15. P10, L32, I’m not sure what you mean...I assume you mean that nonlinearities in climate feedbacks could change the rate of warming (since if the feedbacks were linear, there would be no effect beyond the dynamic one you already mentioned regarding ocean equilibration timescales). It is certainly true that the ice albedo feedback will have some nonlinearity in it, but I would expect that to behave with opposite sign – that is, in the warmer world, there is less sea ice left to be melted, less change in sea ice per unit increase in warming, and thus that positive feedback that amplifies warming would start to saturate. Re first line of page 10, why do you say that ice area is “clearly higher”? What figure shows this? It isn’t obvious to me why it should be higher (aside from global temperatures being slightly lower, but since I know that at least with EQ you overcool tropics more than the poles, the poles are probably warmer in 2070 compared to 2010, so ice area could easily be lower, not higher).

The Arctic temperature did not change linearly with global mean temperature. We have included some numerical values of the Arctic temperature and sea ice extent to the manuscript as well as some discussion concerning cooling in the Arctic.

The text now reads:

“Over the latitudes higher than 70 N, the mean temperature is on the average still 0.6 (+- 0.5) K cooler in SRM scenarios during the years 2060-2070 compared to the years 2010-2020 even though the global mean temperature was roughly compensated. Simultaneously, the sea ice cover is 7 % larger. The cooling of the Arctic has not seen in previous studies in which solar radiation management has been investigated (Schmidt et al., 2012; Niemeier et al., 2013; Jones et al., 2016). The reason behind our simulation result is not totally clear. Section 3.1.2 showed that the AOD was relatively large at high latitudes which would have an impact on the radiation in summer months. On the other hand, the total received the energy in the arctic area depends also on energy transferred by the oceans and the atmosphere. Figures 6 a and b show that there is warming in the subpolar North Atlantic. In this area, the sea surface temperature (SST) increases by 2-4 K in scenario EQ. On the other hand, there is a 1-2 K cooling in the SSTs in the Arctic Ocean. This indicates that there are changes in the ocean circulation.

Since these patterns are seen also in scenario RCP45, they likely originate from in our reference years 2010-2020. The pattern of SST regions is similar to what is seen in CMIP5 RCP scenarios, where there was an amplified SST increase in the Nordic seas while in sub-Polar North Atlantic the warming rate was subdued compared to the global average trend (Sgubin et al. 2017). However, investigating the changes in the ocean circulation is out of scope of this study. Overall, different warming rates in SRM and RCP45 scenarios might also be affected by the asymmetric climate system response to the increase or decrease of forcings (Schaller et al., 2014). It has been shown that there is a slow decrease in the temperature still decades after a decrease in shortwave radiation (Schaller et al., 2014). Kashimura et al. (2017) studied the GeoMIP G4 scenario in several models. Their study showed that the difference in global mean temperature between the RCP 4.5 and SRM scenarios increased for 10-25 years after solar radiation management was started. Here the amount of injected sulfur was twice as large as in G4 and Kashimura et al. (2017) which can explain why here the temperature difference increased until SRM was suspended.”

16. P11, L17-19, slightly confusingly written (being generous; it is unequivocally false as written). A uniform reduction in SW does not lead to warming in high latitudes, indeed in every GeoMIP model, the high latitudes cool *more* than low latitudes in response to solar reduction, this is due to the spatial pattern of climate feedbacks. However, the polar amplification is even stronger for CO2 warming, so that the net effect is that the solar reduction overcools the tropics and undercools high latitudes relative to CO2.

These sentences now read:

“If the global mean temperature change due to the increased GHG concentration is compensated by a relatively uniform reduction in the SW radiation (reduction in the solar constant), it has been shown to lead to warming in the high latitudes and cooling in the low latitudes compared to the temperature before the increase in GHG concentration and SRM (Kravitz et al., 2013c; Schmidt et al., 2012).”

17. And following from that, it is quite surprising that your equatorial case cools the Arctic more than the mid-latitudes; if I look at GeoMIP G1, there is not a single model that does that, and I would expect equatorial SO2 injection to have an even stronger ropical cooling relative to arctic cooling than G1. The sentences on P11, L20,21, does not really explain why this model should behave differently from the models in G1 (including MPI). Regarding the one ensemble member that is significantly warmer in 2010-2020 in this region, you can look at what pattern you get if you exclude that member, and then state whether or not that explains the result, rather than simply commenting that it might explain the result; this isn’t hard to test.

Even though the mentioned temperature patterns of the one ensemble member differ from those of the other two, excluding this one member did not lead to a different sign in arctic area. This issue is now discussed more in section 3.2.1 as was replied to comment 15.

Sentences on P11 are now rewritten as:
"However there is also cooling at the Arctic (Fig 6b) which was discussed in section 3.2.1. Overall the size of the area of this arctic cooling region is small compared to the regions in the midlatitudes which have warmed after the year 2020."

18. Fig 6e is repeated twice and 6f is missing.
Figure 8 (originally 6) is now fixed. In addition, the map projections were changed so that the projections do not stretch the latitudes and the hatching shows areas which are not statistically significant (instead of significant differences)

**19. So NH case has slightly lower SO4 burden, slightly lower globally averaged radia-
tive forcing, but preferentially loaded in the North. Not surprising that it is more effective at cooling the Arctic than EQ in the summer, nor that EQ is more effective in boreal winter, but the idea that it is actually LESS effective at cooling high northern latitudes than equatorial injection when averaged over the year does seem remarkable; this is also inconsistent with other model results that I have been shown but that have not yet been published.**

From Fig 7, the NH does indeed cool the Arctic more in the boreal summer than EQ does, as expected, and supports the idea that if the only thing you cared about was Arctic ice cover (in September), then the NH case ought to be better, in contrast to your unsupported claim. If you are going to make a claim, even for just this model, that EQ prevents melting of arctic ice better than NH, you should show a plot of it, because Fig 7 doesn't actually support that claim and looks contradictory.

Unfortunately our original text was misleading. In the polar region north of Eurasia, the ice cover is larger in the case of equatorial injections, also in the boreal summer months. However, if we take into account the total sea ice cover in the northern hemisphere (also outside the Arctic Circle) there is not a large difference in the yearly total ice cover between the scenarios. This is now discussed in more detail in the manuscript and we also added one figure (9) related to the issue.

Text in the manuscript reads now:
"If the stratospheric sulfur injections were concentrated to the Northern Hemisphere (NH), it would lead to a significant cooling in the northern midlatitudes compared to the injections to the Equator (EQ). However, the polar region north of Eurasia in NH is not cooler compared to the scenario EQ. The Arctic area is warmer than in EQ especially in the boreal winter, when the cooling effect of the particles from the NH injections is weak (Fig 7a). On the other hand, in the EQ scenario

the mean global climate will be cooler, which can affect the Arctic temperatures through oceanic and atmospheric circulation. Figure 10 shows the difference in the Arctic sea ice cover between the EQ and NH scenarios in the boreal summer and winter. Scenario NH leads to a larger ice cover north of the North America and East Siberian Sea in the boreal summer and over the Atlantic and Pacific in the boreal winter. However over the Barents and Kara seas there is more sea ice cover in the EQ scenario. This area is affected by the warm Gulf Stream and the Norwegian current. In the EQ scenario, the Atlantic SST is cooler than in scenario NH and sea ice cover north of Eurasia is larger in scenario EQ also in the boreal summer months, when sulfate from NH scenario reflects radiation most efficiently. Thus, based on these results, the injections only to the Northern Hemisphere do not increase the yearly arctic sea ice cover compared to the injections to Equator. A more detailed analysis would be required to generalize these findings; however, it is out of the scope of this study. Furthermore, it would be beneficial to repeat these scenarios also with other climate models to see whether the simulated response is robust across models."

20. P12 L19, chapter should be section

"Chapter" changed to "section"

21. P13, L19, I don't recall seeing any optimization in this paper what do you mean by optimize?

This sentence now reads: *"We estimated how different emission areas of stratospheric sulfur could be used to prevent the overcooling of the tropics and undercooling of the midlatitudes and the Arctic without a decrease in the global mean radiative forcing of the stratospheric sulfur injections."*

22. Bottom of P13, can you be more consistent? You use one set of metrics to compare EQ and p2w, and a different set of metrics to compare p2

This now reads:

"Thus the radiative forcing was relatively larger in the summer hemisphere (17% in the Northern and 14% in the Southern) and relatively weaker in the winter hemispheres (14% in the Northern and 16% in the Southern) compared to EQ."

23. P14, L6, what do you mean be efficiency here?

This is now rewritten as: *"Our simulations indicate that the global mean radiative forcing of the aerosol was not significantly increased in any of our simulations compared to the equatorial injection scenario EQ."*

We also added:

"However, the scenarios studied here are only a first step towards more optimal injection scenarios. A full optimization would require a more detailed analysis of incoming and reflected solar radiation, atmospheric circulation and how it is affected by sulfur fields as well as aerosol microphysics and chemistry. Overall, however, results of this study already show the potential of time-varying injection scenarios."

24. P14, L11-13, meant to comment on this earlier, but was this effect seen in previous G4 simulations? If it was, not really something to highlight in conclusions here, since it is rather tangential to the purpose of this paper. If it wasn't, why not? (Obviously wouldn't show up in models without a real ocean, but at least some of those did?)

This was not seen in G4 simulations (at least to our knowledge) and thus it was mentioned in the conclusions. In Kashimura et al 2017 a similar behaviour as here is seen, but only for few decades. However, here the amount of injected sulfur was twice as large as in G4.

This is now discussed in section 3.2.1:

"Kashimura et al. (2017) studied the G4 scenario with several models. Their study showed that the difference in the global mean temperature between RCP 4.5 and SRM scenarios increased for 10-25 years after solar radiation management was started. In the current study the amount of injected sulfur was twice as large as in G4 and Kashimura et al. (2017), which can explain why here the temperature difference increased until SRM was suspended."

However as this was not main interest of this study, we removed these lines from the conclusions.

25. P14, L20, just to reiterate, you haven't shown this. (It may be true in your simulations, but you haven't shown any simulation results to back that up.

These lines were removed. Making final conclusions on this would require a more detailed study on this topic and simulations with other models.

Referee #3 comments:

General Comments:

This study aims to investigate how different sulfate injection strategies (from different locations) would affect the changes of radiative forcing, temperature and precipitation using ECHAM-HAMMOZ and MPI-ESM. This type of study is a good fit for ACP GeoMIP special issue. However, more clarifications and analysis are needed. More detailed model description and the experiment design are needed. It is not clear whether the model has chemistry involved, how the experiments are set up, e.g. whether the injection is continuously over the year or just couple individual injections in different seasons? What is the amount for each individual injection?

Based on the referee suggestions, we have clarified our model description and the experiment design. We have also included more analysis on the aerosol microphysical processes in the simulations with ECHAM-HAMMOZ (see also replies to referees #1 and #2).

The injections were done continuously over the year. While this was mentioned in the abstract and conclusions, it was missing from the model description. Section 2.1.1 now reads:

"Eight zonally different sulfur injection strategies were simulated. In all of these scenarios, 5 Tg(S)/yr of gaseous SO2 was injected continuously over the year to the stratosphere at the height of 20 km and to a 20 degree wide latitude band specified below (2 bands in one of the simulated scenarios). "

In section 2.1.2 we added:

"The model contains an explicit description of sulfur dioxide oxidation chemistry (Feichter et al 1996. The hydroxyl radical (OH) and ozone concentrations are accounted for through prescribed monthly mean fields. Thus, the effect of sulfur injections on the ozone layer is not simulated in our model.". *"*

The set-up of this experiment (separating the aerosol model and the climate circulation model) limits the soundness of the conclusion. The offline calculation of radiative properties of stratospheric aerosol will prohibit the feedback between the stratospheric circulation change (e.g. Brewer Dobson Circulation) and the aerosol transport. There should more discussion on this.

The dynamical feedback of the injected particles to the stratospheric circulation was taken account in our simulations with ECHAM-HAMMOZ. However the changes in the atmospheric circulation due forcings given by RCP45 scenario are not taken account in the aerosol simulations and may affect the transport of aerosol so that they would differ from those simulated by ECHAM-HAMMOZ.

To clarify to reasons to use of two models and possible disadvantages we added following text to section 2.2: *"The two-step approach was selected because the currently available middle atmosphere configuration of MPI-ESM does not include a prognostic calculation of aerosol properties. In addition, modelling aerosol microphysics is computationally heavy. Thus it was feasible to simulate aerosol microphysics only relatively short period (few years) and use the ECHAM-HAMMOZ simulated aerosol fields as prescribed fields in the longer simulations in MPI-ESM. Simulations with ECHAM-HAMMOZ were carried out using a free running setup to include the dynamical feedback resulting from the additional heating due to absorption radiation by the injected aerosols. However, stratospheric circulation could also be altered by changes in atmospheric GHG concentration (in our case following the RCP4.5 scenario) and its impacts on tropospheric climate; however, these impacts were not taken account when the aerosol fields were calculated in ECHAM-HAMMOZ."*

More analysis are needed on the aerosol microphysics (e.g. the aerosol size distribution change, how long it takes for SO2 changing to H2SO4?), aerosol chemistry (e.g. OH map in different seasons?   whether the model includes ozone chemistry in the stratosphere?), and the trajectory (e.g. stream function of the stratospheric circulation to indicate how sulfate aerosol is transported under different injection strategies? The transport of SO2 and H2SO4?

We added two new figures in the manuscript and the topic is now discussed in a new section 3.1.2. Figure 3 shows the zonal mean effective radius and Figure 6 shows the time dependent zonal mean of AOD for 533nm and stratospheric circulation at the height of the sulfate field. Section 3.1.1 was also amended with couple of clarifying sentences. See replies to Referee #1 and #2 for details. The ozone chemistry is now mentioned in section 2.1.2.

Specific comments:

Page 1:

-Lines 11-12: "In geoengineering studies these injections are ... the solar radiation is

highest". This sentence sounds like the only reason of tropical injection is because of the highest solar radiation. But actually, there is another important reason: the strong upwelling in the tropics brings sulfate aerosols polar-ward through Brewer Dobson Circulation.

-Lines 12-13: "However, it may not be the most optimal

::

the meridional temperature gradient". What is 'optimal'? Why do we need to keep the meridional temperature gradient as the same as before geoengineering?

We agree that 'optimal' is a wrong term in the context of our study design, and hence we have reformulated the text accordingly.

These lines pointed out by the referee now read:

"In geoengineering studies, these injections are commonly targeted to the Equator, where the yearly mean intensity of the solar radiation is highest and from where the aerosols disperse globally due to the Brewer Dobson Circulation. However, compensating the greenhouse gas induced zonal warming by reducing the solar radiation would require a relatively larger radiative forcing to the mid and high latitudes and a lower forcing to the low latitudes than what is achieved by continuous equatorial injections"

-Line 20: should it be "the reduction of shortwave radiative forcing decreased by 27%
..and increased by 15%"? As shown in Figure 3.
-Lines 21-23: "Compared to the continuous...hemispheres respectively". This sentence is confusing. In summer months, radiative forcing increase in both hemispheres when comparing p2 to EQ? But figure 4 shows different results.

We acknowledge that it is challenging to discuss changes in negative forcings in a way that is both easy for the reader to follow and mathematically accurate. While the referee's suggestion is the latter, we feel it would not necessary be the former.

In a hope of clarifying this issue, we have added to the manuscript the following explanation:

"In this section we investigate the radiative forcing resulting from the aerosol microphysical simulations of different injection scenarios. When talking about the changes in the aerosol short-wave (SW) radiative forcings (which are typically negative), we have applied a commonly used and intuitively clear convention: decrease in the forcing refers to the numerical value of

the forcing getting closer to zero (i.e. in strictly mathematical sense increasing); similarly, an increase in forcing refers to the numerical value getting more negative."

Line 23: How to qualify "significant changes in temperatures"?

This line now reads: *"However, these forcings do not translate into as large changes in temperatures"*

-Lines 23-25: Please rewrite "Based on ESM scenarios studies here." It is not clear which scenarios are compared here

Sentence was rewritten:

" However, these changes in forcing would lead only to 0.05 K warmer winters and 0.05 K cooler summers in the Northern Hemisphere which is roughly 3 % of the cooling resulting from solar radiation management scenarios studied here"

Page 3:

-Lines 7-16: Are injections in EQ, NH, NHSH once a year? If so, when?

First line was rewritten:

"In three of the studied injection scenarios, the area of continuous sulfur injections remained fixed throughout the year. "

-Lines 18-24: Are injections in p0, p2, p4, p6 and p2w continuous? If so, what is the flux? If not, what is the amount for one injection? The location is changing in what time step? Monthly or seasonally? Figure 2 shows very smooth change of the locations.

Section 2.1 now explains that the injections were continuous in all of the studied scenarios. The location was changed monthly and this is now mentioned in second line of section 2.1.2

"In four of these scenarios, the 20-degree wide sulfur injection area changed monthly between the latitudes from 30° S to 30° N in different phases."

Page 5:

-Line 8: Add citation for HAM. And add couple sentence to evaluate

Lines in section 2.1.1 now read:

"The radiative properties of aerosol fields resulting from the 5 Tg(S)/yr stratospheric sulfur injections were defined by using the global aerosol-climate model MAECHAM6.1-HAM2.2-SALSA (Zhang et al., 2012, The European Centre Hamburg Model coupled with Hamburg Aerosol Model including a Sectional Aerosol module for Large Scale Applications). The model has

been shown to simulate the stratospheric aerosol loads and radiative properties consistently compared to the observations of Mt Pinatubo eruption as well as other models (Laakso et al., 2016)." *(Laakso et al., 2016)."*

-Lines 15-19: Does MPI-ESM include atmospheric chemistry, such as ozone chemistry? Does the land model and the ocean model (as well as the ocean biochemistry model) fully coupled or just data model?

Ozone is included as prescribed.

Text "*The hydroxyl radical (OH) and ozone concentrations are accounted for through prescribed monthly mean fields. Thus, the effect of sulfur injections on the ozone layer is not simulated in our model* "was added to section 2.2.1

We now added that echam is *"fully"* coupled and mention that JSBACH and HAMOCC are *"active"* in the simulations.: *"The model consists of the atmospheric component ECHAM6.1 (Stevens et al., 2013) which is fully coupled to the Max Planck Institute Ocean Model (MPIOM) (Junglaus et al., 2012). MPI-ESM also includes land model JSBACH (Reich et al., 2013) and the ocean biochemistry model HAMOCC (Ilyina et al., 2013) as active components. Atmospheric GHG concentrations follow the RCP 4.5 scenario (Moss et al., 2010; van Vuuren et al., 2011))"*

Page 6:

-Line 17: not just because "in these two scenarios sulfur is injected to an area where solar intensity is on average weaker', but also the transport of sulfate aerosol in NH and NHSH is not as efficient as in EQ. It would be very helpful to look at how the aerosol transport evolves in difference scenarios.

This line is rewritten as:

*"…*since in these *two scenarios sulfur is injected to an area where the solar intensity is on the average weaker and from where the Brewer Dobson Circulation transports sulfur mainly towards higher latitudes (Robock et al., 2008). "*

We added monthly zonal mean figures of AOD at 533nm and new section 3.1.2 to discuss in more detail the transportation of the aerosol in the studied scenarios as well as the optical properties of aerosols at different time and location.

-Line 25: It would be helpful to look at the size distribution in different scenarios.

In addition to AOD figure and section 3.1.2, we added a figure 3 for zonal mean effective radius during summer and winter seasons. See also replies to referees #1 and #2.

Page 7:

-Line 12: Is OH specified in the model, or there is interaction with the UV and water vapor change?

OH was prescribed in the model as monthly means.

Text *"The hydroxyl radical (OH) and ozone concentrations are accounted for through prescribed monthly mean fields."* was added to section 2.2.1.

Page 8:

-Lines 5-14: There should be sentences discussing this sulfur distribution doesn't include the changes in stratospheric dynamics induced by the sulfate injection geoengineering.

Part of the dynamical feedback is accounted for in our simulations, as stated in 2.2.1 (now moved to 2.2); however, circulation changes induced by GHG and following energy flux changes between the surface and the atmosphere were not simulated when defining the sulfur fields with ECHAM-HAMMOZ. This is discussed more explicitly in 2.2.

"Simulations with ECHAM-HAMMOZ were carried out using a free running setup to include the dynamical feedback resulting from the additional heating due to absorption radiation by the injected aerosols. However, stratospheric circulation could also be altered by changes in the atmospheric GHG concentration (in our case following the RCP4.5 scenario) and resulting the tropospheric climate; however, these impacts were not taken into account when the aerosol fields were calculated in ECHAM-HAMMOZ"

Page 9 - 10:

-Lines 29 (p9)-5(p10): Does this model include water vapor radiation? In sulfate injection scenarios, temperature reduction would reduce the water vapor content in the atmosphere, which reduces water vapor greenhouse effect as well.

The model includes the effect of water vapor on the radiation. The impact correlates linearly with the temperature and thus does not explain what caused the different warming rates. However, it might amplify the difference in warming rates.

-Line 16-19: Please reorganize this sentence "climate was clearly over cooled before SRM was suspended compared to years before SRM when G4 tempters has been kept Same"

These lines are now rewritten:

"However here, in scenarios which were based on the G4 scenario with 5 Tg(S)/yr injections, climate was clearly overcooled after year 2020 and in most of the scenarios the climate was still cooler before SRM was suspended compared to years 2010-2020. In contrast, in G2, simulated by Jones et al. (2013), the global mean temperature was kept at the same level, or slightly warmer after SRM was started in year 2020 and suspended in year 2070."

Page 12:

-Line 2-17: Since the goal of the experiment design is to reduce the tropic-polar temperature gradient change due to sulfate aerosol injection, it would be better to plot Figure 7 in a different way. Instead of using EQ as the base line, it might be better to use RCP4.5. In that way, we could see how EQ changes the temperature gradient as well as other scenarios. Also it might be better to calculate the tropic-polar temperature gradient and plot the time series change under different scenarios.

The choice of using EQ as the base line scenario instead of RCP4.5 (years 2010-2020 or 2060-2070) was done because we wanted to show results which would be easy to adapt for different background conditions. As seen in figure 6 (fig 8 in revised version) b (and partly a), the arctic cooling was caused mainly by temperatures in year 2010-2020, and thus our results depend on the chosen reference years. If years 2060-2070 from RCP45 scenario were chosen as baseline, the regional temperature/precipitation patterns would be dependent on our choice for the amount of injections. For example Kravitz et al 2016 (fig 1) showed that different solar reductions (amount of injected sulfur) would lead to clearly different zonal mean temperature changes. Thus as was said by Kravitz et al "many of the climate effects of geoengineering are design choices".

Page 13:

Summary and conclusion: This part has too many repeating from the method and results sections. It would be better to add more discussion on the uncertainty of this work

As the referee suggested, we removed some repetition from the results section and included more discussions about injections strategies studied here.

These lines are added or modified in the conclusion section:

"However, the scenarios studied here are only the first step towards more optimal injection scenarios. A full optimization would require a more detailed analysis of incoming and reflected solar radiation, atmospheric circulation and how it is affected by sulfur fields as well as aerosol microphysics and chemistry. Overall, however, results of this study already show the potential of time-varying injection scenarios. "

"Even though seasonally varying injection areas could allow for more control over the geographic pattern of the radiative forcing compared to equatorial injections, this might not lead to large differences in regional climate impacts. This is because the heat transport via the oceans and the atmosphere greatly smooths out the impacts from spatially inhomogeneous aerosol forcing. In addition, due to the atmospheric transport, it is impossible to concentrate the radiative forcing from sulfur injections to any limited area. Thus, stratospheric sulfur injections are not an effective method with which to aim for certain regional temperature or precipitation impacts. Despite this, our results indicate that seasonally changing injection areas could resolve some of the spatial inhomogeneities resulting from more commonly studied equatorial injections. "

These lines were removed from conclusions:

"Compared to RCP45 the warming rate between years 2030-2070 was reduced from 1.95 K / 100 yr to 1.25 K / 100 yr in SRM scenarios due to the ocean cooling caused by aerosol radiative effect. This highlights the role of feedbacks and ocean temperature which reacts slowly to the radiation changes in the atmosphere."

"However modelling precipitation changes is very uncertain and making valid conclusions about regional precipitation by using global model is challenging."

"Results of this study also indicate that the melting of arctic sea ice is more efficiently prevented by tropical injections than *injection only to northern hemisphere (30° N - 10° N, scenario NH), in which case the cooling effect at boreal winter is relatively weak. "*

Radiative and climate effects of stratospheric sulfur geoengineering using seasonally varying injection areas

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Abstract. Stratospheric sulfur injections have often been suggested as a cost effective geoengineering method to prevent or slow down global warming. In geoengineering studies, these injections are commonly targeted to the Equator, where the yearly mean intensity of the solar radiation is highest and from where the aerosols disperse globally due to the Brewer~~-~~–Dobson Circulation. However, compensating the greenhouse gas induced zonal warming by reducing the solar radiation would require a relatively larger radiative forcing to the mid and high latitudes and a lower forcing to the low latitudes than what is achieved by continuous equatorial injections~~. In geoengineering studies these injections are commonly targeted to the equator, where the intensity of the solar radiation is highest. However, .~~ ~~it may not be the most optimal aerosol injection strategy because the radiative forcing concentrating over the equator decreases the meridional temperature gradient.~~ In this study we employ alternative aerosol injection scenarios to investigate if the resulting radiative forcing can be ~~optimized~~ targeted to be zonally more uniform without decreasing the global the mean radiative forcing of stratospheric sulfur geoengineering~~efficacy~~. We used a global aerosol-climate model together with an Earth system model to study the radiative and climate effects of stratospheric sulfur injection scenarios with different injection areas. According to our simulations, varying the SO_2 injection area seasonally would result in a similar global mean cooling effect as injecting SO_2 to the ~~equator~~Equator, but with a more uniform zonal distribution of shortwave radiative forcing. Compared to the case of equatorial injections, in the seasonally varying ~~optimized~~ injection scenario where the maximum sulfur production from injected SO_2 followed the maximum of solar radiation, the shortwave radiative forcing decreased by 27% over the ~~equator~~Equator (~~between~~ the latitudes ~~-~~between 20° N and 20° S) and increased by 15% over higher latitudes. Compared to the continuous injections to the ~~equator~~Equator, in summer months the radiative forcing was increased by 17% and 14% and winter months decreased by -14% and -16% in~~at~~ N~~n~~orthern and S~~s~~outhern H~~h~~emispheres respectively. However, these forcings do not translate into as large ~~very significant~~ changes in temperatures. ~~Based on ESM simulations,~~The changes in forcing would lead only to 0.05 K warmer winters and 0.05 K cooler summers in~~at~~ the N~~n~~orthern H~~h~~emisphere which is roughly 3 % of the cooling result~~ed~~ing from solar radiation management scenarios studied here~~. At the same time the meridional temperature gradient was better maintained.~~

1 Introduction

Solar radiation management (SRM) by increasing the atmospheric aerosol particle concentration has been shown to have the potential to counteract at least some of the ongoing global warming, and has therefore been considered a possible option to reduce the risks of climate change caused by increased greenhouse gas concentration in the atmosphere (Royal Society, 2009). One of the proposed methods is to produce sulfate particles into the stratosphere, where they efficiently reflect solar radiation back to space and thus cool the surface climate. It has been suggested that sulfur for geoengineering purposes could be injected as SO_2 which is oxidized to H_2SO_4 and subsequently forms sulfate particles (Kravitz et al., 2013a; Royal Society, 2009). Because of the stability of the stratosphere and the lack of efficient removal mechanisms which are prevalent in the troposphere, the stratospheric lifetime of sulfate particles is 1-2 years which would lead to a longer lasting cooling than aerosol emissions at the surface.

Most previous modelling studies have investigated scenarios which inject sulfur along or close to the equatorEquator. This choice of an injection region is well justified because the equatorEquator, on the average, receives the highest levels of solar radiation. In addition, the stratospheric circulation transports particles efficiently from the equatorEquator around the global atmosphere (Robock et al., 2008). However it has been found in several studies that preventing greenhouse gas (GHG) induced warming by equatorial injections of sulfur would lead to overcooling of the tropics and undercooling of the polar regions, compared to the global mean decrease in temperature (Aswathy et al., 2015; Jones et al., 2010; Jones et al., 2016; Kravitz et al 2016, McCuskter et al., 2012; Yu et al., 2015). This would also lead to a reduced meridional temperature gradient, which, for example, could reduce the midlatitude precipitation (Schmidt et al., 2012). Therefore, it is worth investigating whether different spatial injection patterns could lead to more uniform cooling around the globe.

The previous research on this topic has shown that the temperature response would indeed be zonally more uniform if radiative forcing were concentrated to the extra-tropics. These studies have, however, used either a reduced solar constant (MacMartin et al., 20132, Kravitz et al 2016) or prescribed aerosol fields (Modak and Bala, 2014) to approximate the climate impacts of the stratospheric sulfur injections. While such simplified scenarios are useful for studying the climate response in idealized scenarios and easily be implemented intto various climate models, the applied radiative forcing does not necessarily correspond to the forcing that would result from actual stratospheric injections of SO_2. This is because a reduced solar constant or prescribed aerosol fields do not account for the transport of gas and particulate phase sulfur in the stratosphere, which impacts the spatial distribution of the sulfate particles., Nnor does it takes into account the aerosol microphysics, which can significantly affect the radiative properties and the lifetime of the aerosol population (Heckendorn et al., 2009). Thus, climate model studies using a description of aerosol microphysics and sulfur chemistry are required for more realistic simulations of stratospheric sulfur injection strategies. The only studies of where other than equatorial injection were studied by a global aerosol-climate model ~~this kind~~ to date (Robock et al., 2008; Volodin et al., 2011) injected sulfur at~~to~~ high latitudes which led~~ad~~ to a significantly smaller radiative forcing than equatorial injections.

In this study, we have investigated injection scenarios that aim to produce a geographically more even radiative forcing pattern than equatorial sulfur injections, while still maintaining a high global mean forcing. Such scenarios are sought via seasonally varying injection areas in which the ~~target~~injection area follows the maximum solar intensity with different time lags. These scenarios are compared to more commonly used strategies with fixed injection areas. This study should be taken as a first step in evaluating optimal injection strategies in terms of geographically more uniform aerosol fields/radiative forcing/climate impacts without losing the effectiveness of geoengineering compared to continuous equatorial injections. In order to fully optimize the injection strategy, one should try to also account for the effect of stratospheric circulation on aerosol transport, together with existing planetary reflectivity and a detailed analysis of aerosol microphysics. These aspects are out of the scope of this study.

The simulations are done in two steps. First, we use the global aerosol-climate model ECHAM-HAMMOZ to investigate the radiative forcing from the zonally different injection areas and to define aerosol~~s~~ fields. Second, the global and regional temperature and precipitation responses are studied using the coupled climate-ocean model MPI-ESM (Max Planck Institute's Earth System Model), which does not include a prognostic calculation of aerosol processes in its current configuration.

2 Methods

2.1 Simulated SRM scenarios

Eight zonally different sulfur injection strategies were simulated. In all of these scenarios 5 Tg(S)/yr of gaseous SO_2 was injected continuously over the year to the stratosphere at the height of 20 km and to a 20 degree wide latitude band specified below (2 bands in one of the simulated scenarios).

2.1.1 Fixed injection areas

In three of the studied injection scenarios, the area of continuous sulfur injections remained fixed throughout the year. ~~In three of the studied injection scenarios, the injection area remained fixed throughout the year.~~ In scenario **EQ**, sulfur was injected over~~to~~ the ~~equator~~Equator between latitudes 10° N and 10° S (Figure 1a). This injection strategy corresponds to the injection scenarios in most previous studies, although they have used different widths for the injection area (Heckendorn et al., 2009; Jones et al., 2016; Niemeier et al., 2011; Pierce et al., 2010; Pope et al., 2012; Tilmes et al., 2015). In the **NH** scenario, sulfur was injected only in~~to~~ the N~~n~~orthern H~~h~~emisphere between latitudes 10° N and 30° N (Figure 1b). In scenario **NHSH** 2.5 Tg(S)/yr sulfur was injected to the N~~n~~orthern H~~h~~emisphere between latitudes 10° N and 30° N and 2.5 Tg(S)/yr to the S~~s~~outhern H~~h~~emisphere between latitudes 10° S and 30° S (Figure 1c) to reduce the overcooling in the tropics inherent to equatorial injections at the same time aiming at reducing the change in the meridional temperature gradient compared to the scenario **EQ**. However, **NH** and **NHSH** are expected to result in a smaller global cooling effect than **EQ** because the resulting distribution of aerosols is concentrated to the injection area and~~sulfur is injected~~ at~~to~~ latitudes where the annual mean solar radiation is smaller than over the ~~equator~~Equator.

2.1.2 Seasonally changing injection areas

In addition to the above-mentioned scenarios, five scenarios where the sulfate injection area is varied throughout the year were simulated. In four of these scenarios, the 20-degree wide sulfur injection area changed monthly between the latitudes ~~from~~ 30° S – 30° N in different phases. In the **p0** scenario, the injection area was set to follow the maximum intensity of solar radiation (Fig. 2). Therefore, the sulfur injection area is at~~in~~ its northernmost position (30° N to 10° N) in June coinciding with the location of the **NH** scenario. In March and September, the center of the injection area is at~~in~~ the ~~equator~~Equator, thus coinciding with the injection area of the **EQ** scenario. The injections are at their southernmost location between 30° S to 10° S in December.

However, sulfur injected as SO_2 takes weeks to months before it is oxidized and forms large enough particles to reflect solar radiation efficiently. Thus to obtain maximum aerosol forcing, one strategy could be to inject sulfur before the intensity of solar radiation has reached its maximum value at the injection latitude, thus leaving enough time for oxidation and particle growth. However if sulfur was injected too early, SO_2 and formatted sulfate particles would be already transported to the higher latitudes when the intensity of the solar radiation starts to increase. To test this strategy, we repeated **p0** with different temporal phases of the injection area change. In the **p2** scenario, the northernmost injection area is reached in April, two months earlier than in the **p0** scenario. In the **p4** scenario, the northernmost injection area is reached in February and in **p6** in December. Based on the oxidation time of SO_2-, **p4** and **p6** scenarios are expected to lead to a smaller radiative forcing than **p2**. However, these scenarios are simulated to study how different phase of the changing injection area alters the radiative forcing. Injection areas in these scenarios are presented in figure 2. Based on the model simulations with ECHAM-HAMMOZ in Laakso et al. (2016), in the case of Pinatubo eruption, 75% of the erupted SO_2 was oxidized after the first two months from the eruption. In these simulations, the global mean radiative forcing of aerosols was also at its largest roughly at the same time. Thus, it could be expected that scenario **p2** would lead to a stronger global mean radiative forcing than the other scenarios studied. To test the impact of concentrating the radiative forcing to even higher latitudes, simulation **p2** was repeated so that the latitude range for the monthly-shifting injection area was wider. In this **p2w** scenario, the phase and the injection areas is as wide as in **p2** (20° in latitudinal direction), but the northernmost location of the injection area in April is between 40° N and 20° N and southernmost in October between 20° S and 40° S.

2.2 Model description

As explained above, Tthe model simulations were done in two steps: First, the different injection strategies described in sect. 2.1 were simulated with the global aerosol-climate model ECHAM-HAMMOZ that contains an explicit description of SO_2 oxidation chemistry as well as aerosol microphysics. These simulations were used to calculate the radiative forcing resulting from the stratospheric injections, as well as to provide the optical properties of stratospheric aerosol fields for the MPI-ESM simulations in step two. Second, the coupled earth system model MPI-ESM was used to the simulate temperature and precipitation effects of stratospheric sulfur injection strategies against the Representative Concentration Pathway 4.5 (RCP4.5, Moss et al., 2010; van Vuuren et al., 2011). The tTwo step approach was selected because the currently available configuration of -MPI-ESM does not include a prognostic calculation of aerosol processes.. in its current configuration. In addition, modelling aerosol microphysics is computationally heavy. Thus it was feasible to simulate aerosol microphysics only for a relatively short period (few years) and use the ECHAM-HAMMOZ simulated aerosol fields as prescribed fields in the longer simulations in MPI-ESM. Simulations with ECHAM-HAMMOZ were carried out using a free running setup to include the dynamical feedbacks resulting from the additional heating due to absorption of radiation by the injected aerosols. However, stratospheric circulation could also be altered by changes in the atmospheric GHG concentration (in our case following the RCP4.5 scenario) and its impacts on the tropospheric climate; however, these impacts were not taken into account when the aerosol fields were calculated in ECHAM-HAMMOZ. Simulations were carried out using a free running setup to include the dynamical feedback resulting from the additional heating due to absorption radiation by the injected aerosols..

2.2.1 Defining aerosol fields using ECHAM-HAMMOZ

As mentioned above, tThe radiative properties of aerosol fields resulting from the 5 Tg(S)/yr stratospheric sulfur injections were defined by using the global aerosol-climate model ECHAM-HAMMOZ (MAECHAM6.1-HAM2.2-SALSA (Zhang et al., 2012, The middle atmosphere configuration of the European Centre Hamburg Model coupled with Hamburg Aerosol Model including a Sectional Aerosol module for Large Scale Applications)). The model has been shown to simulate the stratospheric aerosol loads and radiative properties consistently compared to the observations of the Mt Pinatubo 1991 eruption as well as other models (Laakso et al., 2016). -Nine-year long simulations were performed for each of the scenarios. The simulations started in conditions without SRM and included a two-year ramp-up period where continuous SO_2 injection whas started (5 Tg(S)/yr). This two-year ramp-up was long enough for the formation of a steady-state stratospheric sulfate field where in average the averagely same amount of sulfur is removed from the atmosphere asthan was injected. The ramp-up period was followed by a five-year steady-state period during which the sulfur field was maintained by continuous 5 Tg(S)/yr injections. Furthermore, two additional years were ran tofor simulate the suspension of solar radiation management. In the beginning of this ramp-down period the sulfur injections weare suspended. After two years, sulfate particles from the injections are removed from the atmosphere.

For further analysis, the radiative forcings and stratospheric sulfur burdens were calculated as five-year mean values over the steady-state period and compared to the CTRL simulation which included only standard tropospheric emissions (see below). Furthermore, for the climate simulations, the radiative properties of the aerosol fields were calculated and implemented in MPI-ESM as monthly means.

Simulations were performed with a T63L47 resolution, which corresponds approximately to a 1.9° x 1.9° horizontal grid and in which the atmosphere is divided into 47 height levels reaching up to ~80 km. The aerosol module HAM is coupled interactively to ECHAM and includes an explicit sectional aerosol scheme SALSA (Bergman et al., 2012; Kokkola et al., 2009; Laakso et al., 2016), which calculates the microphysical processes of nucleation, condensation, coagulation and hydration. In the SALSA configuration used, aerosols are described by aerosol number and volume size distributions with 10 size sections for internally and 7 size sections for externally mixed particles (see Laakso et al., (2016) for details). The HAM module calculates the aerosol emissions, removal, gas and liquid phase chemistry, and the radiative properties for the major global aerosol compounds of sulfate, organic carbon, black carbon, sea salt and mineral dust. Aerocom II (Aerosol Comparisons between Observations and Models) tropospheric emissions for year 2010 were used in all simulations (Dentener et al., 2006). ~~Simulations were carried out using a free running setup to include the dynamical feedback resulting from the additional heating due to absorption radiation by the injected aerosols.~~ The model contains an explicit description of sulfur dioxide oxidation chemistry (Feichter et al., 1996). The hydroxyl radical (OH) and ozone concentrations are accounted for through prescribed monthly mean fields. Thus, the effect of sulfur injections on the ozone layer is not simulated in our model. The ECHAM-HAMMOZ simulations were done using CMIP5 (Coupled Model Intercomparison Project) AMIP2 (Aerosol Chemistry Climate Model Intercomparison Project) climatological sea surface temperatures and sea ice distributions which are derived as a mean values between years 1979-2008 (Taylor et al., 2008).

2.2.2 Simulating climate effects using MPI-ESM

To study the climate effects of the different stratospheric sulfur injection scenarios, we used the Max Planck Institute's Earth system model (MPI-ESM) (Giorgetta et al., 2013). The model is a state-of-the-art coupled three-dimensional atmosphere-ocean-land surface model. The model consists of the atmospheric component ECHAM6.1 (Stevens et al., 2013) which is fully coupled to the Max Planck Institute Ocean Model (MPIOM) (Junglaus et al., 2012). MPI-ESM also includes active components of the land model JSBACH (Reich et al., 2013) and the ocean biochemistry model HAMOCC (Ilyina et al., 2013). However atmospheric GHG concentrations follow the RCP 4.5 scenario (Moss et al., 2010; van Vuuren et al., 2011).).

In this study, global fields of radiative properties of stratospheric aerosol from ECHAM-HAMMOZ simulations were implemented to MPI-ESM. The aerosol optical depth, single scattering albedo and asymmetry factor for the stratospheric aerosol field were first calculated for 30 wavelength bands using ECHAM-HAMMOZ and then used as an input for MPI-ESM. The implementation method used here is an improvement to that presented by Laakso et al. (2016), where the aerosol radiative properties in MPI-ESM were calculated based on a single modal size distribution with a fixed mode width and monthly mean values of aerosol effective radius and aerosol optical depth (AOD) at 550 nm resulting from simulations with ECHAM-HAMMOZ. Thus particle size distribution in MPI-ESM was described by single mode, which did not correspond to the sectional size distribution in ECHAM-HAMMOZ. This led to a slightly different aerosol radiative forcing in MPI-ESM than what was calculated by ECHAM-HAMMOZ (Laakso et al., 2016). In the current study the only difference in the stratospheric aerosol radiative properties between ECHAM-HAMMOZ and MPI-ESM~~ in this study~~ is that in MPI-ESM simulations the stratospheric aerosol fields are described as zonal monthly mean values. This difference is not expected to affect the results significantly; however, the chosen approach keeps the size of the aerosol input files for MPI-ESM manageable. To describe the properties of the tropospheric aerosol in MPI-ESM, we used the tropospheric aerosol climatology of Kinne et al., 2013 in all simulations.

In the c~~C~~limate simulations with MPI-ESM, our setup of scenarios was similar to ~~ were based on ~~the Geoengineering Model Intercomparison Project (GeoMIP) G4 scenario (Kravitz et al., 2011, Kravitz et al., 2013a); however, in our study 5 Tg(S)/yr is injected instead of 2.5 Tg (S)/yr to get stronger climate signal. As with GeoMIP, we started our simulations from year 2010 and continued until 2100. The baseline scenario with no SRM followed the RCP 4.5 scenario. All SRM scenarios also included the RCP4.5 tropospheric emissions but they also included additional stratospheric sulfur injections starting in~~ the~~ year 2020. The sulfur injections were applied for 50 years and then suspended. After that, the simulations were continued for 30 years until year 2100 to simulate the~~d~~ termination effect of geoengineering (Jones et al., 2013; Kravitz et al., 2011). The emerging stratospheric~~Growing~~ sulfur field in the two-year ramp-up period simulated by ECHAM-HAMMOZ was used in MPI-ESM for years 2020-2021. The ramp-down period sulfur field, when sulfur injections are suspended and sulfate particles are removed from the atmosphere was used for years 2070-2071. Between the ramp-up and ramp-down periods (2022-2070) steady-state stratospheric sulfur field from 5 Tg (S)/yr injection from simulations with ECHAM-HAMMOZ were used.

3 Results

3.1 ~~Radiative forcings of alternative injection scenarios – ~~Atmosphere-only simulations using ECHAM-HAMMOZ

In this section we investigate the radiative forcing resulting from the aerosol microphysical simulations of different injection scenarios. When talking about the changes in the aerosol short-wave (SW) radiative forcings (which are typically negative), we have applied a commonly used and intuitively clear convention: decrease in the forcing refers to the numerical value of the forcing getting closer to zero (i.e. in strictly mathematical sense increasing); similarly, an increase in forcing refers to the numerical value getting more negative.

3.1.1 Radiative forcing of alternative injection scenarios

Table 1 shows the global SO_2 and sulfate burdens and the global mean all-sky short-wave (SW) radiative forcing in the studied sulfur injection scenarios. The baseline **EQ** scenario leads to an all-sky SW radiative forcing of -3.72 W/m^2. As expected, both **NH** and **NHSH** scenarios give clearly smaller radiative impacts (-3.21 and -3.30 W/m^2, respectively) than **EQ**. This is becaus~~e~~e in these two scenarios sulfur is injected to an area where the solar intensity is on the average weaker and from where the Brewer~~-~~–Dobson Circulation transports sulfur mainly towards higher latitudes (Robock et al., 2008). Further contributing to the smaller forcing in **NH** and **NHSH** is the fact that the lifetime of stratospheric sulfur is longer when injected to the ~~equator~~Equator (Robock et al., 2008).

~~It is interesting to note that~~ Scenarios **NH** and **NHSH** produce somewhat different global mean SW radiative forcings as well as stratospheric SO_2 and sulfate burdens even though in both cases the sulfur is injected in~~to~~ regions with equal distances from the Equator. The difference between these two scenarios is that in scenario **NH**, the same amount of sulfur is injected to a smaller total area than in **NHSH**. Previous research has shown that higher injections per unit volume lead to relatively larger particles, which in turn leads to a relatively shorter lifetime of particles in the atmosphere (Heckendorn et al., 2009; English et al., 2012; Niemeier et al., 2011). Thus the particle effective radius is clearly smaller in scenario **NHSH** than in scenario **NH**, especially in the northern hemisphere (Fig 3). ~~-~~The forcing in the **NH** scenario is further reduced compared to **NHSH** by the fact that the Earth's surface albedo is higher in the northern than in the S~~s~~outhern H~~h~~emisphere.

The global burdens and mean forcings in the scenarios with seasonally changing sulfur injection area (**p0**, **p2**, **p4**, **p6**) are quite close to those in the **EQ** scenario (Table 1). However, ~~it is noteworthy that~~ out of all the scenarios the largest radiative forcing of -3.82 W/m^2 (i.e. 0.1 W/ m^2 larger than in **EQ**) is simulated in scenario **p2**. When the injection area is varied throughout the year in a well-timed phase, the reflective sulfate particles are on the average concentrated in~~to~~ latitudes with larger solar intensity than if sulfur is injected only to the ~~equator~~Equator (**EQ**). It can be expected that the difference in the ~~efficiency~~ the global mean radiati~~o~~ve forcing between scenarios **EQ** and **p2** would increase even more if a larger amount of sulfur were injected, because of a sub-linear correlation between the amount of annual sulfur injections and the radiative forcing (Heckendorn et al., 2009). Such losses are slower when the injection area is varied and thus the injection~~s~~ per unit volume of air is smaller, and thus more newly formed particles survive to become large enough to scatter radiation efficiently. As a result, the number concentration of smaller particles increases. Figure 3 shows that the particle effective radius is on average smaller in scenario **p2** than in **EQ**.

~~**EQ**~~

Based on the scenarios used here, to achieve maximum aerosol forcing the varying sulfur injection area should reach its northernmost location two months (April) earlier (**p2**) than the solar radiation reaches its maximum (June). This way, the formed particles from the SO_2 injection reach the optimal size at the time of maximum solar radiation. On the other hand, in **p0** and **p6** scenarios the seasonality of the solar radiation intensity and its impacts on the seasonality of hydroxyl radical (OH) concentration lead to a lower global forcing than in most other scenarios (**EQ**, **p2**, **p4**, **p2w**). This is because OH is the main oxidant that converts SO_2 to sulfuric acid (H_2SO_4) which together with H_2O molecules nucleates and grows the stratospheric aerosol particles. In the **p0** scenario, the SO_2 injection area follows the area which receives the highest amount of solar radiation. These latitudes have high OH concentration which leads to faster oxidation than in other scenarios, as can be seen from the smallest SO_2 burden in Table 1. However, it takes a couple of months before the formed particles have grown large enough to reflect solar radiation effectively, and by the time this happens, the solar intensity has already decreased at the latitudes where the particulate sulfur burden has increased the most. On the other hand, in **p6** sulfur is injected always during the months when the injection region experiences its lowest annual solar radiation. This leads to a relatively slow oxidation rate, as can be seen from the large SO_2 burden. However, because of the lifetime of sulfate particles is over one year, most of the injected sulfur is still in the atmosphere in the summer around 6 months after the injection, and thus the global mean radiative forcing is not significantly smaller than in the other scenarios. In addition, here sulfur is injected in all **p0**, **p2**, **p4** and **p6** scenarios to the low latitudes (between 30° N and 30° S) which receive high solar radiation throughout the year. Thus considerably large differences in the global yearly mean radiative forcing between the scenarios are not expected.

Finally, in **p2w** the injection area changes between 40° N and 40° S instead of 30° N and 30° S. Because sulfur is injected at a larger distance from the ~~equator~~Equator than in **p2**, the global mean all-sky shortwave radiative forcing is 3% (0.1 W/m^2) smaller than in **p2** (Table 1). Figure 3 shows that in scenario **p2w** particles are consistently smaller than in **p2**. However, due to the atmospheric circulation, which transports particles mainly towards poles, in scenario **p2w** particles are removed more quickly from the atmosphere because sulfur is injected at a larger distance from the equator. In addition, the tropopause height varies with latitude and when injecting sulfur to higher latitudes in **p2w** scenario, some of the sulfur is injected into the upper branch of the stratospheric circulation. Overall there is no difference in stratospheric sulfur burden between **p2** and **p2w** scenarios (Table 1). While the all-sky forcing is as large as in **EQ** (Table 1), ~~it is noteworthy that~~ the clear-sky forcing is 0.16 W/m^2 larger in scenario **p2w** than in scenario **EQ** (5.76 W/m^2 and 5.60 W/m^2, respectively). This is because in scenario **p2w** more sulfur resides in the mid-latitudes (40° - 60°) where the cloud cover is larger than in the low latitudes and therefore the original albedo is larger. This decreases the all-sky radiative forcing of **p2w** compared to **EQ**.

Overall the results show that extending the injection area to the mid-latitudes for a part of the year can, in terms of the global forcing, be as effective as the injections to the ~~equator~~Equator if the injection area is changed in a certain phase. However, the zonal differences between these two injection strategies can be very different, as will be illustrated in the following.

Figure 4~~3~~ shows the five-year zonal mean shortwave radiative forcing in **EQ**, **NH**, **NHSH**, **p2** and **p2w** scenarios. As expected, scenario **EQ** (black line) leads to the strongest radiative forcing at the ~~equator~~Equator; however, outside the tropics the forcing declines fast (**EQ**)~~)~~ as seen ~~,~~also in the case of equatorial injection in~~-~~ Niemeier et al. (2011). In the **p2** (~~purple~~pink solid line) and **p2w** (~~purple~~pink dashed line) scenarios the forcing is distributed much more evenly throughout the tropics and the midlatitudes. Compared to **EQ**, **p2** shows 7% lower mean forcing between 20° N and 20° S~~,~~ but 10% larger forcing in higher latitudes. The difference between **p2w** and **EQ** is even larger: 27% between 20° S and 20° N and 15% in the higher latitudes. Thus these results show that by varying the injection area it would be possible to obtain a more evenly distributed zonal forcing or even concentrate the maximum forcing to mid-latitudes, while achieving similar or even larger global mean radiative forcing than in scenario **EQ**. This could prevent some of the decrease of the meridional temperature gradient due to geoengineering and GHG induced warming.

While the scenario **NHSH** (orange line) also leads to a relatively evenly distributed zonal forcing in most latitudes, the total global forcing is clearly lower than in the case of **EQ**, **p2** and **p2w** scenarios (Table 1). In scenario **NH** (green line), the forcing is concentrated mainly to the N~~n~~orthern H~~h~~emisphere (-4.42 W/m^2). There is also a moderate ~~cooling effect~~radiative forcing in the S~~s~~outhern H~~h~~emisphere (-2.00 W/m^2).

Further insight into the different zonal and global radiative effects between the scenarios can be obtained from Figure 5~~4~~, which shows the burden of stratospheric sulfate particles and the zonal distribution of the incoming solar radiation (shown in orange in the figure), in boreal winter (DJF) (fig5~~4~~a) and summer (JJA) (fig5~~4~~b). Sulfate burden and solar radiation are shown per meter in meridional direction. Thus the different length of the circumference along an individual latitude is taken account in the figure.

In the depicted seasons, the maximum solar radiation is received about 15 degrees south or north of the ~~equator~~Equator. In scenario **EQ**, sulfate is concentrated near the injection area in Equator and near the 50° N and 50° S latitudes as shown in earlier studies (English et al., 2012; Jones et al., 2016; Niemeier et al., 2011). Thus in scenario **EQ**, much of the zonal sulfate burden peaks around the ~~equator~~Equator being less than ~~is not~~ optimally located (black line) with respect to the incoming radiation. In addition, the meridional wind component over the ~~equator~~Equator (10° N – 10° S) in the stratosphere (20 - 25 km altitude) is on the average towards the north in the northern autumn and towards the south in the northern spring. Thus, there is more sulfate in scenario **EQ** in the midlatitudes of the winter hemisphere, which gets significantly less solar radiation than the summer hemisphere. Thus, when the sulfate particles are concentrated to the winter hemisphere, they reflect less solar radiation making solar radiation management less efficient. On the other hand, in the **p2** scenario, the maximum of zonal mean sulfur burden is roughly at the same latitudes as the maximum solar radiation and, compared to scenario **EQ**, more sulfate is in the summer hemisphere. This leads to a larger radiative effect in scenario **p2** than in scenario **EQ** during the summer months and but also to a smaller radiative effect in the winter months, as can be seen Figures 5~~4~~c and d. Compared to scenario **EQ**, the total sky SW radiative forcing in scenario **p2** is 15% larger in the boreal summer months and 15% smaller in the winter months in the N~~n~~orthern H~~h~~emisphere. The difference can be seen especially in high latitudes (north of 50° N), where the mean radiative forcing is 23% larger in **p2** than in **EQ** in June-July-August (not shown). On the other hand, compared to scenario **EQ**, scenario **p2w** leads to 17% and 14% larger radiative forcing in the summer months over the N~~n~~orthern and S~~s~~outhern H~~h~~emispheres, respectively. In winter months the radiative forcing is -14% and -16% lower in the N~~n~~orthern and S~~s~~outhern H~~h~~emisphere respectively compared to scenario **EQ**.

3.1.2 Aerosol Optical Depth (AOD), solar radiation and stratospheric circulation

In this study the choice of the injection strategy was based only on the seasonality of the solar radiation. However, more optimal strategies, for example for achieving the strongest global radiative forcing of geoengineering or achieving the maximum cooling for specific latitudes, would require a more specific investigation. The aerosol radiative effects would also depend on e.g. the size and the optical properties of the particles as well as on the stratospheric circulation and how it will change due to the dynamical feedback caused by the injected sulfur. Figures 6a-e show the zonal mean 533nm wavelength AOD of stratospheric particles at different times of the year. Figure 6f shows the meridional zonal mean wind component which indicates how injected sulfur transports in the atmosphere. The wind component is calculated at the height of the maximum AOD. The height was calculated based on scenario **EQ** but was the same in the other studied scenarios. The height of the AOD maximum was laying above the tropopause and was roughly at 20 – 21 km height over the tropics and decreased over the midlatitudes to 15 km over the highlatitudes

In the case of equatorial injections, the AOD is clearly larger close to the Equator and in high latitudes than in mid latitudes (fig 6a). This is consistent with earlier studies (English et al., 2012; Jones et al., 2016; Niemeier et al., 2011). Because of stratospheric circulation (fig 6f), AOD is clearly smaller at subtropics (10° - 30°) in all of the studied scenarios. This happens also in the scenarios where sulfur was injected continuously to subtropics (scenarios **NH** and **NHSH**, boundaries of injection area shown by blue lines) and the AOD at the subtropics was lower than in higher latitudes. Especially during the boreal winter, the strong stratospheric winds (fig 6f) transport particles farther north.

The hatched area in figure 6 shows the latitudes which receive over 50% of the monthly solar radiation. In scenario **p2** the tropical high AOD values reside over this area more often than in the other scenarios. The high AOD combined with the large solar intensity in these latitudes led to the largest global mean radiative forcing in scenario **p2** compared to the other studied scenarios. As was the intention of this scenario, it led to smaller AOD in the Equator and higher AOD in higher latitudes, especially in the summer months, compared to scenario **EQ**. In scenario **p2w** AOD was larger in the highlatitudes and smaller in the tropical area than scenario **p2**. The subtropical AOD was the largest in the late summer months. In the late winter months and spring months, the injection area was located to latitudes where the strong winds to polar direction transports SO_2 and formed particles to higher latitudes and the subtropical AOD was relatively small at the spring months when the solar intensity was large (fig 6 e and f).

These results show that trajectory analysis would be needed for more effective solar radiation management or when aiming radiative forcing more optimally to the specific latitudes. In addition, the radiative forcing of stratospheric sulfur injections is affected by many other factors. The hatched area in figure 6 shows the solar radiation in clear sky condition. The cloud cover is relatively smaller in the subtropics where the particles would then have a larger contribution to the radiation. In addition, the albedo of the surface and existing tropospheric aerosols should also be taken account when framing the optimal injection strategy. The solar forcing is also slightly larger in the Southern Hemisphere because the orbit of the Earth is closer to the Sun in boreal winter months.

Overall, these results show that the radiative forcing from the stratospheric sulfur injection can be concentrated to the midlatitudes with a small increase in the global mean radiative forcing when using a relatively simple injection strategy. As figure 6 shows, this impact would be possible to be increased by planning the injection strategy more specifically. However, the most optimal strategy and results depend on the objectives of the injections (Kravitz et al. 2016). In addition, here the latitudinal temporal dependence was chosen to be the only adjustable parameter while an optimal scenario would require the inclusion of also other adjustable parameters e.g. the altitude of the injections and the composition of the injected aerosol.

3.2 Temperature and precipitation change - results of MPI-ESM simulations

In this section we investigate how the aerosol radiative effects simulated for the different injection scenarios in sect. 3.1 translate to global and regional climate impacts. The mean values for different scenarios were derived from ensembles of 3 simulations.

3.2.1 The global mean temperature and precipitation response

In SRM scenarios (**EQ**, **NH**, **NHSH**, **p2** and **p2w**), stratospheric sulfur injections are started at full force (5 Tg(S)/yr) in year 2020 and suspended in year 2070. Compared to the global mean 2-meter temperature without SRM (**RCP45**), all scenarios lead to a fast and relatively similar global mean cooling after the injections were started (fig 7~~5~~a). After that, the climate warms quickly due to the increased greenhouse gas concentrations in RCP4.5. In **RCP45** scenario, between the years 2060-2070 the global 2-meter temperature is 1.18 K warmer compared to years 2010-2020. Compared to **RCP45**, the global mean temperature is -1.27 (± 0.18), -1.13 (± 0.13), -1.21(± 0.19), -1.34 (± 0.14) and -1.29 (± 0.15) -K cooler in scenarios **EQ**, **NH**, **NHSH**, **p2**, and **p2w** (not shown in the figure 7~~5~~) between 2060-2070. Thus, the global mean temperature is close to the value during the 2010s. Scenario **p2** leads to the largest global mean cooling which is slightly larger (4%) than in **EQ** as was expected based on simulations with ECHAM-HAMMOZ. Because SRM is turned on abruptly at full force in 2020, it would lead to a fast cooling. In the real world this kind of action is unlikely but based on the simulations it is plausible if needed for example to prevent a climate warming emergency (Kravitz et al., 2011).

After the very fast cooling in SRM scenarios, the climate starts to warm slowly when as the aerosol reaches its maximum cooling effect and the GHG concentrations in the atmosphere continue~~s~~ to increase. ~~It is notable that~~ E~~e~~ven though this GHG induced warming effect is similar in all SRM scenarios, the warming rate is clearly slower than in RCP4.5. Between the years from 2030 to 2070 the warming rate is 1.95 (± 0.68) K / 100 yr in **RCP45** scenario, but in scenario **EQ** the warming rate is reduced to 1.25 (± 0.55) K / 100 yr. As the amount of injected sulfur does not change, the direct cooling effect of stratospheric sulfate particles does not increase during ~~the~~ years 2030-2070. However the ocean reacts slowly to the abrupt changes in the radiation and the changes in the atmospheric temperature (Giorgetta et al., 2013). Thus the oceans are cooling in the beginning of SRM simulations which leads to a slower warming compared to RCP4.5. In addition, ~~Also~~ the nonlinear climate feedbacks and especially changes in the ice albedo could slow down warming. Over the latitudes higher than 70° N, the mean temperature is on the average still 0.6 (+- 0.5) K cooler in SRM scenarios during the years 2060-2070 compared to the years 2010-2020 even though the global mean temperature was roughly compensated. Simultaneously, the sea ice cover is 7 % larger. The cooling of the Arctic was not seen in previous studies in which solar radiation management has been investigated (Schmidt et al., 2012; Niemeier et al., 2013; Jones et al., 2016). The reason behind our simulation result is not totally clear. Section 3.1.2 showed that theAOD was relatively large at high latitudes which would have an impact on the radiation in summer months. On the other hand, the total received energy in the arctic area depends also on the energy transferred by the oceans and the atmosphere (Trenberth and Solomon, 1994). Figures 8 a and b show that there is warming in the subpolar North Atlantic. In this area, the sea surface temperature (SST) increases by 2-4 K in scenario **EQ**. On the other hand, there is a 1-2 K cooling in the SSTs in the Arctic Ocean. This indicates that there are changes in the ocean circulation. Since these patterns are seen also in scenario **RCP45**, they likely originate from in our reference years 2010-2020. The pattern of SST regions is similar to what is seen in CMIP5 RCP scenarios, where there was an amplified SST increase in the Nordic seas while in sub-Polar North Atlantic the warming rate was subdued compared to the global average trend (Sgubin et al. 2017). However, investigating the changes in the ocean circulation is out of the scope of this study. Overall, different warming rates in SRM and **RCP45** scenarios might also be affected by the asymmetric climate system response to the increase or decrease of forcings (Schaller et al., 2014). ~~Ice area and thus albedo is clearly higher in all of the SRM scenarios before suspending than beginning of the simulation even though global mean temperature is at the same level. Adding to this, the climate system response is asymmetric to the increase or decrease of forcings (Schaller et al., 2014).~~ It has been shown that there is a slow decrease in temperature still decades after a decrease in shortwave radiation (Schaller et al., 2014). ~~Similar behavior of the global mean temperature in G4 scenario was observed also by Kashimura et al. (2016).~~ Kashimura et al. (2017) studied the GeoMIP G4 scenario in several models. Their study showed that the difference in the global mean temperature between the RCP 4.5 and SRM scenarios increased for 10-25 years after solar radiation management was started. Here the amount of injected sulfur was twice as large as in G4 and Kashimura et al. (2017) which can explain why here the temperature difference increased until SRM was suspended.

After the SRM is suspended in 2070 there is a very fast warming, called the termination effect of geoengineering (Jones et al., 2013). This fast warming in the first few years after the SRM is suspended is of the same magnitude as the cooling immediately after the sulfur injection is started. Thus, due to the different warming rates in **RCP45** and SRM scenarios, after the SRM is suspended, the climate remains significantly cooler for decades after the SRM is suspended. If we make an assumption that the climate would warm after year 2020 at warming rate calculated from **EQ** from year 2030 to 2070 (blue dashed line in fig86a), the global temperature would be at the same level after 2070 than as it is in SRM scenarios followed years after suspended sulfur injections the ramp-down period. All of the SRM scenarios start to approachreach the temperature of **RCP45** a year after the suspension of SRM. However, up to the end of the simulation (years 2090-2099) the climate is still (0.17–0.21) K cooler in the SRM scenarios than for **RCP45**. In a multimodel experiment, Jones et al., (2013) studied the termination effect in GeoMIP G2 scenario, where the forcing from 1%/yr increase in atmospheric CO_2 concentration was compensated decreasing the solar constant and the SRM was suspended, similarly to this study, in 2070. Some of the models shows still a cooler climate compared to the RCP4.5 scenario in year 2100, but in MPI-ESM temperatures were at the same level in both G2 and RCP4.5 scenarios. However in here, in scenarios which were based on the G4 scenario with 5 Tg(S)/yr injections climate was clearly overcooled after year 2020 and in most of the scenarios the climate was still cooler before SRM was suspended compared to years 2010-2020. In contrast, in scenario G2, simulated by Jones et al (2013), the global mean temperature was kept at the same level, or slightly warmer after SRM was started in year 2020 and suspended in year 2070. , climate was clearly over cooled before SRM was suspended compared to years before SRM when G2 temperatures has been kept same. Thus in scenarios here, oceans heat uptake isThus in the scenarios here, ocean's heat uptake are reduced more than in G2. Kashimura et al. (2016) studied G4 scenario in several models. Most of the models show similar behavior after suspending SRM as seen here. However, here the amount of injected sulfur was two times as large as Kashimura et al. (2016).

Compensating the GHG induced global warming using SRM has been suggested to lead leads to a reduction in the global mean precipitation (Kravitz et al., 2013b; Ferraro and Griffiths, 2016). This is also supported by our simulations. Immediately after the injection has been started, the global mean precipitation falls clearly under the level of year 2010 as can be seen in figure 75b. After a few years, the global mean precipitation starts to increase slowly (daily average precipitation 0.048 mm/day/100yr in scenario **EQ** between the years from 2040 to 2069). The cChange rate of the precipitation is clearly smaller than in the **RCP45** scenario (daily average precipitation 0.08 mm/day/100yr).

Between the years from 2060-2070, there is significantly less precipitation in all SRM scenarios than in 2010, even though temperatures are at the same level. Compared to years 2010 - 2020 the global mean precipitation has been changed by +0.044 (± 0.013), -0.051 (± 0.013), -0.036 (± 0.013), -0.043 (± 0.015), and -0.054 (± 0.011) and -0.05 (± 0.014) mm/day in **RCP45**,

EQ, **NH**, **NHSH**~~, and~~ **p2** and **p2w**, respectively. Precipitation is thus more affected by the SRM than CO_2. There are mainly two causes for the changes in the global mean precipitation. One cause is the temperature change (Bony et al., 2013; Ferraro et al., 2014; Kravitz et al., 2013b) which inflicts a feedback response due to the increased humidity in the atmosphere. The second mechanism is the temperature independent atmospheric forcing (the change in the radiation between the surface and the top of the atmosphere) (Ferraro et al., 2014; Ferraro and Griffiths 2016). This is the rapid adjustment which occurs in a short timescale, when the change in the radiative balance is compensated by the changes in the latent and sensible heat fluxes (Bala et al., 2008). Increased CO_2 concentration in the atmosphere produces the temperature-independent forcing and a decrease in precipitation. This is because CO_2 affects the LW radiation in the whole troposphere. However, when the climate warms, water vapor concentration is increased in the atmosphere. This increase would lead to an increase in precipitation which exceeds the decrease in precipitation due to the GHG radiative forcing. In SRM scenarios the GHG induced warming from 2010 (slow response) is roughly compensated between the years 2060-2070 thus counterbalancing the temperature-dependent increase in precipitation. However the temperature independent fast response (decrease in precipitation) due to the increased CO_2 concentration remains and is further amplified by the aerosol radiative effects. Aerosol particles both absorb radiation (which is then emitted as LW radiation) and they reduce the SW radiation at surface. These effects have been suggested to lead to a drier climate (Ferraro and Griffiths 2016).

3.2.2 Spatial pattern of temperature and precipitation responses

Next we concentrate on the regional climate impacts ~~between~~ between years 2060-2070 before the SRM is suspended and where the global mean temperature does not change significantly. It has been suggested that global warming would lead to warmer climate in the A~~a~~rctic and high latitudes than in low latitudes (Stocker et al., 2013). In our simulations there is over 2 K~~degrees~~ warming in the arctic area between the years 2060-2070 compared to the 2010s temperatures in the **RCP45** scenario (fig 8~~6~~a). If the global mean temperature change due to the increased GHG concentration is compensated by~~Together with~~ a relatively uniform reduction in the SW radiation (reduction in the solar constant), it has been shown to lead to warming in the high latitudes and cooling in~~at~~ the low latitudes compared to the temperature before the increase in GHG concentration and SRM (Kravitz et al., 2013c; Schmidt et al., 2012). Our results show that there will be cooling in the tropics and small warming at the midlatitudes in scenario **EQ** as indicated by earlier studies. However there is also cooling at the arctic (fig8~~6~~b) which was discussed in section 3.2.1. This was likely mainly caused by changes ocean circulations in 2010-2020 and not SRM scenarios studied here. ~~. This might be because climate in the northern hemisphere will still be cooler in 2060-2070 than reference years (2010-2020). The arctic sea ice will respond strongly to temperature changes and the ice cover area is 8% larger in~~ ~~**EQ**~~ ~~between years 2060-2070 than in the beginning of the simulation. In addition, this area is significantly warmer in one of the ensemble members between years 2010 – 2020 compared to other simulations.~~ Overall the size of the area of this arctic cooling region is small compared to the regions in the midlatitudes which have been warmed after the year ~~2010~~2020.~~s.~~

Fig 8~~6~~ c-f shows the difference between the alternative injection and scenario **EQ**. In scenarios **p2** and **p2w** there is less radiative forcing at the tropics and a larger radiative effect in the higher latitudes compared to scenario **EQ**. Although this does not translate directly to differences in the regional temperature near the surface as they are affected by other factors in the climate (Stocker et al., 2013), both **p2** and **p2w** show statistically significant cooling at the midlatitudes at North America and Northern Pacific when compared to **EQ**. In these areas scenario **EQ** leads to warming from years 2010-2020. As expected, the ~~equator~~Equator was warmer in **p2w** compared to scenario **EQ**.

If the stratospheric sulfur injections were concentrated to the Northern Hemisphere (**NH**), it would lead to a significant cooling in the northern midlatitudes compared to the injections to the Equator (**EQ**). However, the polar region north of Eurasia in **NH** is not cooler compared to the scenario **EQ**. The Arctic area is warmer than in scenario **EQ** especially in the boreal winter, when the cooling effect of the particles from the **NH** injections is weak (Fig 9a). On the other hand, in the **EQ** scenario the mean global climate will be cooler, which can affect the Arctic temperatures through oceanic and atmospheric circulation. Figure 10 shows the difference in the Arctic sea ice cover between the **EQ** and **NH** scenarios in the boreal summer and winter. Scenario **NH** leads to a larger ice cover north of the North America and East Siberian Sea in the boreal summer and over the Atlantic and Pacific in the boreal winter. However over the Barents and Kara seas there is more sea ice cover in the **EQ** scenario. This area is affected by the warm Gulf Stream and the Norwegian current. In the **EQ** scenario, the Atlantic SST is cooler than in scenario **NH** and sea ice cover in north of Eurasia is larger in scenario **EQ** also in the boreal summer months, when sulfate from **NH** scenario reflects radiation most efficiently. Thus, based on these results, the injections only to the Northern Hemisphere do not increase the yearly arctic sea ice cover compared to the injections to Equator. A more detailed analysis would be required to generalize these findings; however, it is out of the scope of this study. Furthermore, it would be beneficial to repeat these scenarios also with other climate models to see whether the simulated response is robust across models. ~~If stratospheric sulfur injections were concentrated to the northern hemisphere (**NH**) it would lead to a significant cooling in northern midlatitudes compared to injections to the equator (**EQ**). Nevertheless, polar region over Eurasia is not cooler compared to scenario **EQ**. Arctic area is warmer especially in boreal winter, when the cooling effect of the particles from the northern hemisphere injections is weak (fig7a). On other hand in **EQ** scenario the climate will be generally cooler and thus climate also is cooler at the polar regions over Eurasia compared to scenario **NH**. Thus based on these results, for example the melting of the arctic ice cover is prevented more efficiently by injecting sulfur to the equator than concentrating the injections only to the northern hemisphere which would cool area mainly in boreal summer.~~ In scenario **NHSH** the N~~n~~orthern H~~h~~emisphere is generally cooled less by sulfate aerosols and thus polar region is even warmer compared to **NH** and **EQ**. In addition in scenario **NHSH**, the tropical region is warmer compared to scenario **EQ** as was expected based on the distribution and magnitude of radiative forcing in~~on~~ fig 4~~3~~.

Radiative forcing simulated and calculated by ECHAM-HAMMOZ (see Sect. 3.1) showed that scenarios **p2** and **p2w** lead to an amplified seasonal effect of radiative forcing ~~in hemisphere~~ compared to **EQ** (fig5~~4~~c,d). Thus **p2w** leads to a 0.05 K cooler climate in the northern Northern Hhemisphere summer (JJA, fig97b) and a 0.05 K cooler climate in the Ssouthern Hhemisphere summer (DJF, fig97a) than **EQ**. TheIt is noteworthy that sstrong radiative forcing does not translate to large changes in temperature. For example, if we compare the cooling in different scenarios to the scenario without SRM (**RCP45**), compared to the simulation **EQ** the summer time forcging in scenario **p2w** is 17% stronger in the Nnorthern Hhemisphere and 14% in the Ssouthern Hhemisphere. However, scenario **p2w** leads to only 3% cooler climate in the Nnorthern and Ssouthern Hhemisphere summers than scenario **EQ**.

GHG induced climate warming would increase the global mean precipitation as was seen in section chapter 3.2.1. Figure 118a shows that the yearly mean increase in precipitation is largest at the equatorial Pacific. This is in good agreement with intergovernmental panel on climate change (IPCC) estimations (Stocker et al., 2013). These regions correspond to the spatial maximum of sea surface temperature (SST) warming at equatorial Pacific (Xie et al., 2010). Similarly SST warming exceeds the mean SST warming at northern Pacific and Atlantic where precipitation has increased. It has also been also shown that P – E (Precipitation – Evaporationss) will become more intense when climate warms (Seager et al., 2010) which will cause wet areas to become wetter but also drying in the subtropical regions such as Mediterranean, Southern part of Africa and Australia. In the **EQ** scenario, precipitation is decreased in the equatorial Pacific where SST is mainly decreased from the years 2010-2020 (fig118b). The only exception is the eastern part of equatorial Pacific where there has been slight warming in SST which is resulted results in increased precipitation. In addition in **EQ** scenario, P-E is not significantly changed in the subtropical regions and the precipitation is at the same level as in 2010s. However there is clearly less precipitation in the northern part of South-America in both scenarios **RCP45** and **EQ**. This might be due to the change in the Atlantic SST gradient (similar in **RCP45** and **EQ**) and its influence to ITCZ (Haywood et al., 2013). This will lead to reduced moisture which is transported from Atlantic. If sulfur is injected to the Nnorthern Hhemisphere (scenario **NH**), the change in the Atlantic SST gradient is opposite compared to scenario **RCP45** and **EQ** which leads to increased precipitation in northern South-America and drying of Sahel (fig118c).

Overall regional precipitation changes between the studied injection scenarios are not statistically significant. All alternative injection scenarios lead to a slight decrease in the Atlantic SST gradient which leads to drier Sahel but simultaneously to increased precipitation in the southern equatorial Atlantic compared to scenario **EQ**. In aAddition, equatorial Pacific SST is decreased relatively more compared to scenario **EQ** which leads to a larger reduction in precipitation especially in scenarios **p2** and **p2w**. The sSeasonal zonal mean precipitation response is slightly different in scenarios **EQ** and **p2** (fig107c,d).

ForAt JJA there is a relatively large difference in the zonal mean anomalies of precipitation at tropics between the **EQ** and **p2** scenarios (Fig 107c,d). In both case there will be less precipitation compared to the reference years (2010-2020), but the decrease is clearly larger in the northern low latitudes in **p2** than in **EQ** and vice versaopposite at the southern low latitudes. Sobel and Camargo (2011) showed that an increase in the summer hemisphere SST and a decrease in the winter hemisphere

SST leads to the strengthening of easterly trade winds in the winter subtropics and to their weakening in the summer subtropics. This is further associated to Hadley cell circulation and ITCZ which affect strongly to the precipitation response in the Tropics. As has been shown, **p2** leads to a larger cooling effect at the summer hemisphere and a weaker cooling effect in~~at~~ the winter hemisphere when compared to~~than~~ scenario **EQ**.~~, which might explain different seasonal precipitation responses at tropics.~~

4. Summary and conclusions

Here we used an atmosphere-only General Circulation Model~~GCM~~ coupled to an aerosol model to simulate the radiative properties of different stratospheric sulfur injection strategies as opposed~~than~~ injecting sulfur only to the ~~equator~~Equator. In the second part of the study we examined~~studied~~ how the radiative forcings from different injection scenarios translate to temperature and precipitation impacts by using the Max Planck Institute Earth System Model. We estimated how different emission areas of stratospheric sulfur could be used to prevent the overcooling of the tropics and undercooling of the midlatitudes and the Arctic without a decrease in the global mean radiative forcing of the stratospheric sulfur injections. ~~to optimize the aerosol radiative forcing as well as how the decrease in the meridional temperature gradient typical for SRM scenarios could be minimized.~~

In all simulated scenarios, 5 Tg(S)/yr of SO_2 was injected into 20° latitude wide band (2 bands in **NHSH**) and the resulting radiative and climate effects were compared to those in a scenario where sulfur is injected only above the E~~e~~quator. According to our aerosol microphysical simulations by GCM, it would be possible to maintain as large global cooling effect as by injecting sulfur only o~~i~~n the ~~equator~~Equator while concentrating the cooling effect more to the midlatitudes than tropics. This could be achieved if the sulfur injection area is changed during the year. Such a scenario was **p2w** where the injection area changed from its northernmost position (40° N - 20° N) at April to the southernmost position (20° S - 40° S) at October. In this scenario the mean radiative forcing was 27% smaller between 20° N and 20° S latitudes and outside this area 15% larger than in the simulation **EQ** which assumed fixed continuous injection area over the ~~equator~~Equator (10° S - 10° N). If the injection area is changed similarly but between 30° N and 30° S latitudes (**p2**), the global mean shortwave radiative forcing was 3% larger than injecting sulfur only ~~equator~~Equator (**EQ**). More of the injected sulfur was located at the summer hemisphere in **p2w** scenario compared to **EQ**. Thus the radiative forcing was relatively larger in the summer hemisphere (17% in the Northern and 14% in the Southern) and relatively weaker in the winter hemispheres (14% in the Northern and 16% in the Southern) compared to **EQ**. ~~Thus the radiative forcing was relatively larger (15%) in the summer hemispheres and relatively weaker (15%) at winter hemispheres compared to **EQ**~~.

Based on this study the effectiveness of a seasonally changed injection area depends on the seasonality (the intensity) of ~~(intensity)~~ solar radiation, oxidation of SO_2 (which depends on availability of OH) and the lifetime of sulfate particles. ~~It is~~

~~noteworthy that our~~Our simulations indicate that the global mean radiative forcing ~~efficiency~~ of the aerosol ~~radiative forcing in Scenario **EQ**~~ was not significantly increased in any of our simulations compared to the equatorial injection scenario **EQ**. However, the scenarios studied here are only the first step towards more optimal injection scenarios. A full optimization would require a more detailed analysis of the incoming and the reflected solar radiation, atmospheric circulation and how it is affected by sulfur fields as well as aerosol microphysics and chemistry. Overall, however, theresults of this study already show the potential of time-varying injection scenarios.

Scenarios simulated by ESM were based on GeoMIP G4 scenarios, where the aerosols injection (5 Tg(S)/yr instead of 2.5 Tg(S)/yr in G4) is ~~been~~ started at full force in 2020 and then suspended in 2070. Solar radiation management scenarios studied here lead to a cooling of 1.13 – 1.34 K. ~~Compared to **RCP45** the warming rate between years 2030-2070 was reduced from 1.95 K / 100 yr to 1.25 K / 100 yr in SRM scenarios due to the ocean cooling caused by aerosol radiative effect. This highlights the role of feedbacks and ocean temperature which reacts slowly to the radiation changes in the atmosphere.~~

ESM simulations also showed that by changing the injection area during the year, it would be possible to get more cooling to the midlatitudes and less cooling in the~~at~~ tropics compared to injections only to the ~~equator~~Equator. This can be ~~also~~ achieved by injecting sulfur only to 30° N - 10° N and 10° S - 30° S latitudes (**NHSH**). However, then the climate cooling was 15% smaller than in scenarios where the injection area was varying during the year. These injection strategies could be used to avoid reduction of meridional temperature gradient, which has been seen in many previous studies where SRM have been investigated (Schmidt et al., 2012, Kravits et al., 2016). ~~Results of this study also indicate that the melting of arctic sea ice is more efficiently prevented by tropical injections than injection only to northern hemisphere (30° N - 10° N, scenario **NH**), in which case the cooling effect at boreal winter is relatively weak.~~

The global mean precipitation was clearly decreased in all of our SRM simulations even though the temperature changes were~~as~~ roughly compensated. This is consistent with earlier studies. When looking at seasonal values, different injection scenarios led to different results especially at the tropics.

Even though seasonally varying injection areas could allow for more control over the geographic pattern of the radiative forcing compared to equatorial injections, this might not lead to large differences in regional climate impacts. This is because the heat transport via the oceans and the atmosphere greatly smooth~~s~~ out the impacts from spatially inhomogeneous aerosol forcing. In addition, due to the atmospheric transport, it is impossible to concentrate the radiative forcing from sulfur injections to any limited area. Thus, stratospheric sulfur injections are not an effective method with which to aim for certain regional temperature or precipitation impacts. Despite this, our results indicate that seasonally changing injection areas could resolve some of the spatial inhomogeneities resulting from more commonly studied equatorial injections. ~~However modelling precipitation changes is very uncertain and making valid conclusions about regional precipitation by using global model is challenging.~~

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References

Aswathy, V. N., Boucher, O., Quaas, M., Niemeier, U., Muri, H., Mülmenstädt, J., and Quaas, J.: Climate extremes in multi-model simulations of stratospheric aerosol and marine cloud brightening climate engineering, Atmos. Chem. Phys., 15, 9593-9610, doi:10.5194/acp-15-9593-2015, 2015.

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

Bony, S., Bellon, G., Klocke, D., Sherwood, S., Fermepin, S., and Denvil, S.: Robust direct effect of carbon dioxide on tropical circulation and regional precipitation, Nat. Geosci., 6, 447-451, 2013.

Bergman, T., Kerminen, V.-M., Korhonen, H., Lehtinen, K. J., Makkonen, R., Arola, A., Mielonen, T., Romakkaniemi, S., Kulmala, M., and Kokkola, H.: Evaluation of the sectional aerosol microphysics module SALSA implementation in ECHAM5-HAM aerosol-climate model, Geosci. Model Dev., 5, 845–868, doi:10.5194/gmd-5-845-2012, 2012.

Dentener, F., Kinne, S., Bond, T., Boucher, O., Cofala, J., Generoso, S., Ginoux, P., Gong, S., Hoelzemann, J. J., Ito, A., Marelli, L., Penner, J. E., Putaud, J.-P., Textor, C., Schulz, M., van der Werf, G. R., and Wilson, J.: Emissions of primary aerosol and precursor gases in the years 2000 and 1750 prescribed data-sets for AeroCom, Atmos. Chem. Phys., 6, 4321–4344, doi:10.5194/acp-6-4321-2006, 2006.

English, J. M., Toon, O. B., and Mills, M. J.: Microphysical simulations of sulfur burdens from stratospheric sulfur geoengineering, Atmos. Chem. Phys., 12, 4775-4793, doi:10.5194/acp-12-4775-2012, 2012.

Feichter, J., Kjellsttrom, E., Rodhe, H., Dentener, F., Lelieveldi, J., and Roelofs, G.-J.: Simulation of the tropospheric sulfur cycle in a global climate model. Atmospheric Environment, 30(10-11):1693 - 1707, doi:http://dx.doi.org/10.1016/1352-2310(95)00394-0. Joint 8th CAGCP and 2nd IGAC Conference on Global Atmospheric Chemistry, 1996.

Ferraro, A. J., Highwood, E. J., and Charlton-Perez, A. J.: Weakened tropical circulation and reduced precipitation in response to geoengineering, Environ. Res. Lett., 9, doi:10.1088/17489326/9/1/014001, 2014.

Ferraro., A. J. and Griffiths, H. G.: Quantifying the temperature-independent effect of stratospheric aerosol geoengineering on global-mean precipitation in a multi-model ensemble, Environ. Res. Lett. 11 034012, doi.org/10.1088/1748-9326/11/3/034012, 2016.

Haywood, J. M., Jones, A., Bellouin, N., Stephenson, D.: Asymmetric forcing from stratospheric aerosols impacts Sahelian rainfall, Nature Clim. Change, 3, 660–665, doi:10.1038/nclimate1857, 2013.

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, 2009.

Giorgetta, M., Jungclaus, J., Reick, C. H., Legutke, S., Bader, J., Böttinger, M., Brovkin, V., Crueger, T., Esch, M., Fieg, K., Glushak, K., Gayler, V., Haak, H., Hollweg, H.-D., Ilyina, T., Kinne, S., Kornblueh, L., Matei, D., Mauritsen, T., Mikolajewicz, U., Mueller, W., Notz, D., Pithan, F., Raddatz, T., Rast, S., Redler, R., Roeckner, E., Schmidt, H., Schnur, R., Segschneider, J., Six, K. D., Stockhause, M., Timmreck, C., Wegner, J., Widmann, H., Wieners, K.-H., Claussen, M., Marotzke, J., and Stevens, B.: Climate and carbon cycle changes from 1850 to 2100 in MPI-ESM simulations for the coupled model intercomparison project phase 5, J. Adv. Model. Earth Syst., 5, 572–597, doi:10.1002/jame.20038, 2013.

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.

Ilyina, T., Six, K. D., Segschneider, J., Maier-Reimer, E., Li, H., and& Nunez-Riboni, I.. Global ocean biogeochemistry model HAMOCC: Model architecture and performance as component of the MPI-Earth System Model in different CMIP5 experimental realizations.J. Adv. Model. Earth Syst. , 5, 287-315. doi:10.1029/2012MS000178, 2013.

Jones, A., Haywood, J. M., Alterskjær, K., Boucher, O., Cole, J. N. S., Curry, C. L., Irvine, P. J., Ji, D., Kravitz, B., Kristjánsson, J. E.., Moore, J. C., Niemeier, U., Robock, R., Schmidt, H. Singh, H., Tilmes, S., Watanabe, S. and Yoon, J.H.; The impact of abrupt suspension of solar radiation management (termination effect) in experiment G2 of the Geoengineering Model Intercomparison Project (GeoMIP), Journal of Geophysical Research, 118(17), 9743-9752, doi:10.1002/jgrd.50762, 2013.

Jones, A. C., Haywood, J. M., and Jones, A.: Climatic impacts of stratospheric geoengineering with sulfate, black carbon and titania injection, Atmos. Chem. Phys., 16, 2843-2862, doi:10.5194/acp-16-2843-2016, 2016.

Kashimura, H., Abe, M., Watanabe, S., Sekiya, T., Ji, D., Moore, J. C., Cole, J. N. S., and Kravitz, B.: Shortwave radiative forcing, rapid adjustment, and feedback to the surface by sulfate geoengineering: analysis of the Geoengineering Model Intercomparison Project G4 scenario, Atmos. Chem. Phys., 17, 3339-3356, doi:10.5194/acp-17-3339-2017, 2017.Kashimura, H., Abe, M., Watanabe, S., Sekiya, T., Ji, D., Moore, J. C., Cole, J. N. S., and Kravitz, B.: Shortwave radiative forcing and feedback to the surface by sulphate geoengineering: Analysis of the Geoengineering Model Intercomparison Project G4 scenario, Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-711, in review, 2016.

Jungclaus, J. H., Fischer, N., Haak, H., Lohmann, K., Marotzke, J., Matei, D., Mikolajewicz, U., Notz, D., & von Storch, J.-S.. Characteristics of the ocean simulations in MPIOM, the ocean component of the MPI Earth System Model. J. Adv. Model. Earth Syst. , 5, 422-446. doi:10.1002/jame.20023, 2013.

Kinne, S., D. O'Donnell, D., P. Stier, P., S. Kloster, S., K. Zhang, K., H. Schmidt, H., S. Rast, S., M. Giorgetta, M., T. F. Eck, T.F and B. Stevens, B., MAC-v1: A new global aerosol climatology for climate studies, J. Adv. Model. Earth Syst., 5, 704–740, doi:10.1002/jame.20035, 2013.

Kokkola, H., Korhonen, H., Lehtinen, K. E. J., Makkonen, R., Asmi, A., Järvenoja, S., Anttila, T., Partanen, A.-I., Kulmala, M., Järvinen, H., Laaksonen, A., and Kerminen, V.-M.: SALSA – a Sectional Aerosol module for Large Scale Applications, Atmos. Chem. Phys., 8, 2469–2483, doi: 10.5194/acp-8-2469-2008, 2008.

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

Kravitz, B., Robock, A., Forster, P. M., Haywood, J. M., Lawrence M. G., and Schmidt, H.: An overview of the Geoengineering Model Intercomparison Project (GeoMIP), Journal of Geophysical Research, 118, 13103-13107, doi:10.1002/2013JD020569, 2013a.

Kravitz, B.., Rasch, P. J., Forster, P. M., Andrews, T., Cole, J. N. S., Irvine, P. J., Ji, D., Kristjánsson,J. E., Moore, J. C., Muri, H., Niemeier, U., Robock, A., Singh, B., Tilmes, S., Watanabe, S., and Yoon, J.-H.: , An energetic perspective on hydrological cycle changes in the Geoengineering Model Intercomparison Project, J. Geophys. Res. Atmos., 118, 13,087–13,102, doi: 10.1002/2013JD020502, 2013b.

Kravitz, B., Caldeira, K., Boucher, O., Robock, A., Rasch, P. J., Alterskjær, K., Karam, D., B., Cole, J. N. S., Curry, C. L., Haywood, J. M., Irvine, P. J., Ji, D., Jones, A.,Kristjánsson, J. E., Lunt, D. J., Moore, J. C., Niemeier, U., Schmidt, H., Schulz, M., Singh, B., Tilmes, S., Watanabe, S., Yang, S., and Yoon, J.-H.:, Climate model response from the Geoengineering Model Intercomparison Project (GeoMIP), J. Geophys. Res. Atmos., 118, 8320–8332, doi:10.1002/jgrd.50646, 2013c.

Kravitz, B., MacMartin, D. G., Wang, H., and Rasch, P. J.: Geoengineering as a design problem, Earth Syst. Dynam., 7, 469-497, doi:10.5194/esd-7-469-2016, 2016.

Laakso, A., Kokkola, H., Partanen, A.-I., Niemeier, U., Timmreck, C., Lehtinen, K. E. J., Hakkarainen, H., and Korhonen, H.: Radiative and climate impacts of a large volcanic eruption during stratospheric sulfur geoengineering, Atmos. Chem. Phys., 16, 305-323, doi:10.5194/acp-16-305-2016, 2016.

MacMartin, D. G., Keith, D. W., Kravitz, B., and Caldeira, K.: Management of trade-offs in geoengineering through optimal choice of non-uniform radiative forcing, Nat. Clim. Change, 3, 365–368, doi:10.1038/nclimate1722, 20132.

McCusker, K. E., Battisti, D. S. and Bitz, C. M.: The climate response to stratospheric sulfate injections and implications for addressing climate emergencies, J. Clim., 25(9), 3096–3116, doi:10.1175/JCLI-D-11-00183.1, 2012.

Modak, A. and Bala, G.: Sensitivity of simulated climate to latitudinal distribution of solar insolation reduction in solar radiation management, Atmos. Chem. Phys., 14, 7769-7779, doi:10.5194/acp-14-7769-2014, 2014.

Moss, R. H., Edmonds, J. A., Hibbard, K. A., Manning, M. R., Rose, S. K., van Vuuren, D. P., Carter, T. R., Emori, S., Kainuma, M., Kram, T., Meehl, G. A., Mitchell, J. F. B., Nakicenovic, N., Riahi, K., Smith, S. J., Stouffer, R. J., Thomson, A. M., Weyant, J. P., and Wilbanks, T. J.: The next generation of scenarios for climate change research and assessment, Nature, 463, 747–756, doi:10.1038/nature08823, 2010.

Niemeier, U., Schmidt, H., and Timmreck, C.: The dependency of geoengineered sulfate aerosol on the emission strategy, Atmos. Sci. Lett., 12, 189–194, doi: 10.1002/asl.304, 2011.

Pierce, J. R.; Weisenstein, D. K.; Heckendorn, P.; Peter, T.; Keith, D. W.: Efficient formation of stratospheric aerosol for climate engineering by emission of condensable vapor from aircraft, Geophysical Research Letters, 37, doi:10.1029/2010GL043975, 2010.

Pope, F. D., Braesicke, P., Grainger, R. G., Kalberer, M., Watson, I. M., Davidson, P. J., and Cox, R. A.: Stratospheric aerosol particles and solar-radiation management, Nature Clim. Change, 2, 713-719, doi:10.1038/nclimate1528, 2012.

Reick, C., T. Raddatz, T. V., Brovkin, V. and V. Gayler, V., The representation of natural and anthropogenic land cover change in MPI-ESM, J. Adv. Model. Earth Syst., 5, 459-482, doi:10.1002/jame.20022, 2013.

Robock, A., Oman, L., and Stenchikov G. L.: Regional climate responses to geoengineering with tropical and Arctic SO 2 injections, J. Geophys. Res., 113, D16101, doi:10.1029/2008JD010050, 2008.

Royal Society: Geoengineering the climate - Science, governance and uncertainty, RS Policy document 10/09, ISBN: 978-0-85403-773-5, 2009.

Schaller, N.,Sedlácek J., and Knutti R.: The asymmetry of the climate system's response to solar forcing changes and its implications for geoengineering scenarios, J. Geophys. Res. Atmos., 119, 5171–5184,doi:10.1002/2013JD021258, 2014.

Schmidt, H., Alterskjær, K., Bou Karam, D., Boucher, O., Jones, A., Kristjánsson, J. E., Niemeier, U., Schulz, M., Aaheim, A., Benduhn, F., Lawrence, M., and Timmreck, C.: Solar irradiance reduction to counteract radiative forcing from a quadrupling of CO2 : climate responses simulated by four earth system models, Earth Syst. Dynam., 3, 63-78, doi:10.5194/esd-3-63-2012, 2012.

Seager, R., Naik, N., Vecchi, G. A.:Thermodynamic and dynamic mechanisms for large-scale changes in the hydrological cycle in response to global warming. J Clim 23(17):4651–4668. doi: 10.1175/2010JCLI3655.1, 2010.

Sgubin, G., Swingedouw, D., Drijfhout, S., Yannick Mary, Y., Bennabi, A.: Abrupt cooling over the North Atlantic in modern climate models. Nature Communications, 8 DOI: 10.1038/ncomms14375, 2017.

Sobel, A. H. and Camargo, S. J.: Projected future changes in tropical summer climate. Journal of Climate, 24, 473-487, 2011.

Stocker, T., Qin, D., Plattner, G.-K., Tignor, M., Allen, S., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P.: The Physical Science Basis. Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. In IPCC, 2013: Climate Change 2013 . Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2013.

Stevens, B., Giorgetta, M., Esch, M., Mauritsen, T., Crueger, T., Rast, S., Salzmann, M., Schmidt, H., Bader, J., Block, K., Brokopf, R., Fast, I., Kinne, S., Kornblueh, L., Lohmann, U.,Pincus, R., Reichler, T., and Roeckner, E.: The atmospheric component of the MPI-M Earth System Model: ECHAM6, J. Adv. Model. Earth Syst., 5, 1–27, doi:10.1002/jame.20015, 2013.

Taylor, K.E., Stouffer, R.J., Meehl G.A., A summary of the CMIP5 experiment design, World Climate Research Programme (WCRP), http://cmip-pcmdi.llnl.gov/cmip5/docs/Taylor_CMIP5_design.pdf

Trenberth, K.E. and Solomon, A.: The global heat balance: heat transports in the atmosphere and ocean, Climate Dynamics, 10: 107. doi:10.1007/BF00210625, 1994.

Timmreck, C., Graf, H.-F., Lorenz, S. J., Niemeier, U., Zanchettin, D., Matei, D., Jungclaus, J. H., and Crowley T. J.: Aerosol size confines climate response to volcanic super-eruptions (2010), Geophys. Res. Lett., 37, L24705, doi: 10.1029/2010GL045464, 2010.

Tilmes, S., Mills, M. J., Niemeier, U., Schmidt, H., Robock, A., Kravitz, B., Lamarque, J.-F., Pitari, G., and English, J. M.: 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, 2015.

Volodin, E. M., Kostrykin, S. V. and Ryaboshapko, A. G.: Climate response to aerosol injection at different stratospheric locations. Atmosph. Sci. Lett., 12: 381–385. doi:10.1002/asl.351, 2013.

van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G. C., Kram, T., Krey, V., Lamarque, J.-F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S. J., and Rose, S. K.: The representative concentration pathways: an overview, Climatic Change, 109, 5–31, doi:10.1007/s10584-011-0148-z, 2011.

Xie, S., Deser, C., Vecchi, G., Ma, J., Teng, H. and Wittenberg, A.: Global Warming Pattern Formation: Sea Surface Temperature and Rainfall. J. Climate, 23, 966–986, doi: 10.1175/2009JCLI3329.1, 2010.

Yu, X., Moore, J. C., Cui, X., Rinke, A., Ji, D., Kravitz, B., Yoon, J.-H.: Impacts, effectiveness and regional inequalities of the GeoMIP G1 to G4 solar radiation management scenarios. In: Global and Planetary Change. doi: 10.1016/j.gloplacha.2015.02.010, 2015.

Zhang, K., O'Donnell, D., Kazil, J., Stier, P., Kinne, S., Lohmann, U., Ferrachat, S., Croft, B., Quaas, J., Wan, H., Rast, S., and Feichter, J.: The global aerosol-climate model ECHAM-HAM, version 2: sensitivity to improvements in process representations, Atmos. Chem. Phys., 12, 8911–8949, doi:10.5194/acp-12-8911-2012, 2012.

Scenario	***Strat. SO_2 burden Tg(S)***	***Strat. H_2SO_4 burden Tg(S)***	***All-sky SW forcing at TOA (W/m^2)***
EQ	0.69	6.15	-3.72
NH	0.80	5.46	-3.21
NHSH	0.79	5.66	-3.30
p0	0.64	6.15	-3.67
p2	0.66	6.28	-3.82

p4	0.75	6.18	-3.74
p6	0.84	5.98	-3.58
p2w	0.68	6.29	-3.72

Table 1. Five-year mean values of the global stratospheric sulfur dioxide and particulate sulfate burdens and the global shortwave (SW) all-sky forcing. In studied scenarios 5 Tg(S) of sulfur is injected continuously in latitudes showed in figures 1 and 2.

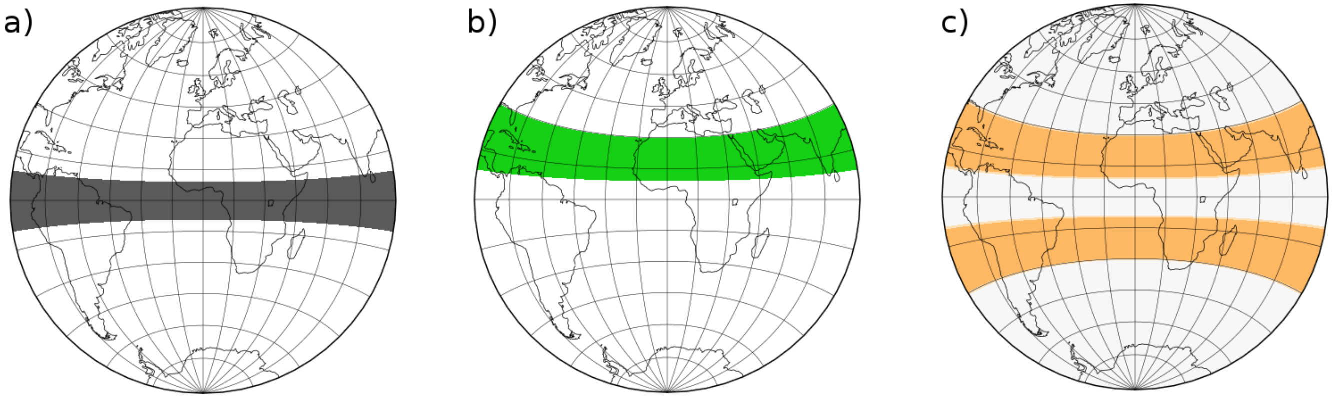

Figure 1. Injection areas in scenarios a) EQ, b) NH and c) NHSH

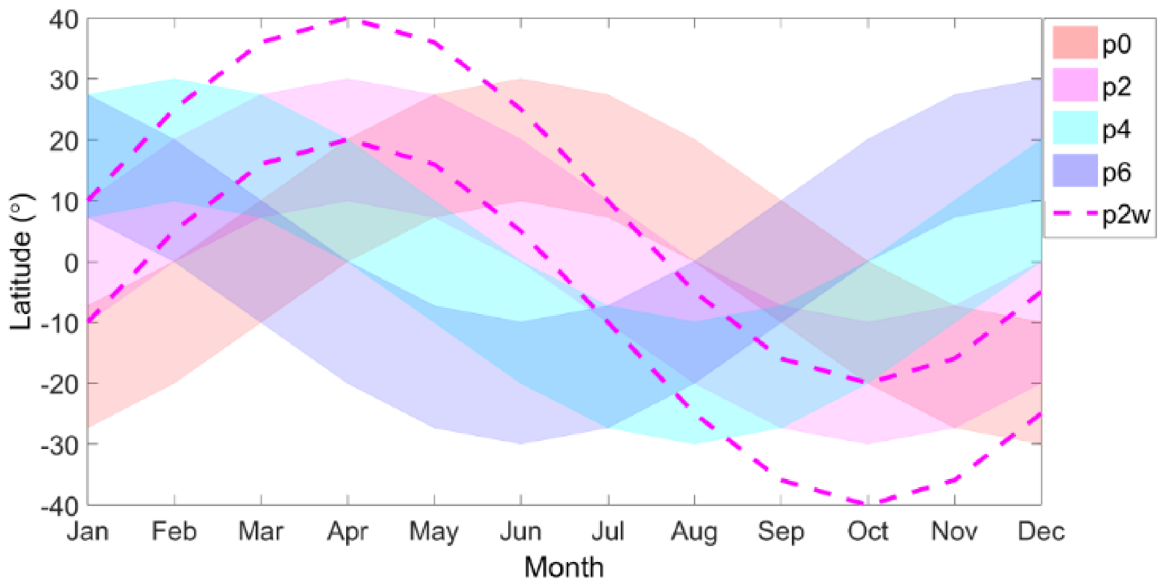

Figure 2. Seasonally changing injection areas in p0, p2, p4 ~~and~~ p6 and p2w scenarios

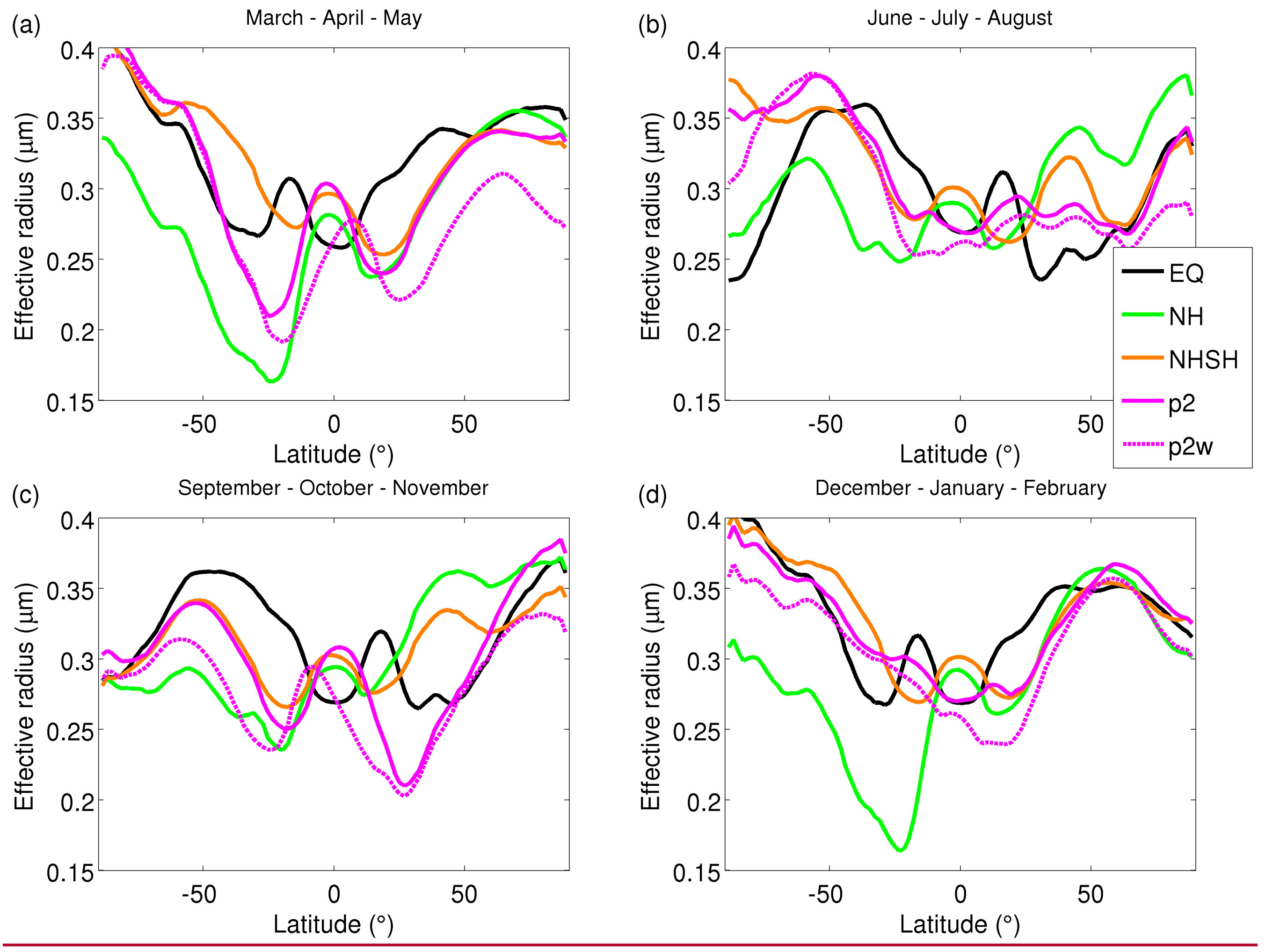

Fig 3. The zonal mean effective radius of the stratospheric particles in a) March – April – May, b) June – July – August, c) September – October – November and d) December – January - February

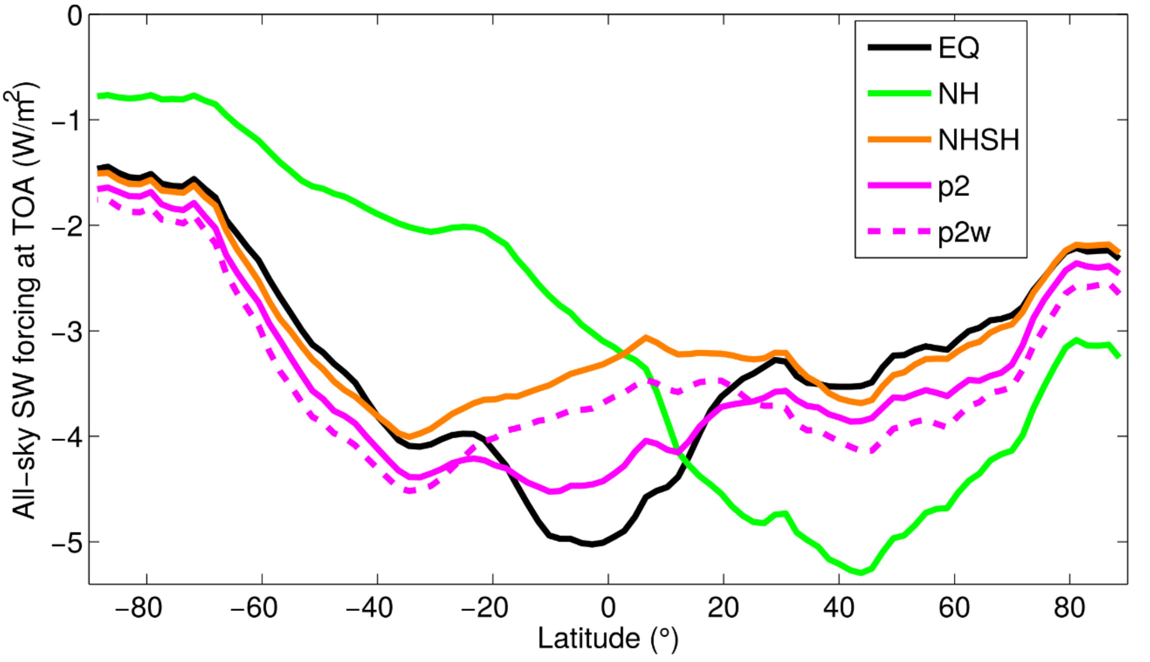

Figure 43. Five-year zonal means of all-sky shortwave radiative forcing in selected scenarios.

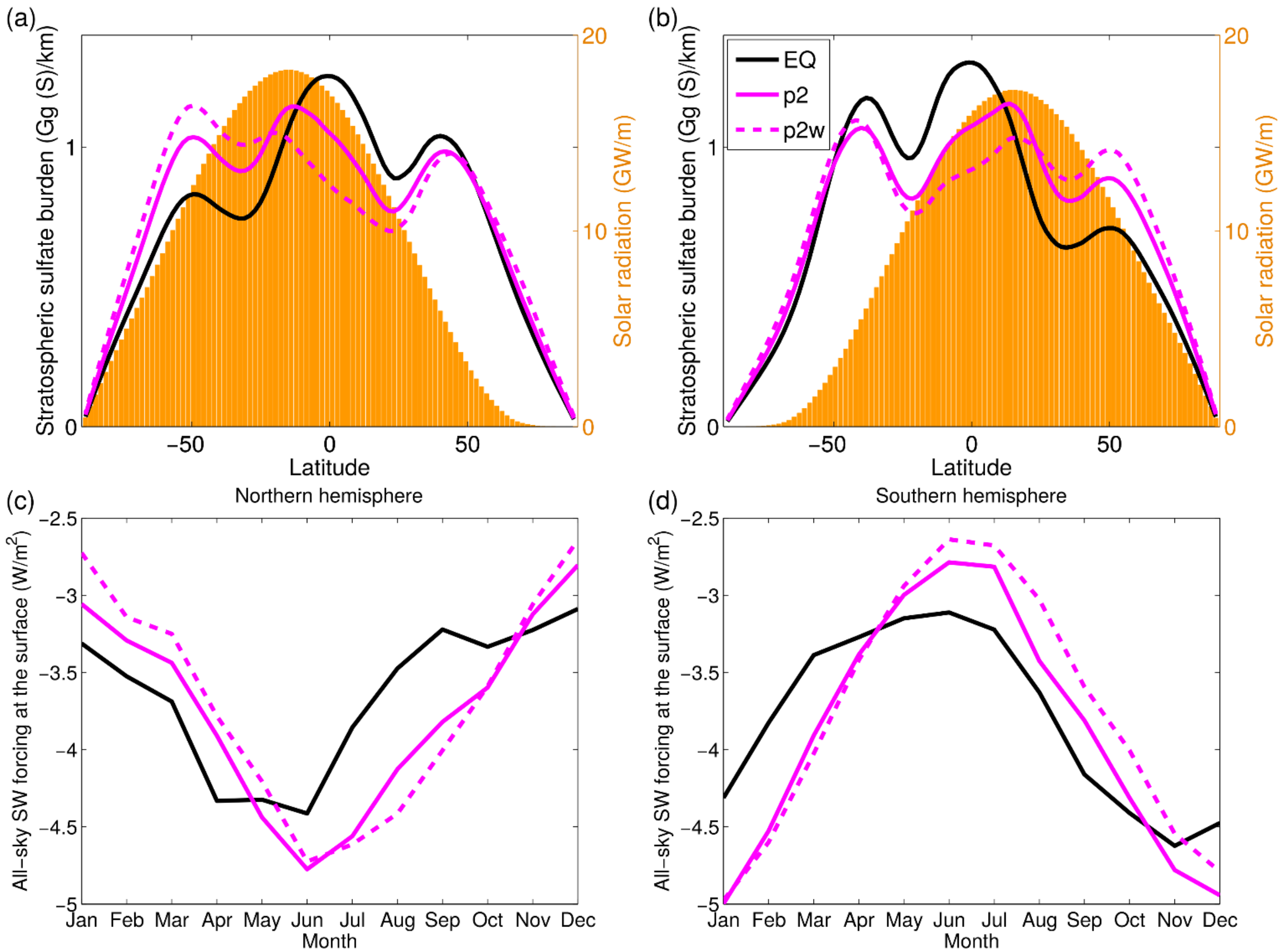

Figure 54. The zonal distribution of stratospheric particulate sulfate burden and the zonally distributed incoming solar radiation in the a) December-January-February and b) June-July-August and the all sky shortwave radiative forcing at c) the Nnorthern Hhemisphere and d) the Ssouthern Hhemisphere. In panels a) and b)- sulfate burden and solar radiation are shown per meridional meter.

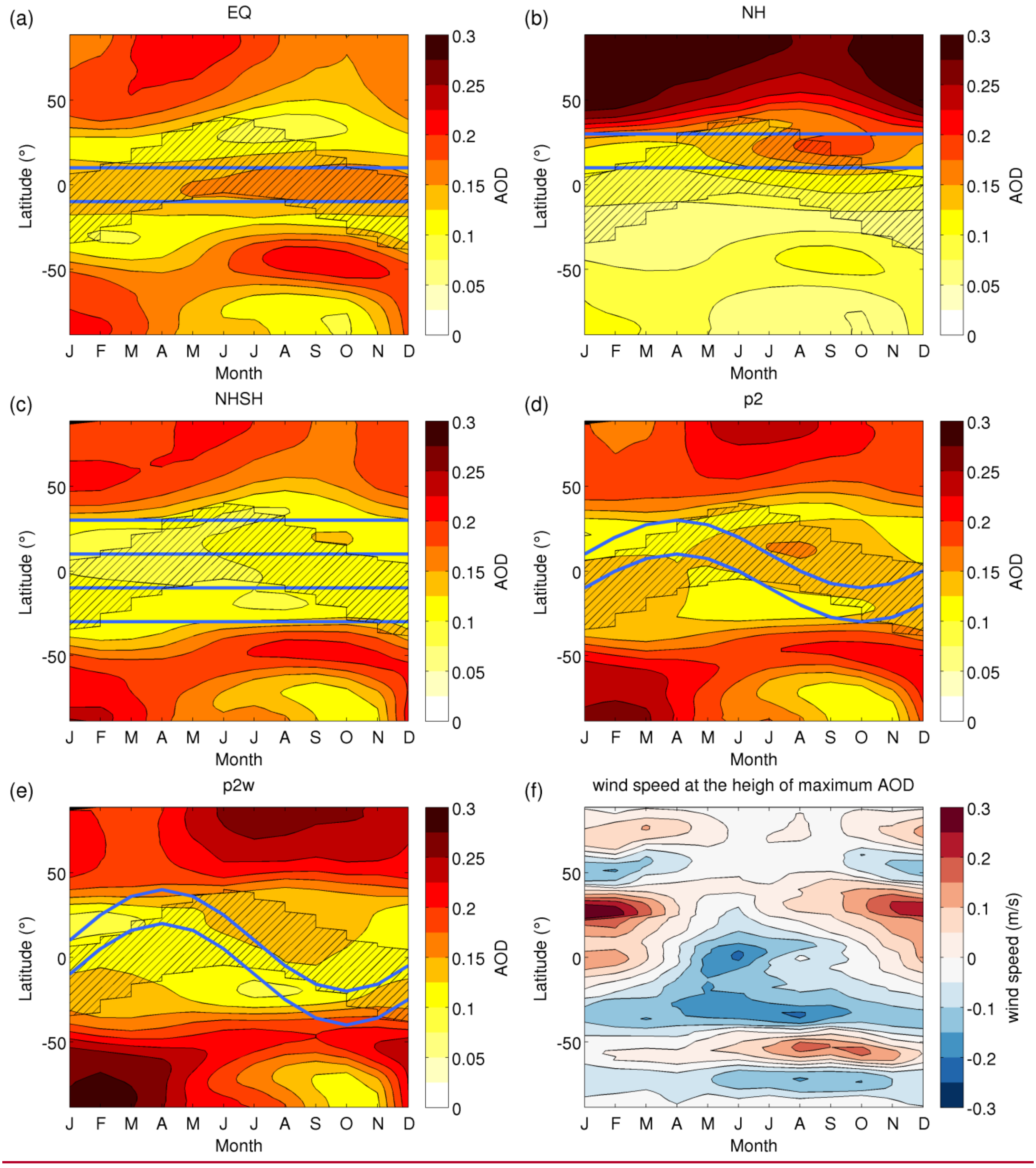
(a)
EQ
(b)
NH
(c)
NHSH
(d)
p2
(e)
p2w
(f)
wind speed at the heigh of maximum AOD
Latitude (°)
Month
J F M A M J J A S O N D
50
0
-50
AOD
0.3
0.25
0.2
0.15
0.1
0.05
0
wind speed (m/s)
-0.1
-0.2
-0.3

Figure 6. The zonal mean stratospheric AOD at 533 nm wavelength in a) EQ, b) NH, c) NHSH, d) p2, e) p2w scenarios and the meridional wind component at the height of maximum AOD (positive values from south to north). The blue lines shows the boundaries of the injection area (two areas at c) NHSH) and the hatching shows latitudes which receive over 50% of monthly solar radiation.

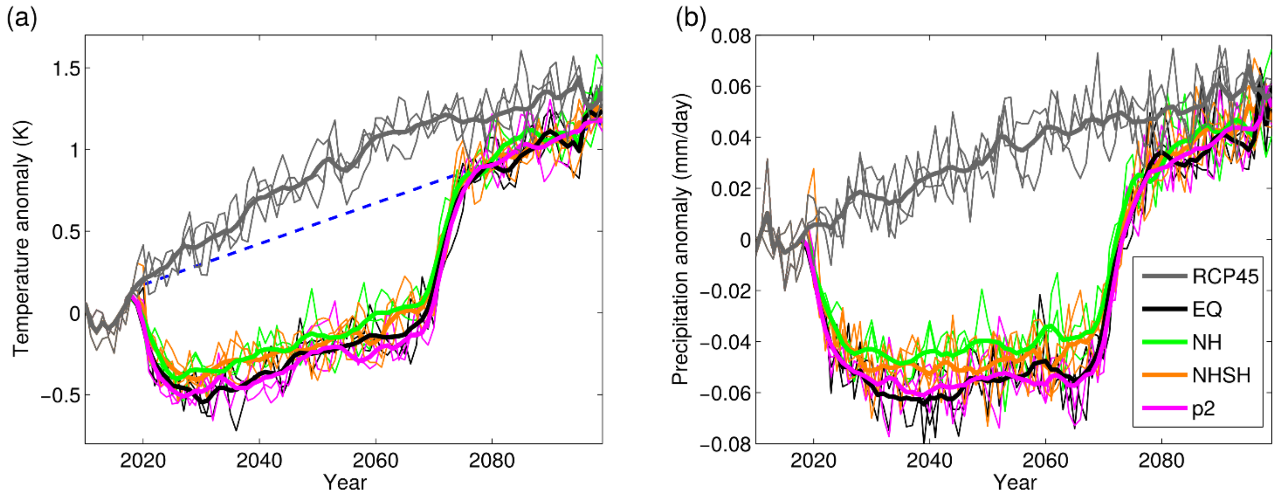

Figure 7~~5~~. Global mean a) temperature, b) precipitation anomaly compared to the mean temperature for~~at~~ 2010-2020~~0s~~. The thick solid line shows the 5-year running ensemble mean values and each narrow line indicates the yearly mean values of one ensemble member. The blue dashed line shows the temperature after year 2020 according to the mean warming rate in EQ between years 2030 and 2070.

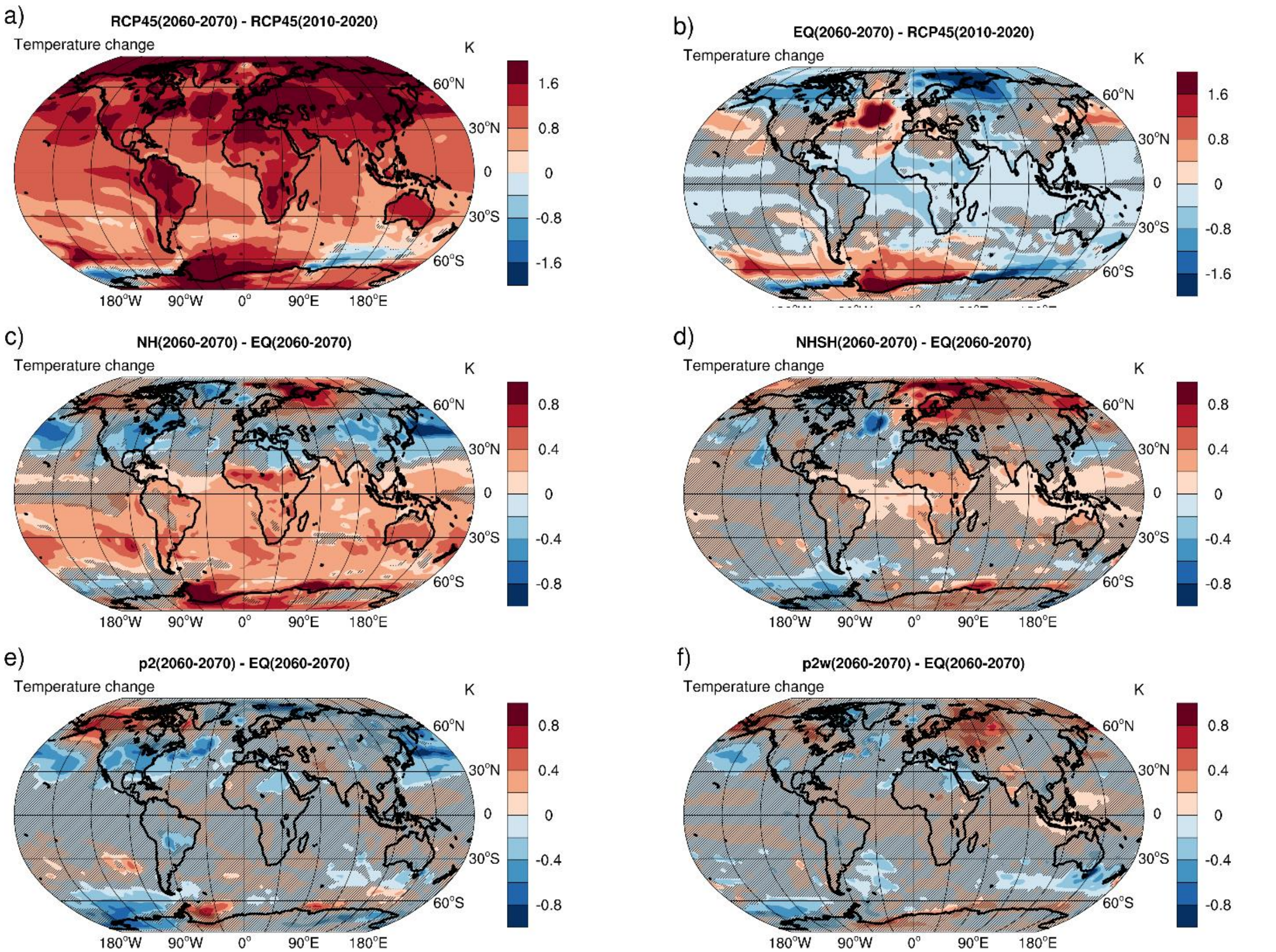

Figure 86. Temperature anomalies for a) RCP45, b) EQ, c) NH, d) NHSH, e) p2 and f) p2w. Anomalies in a) and b) are presented as differences between years 2060-2070 and 2010-2020. Anomalies in c) d) e) and f) are presented as a difference to EQ between years 2060-2070. The hatching indicates regions where the change of the temperature is not statistically significant at 95% level.

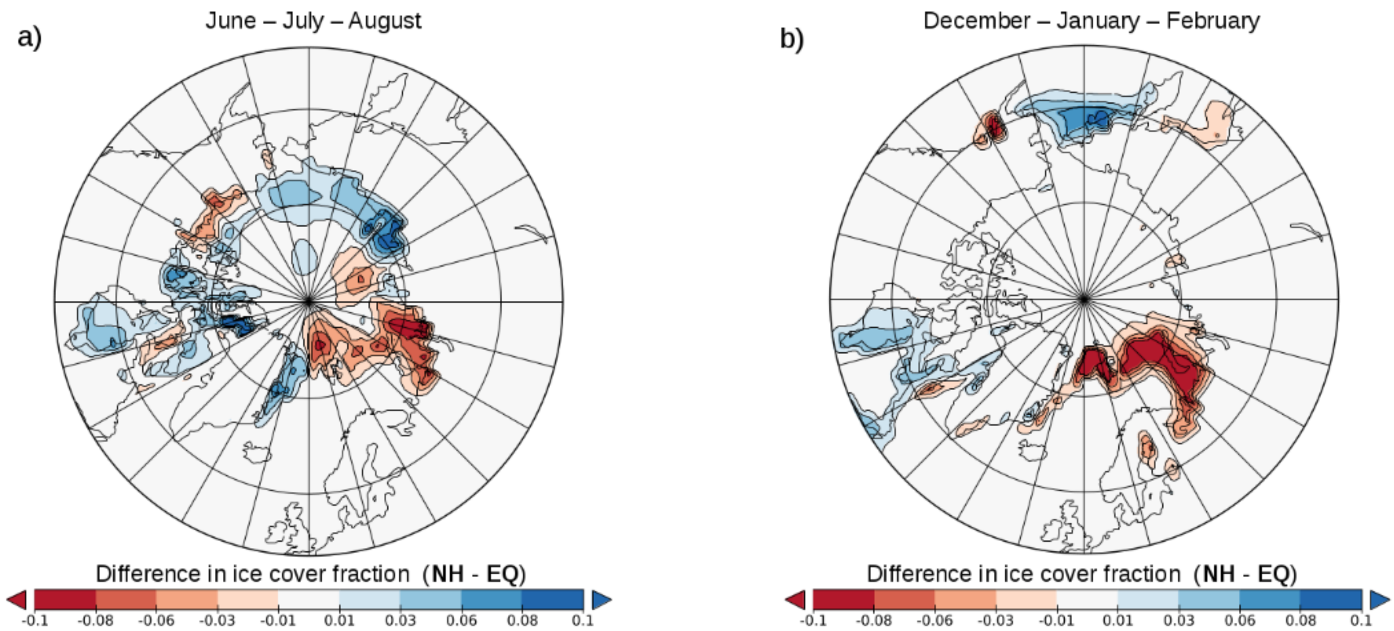

Figure 9. Difference in the ice cover fraction between scenarios NH and EQ in a) June – July – August and b) December – January – February. The blue regions show where the ice cover is larger in scenario NH than in EQ. The red regions shows where ice cover is smaller.

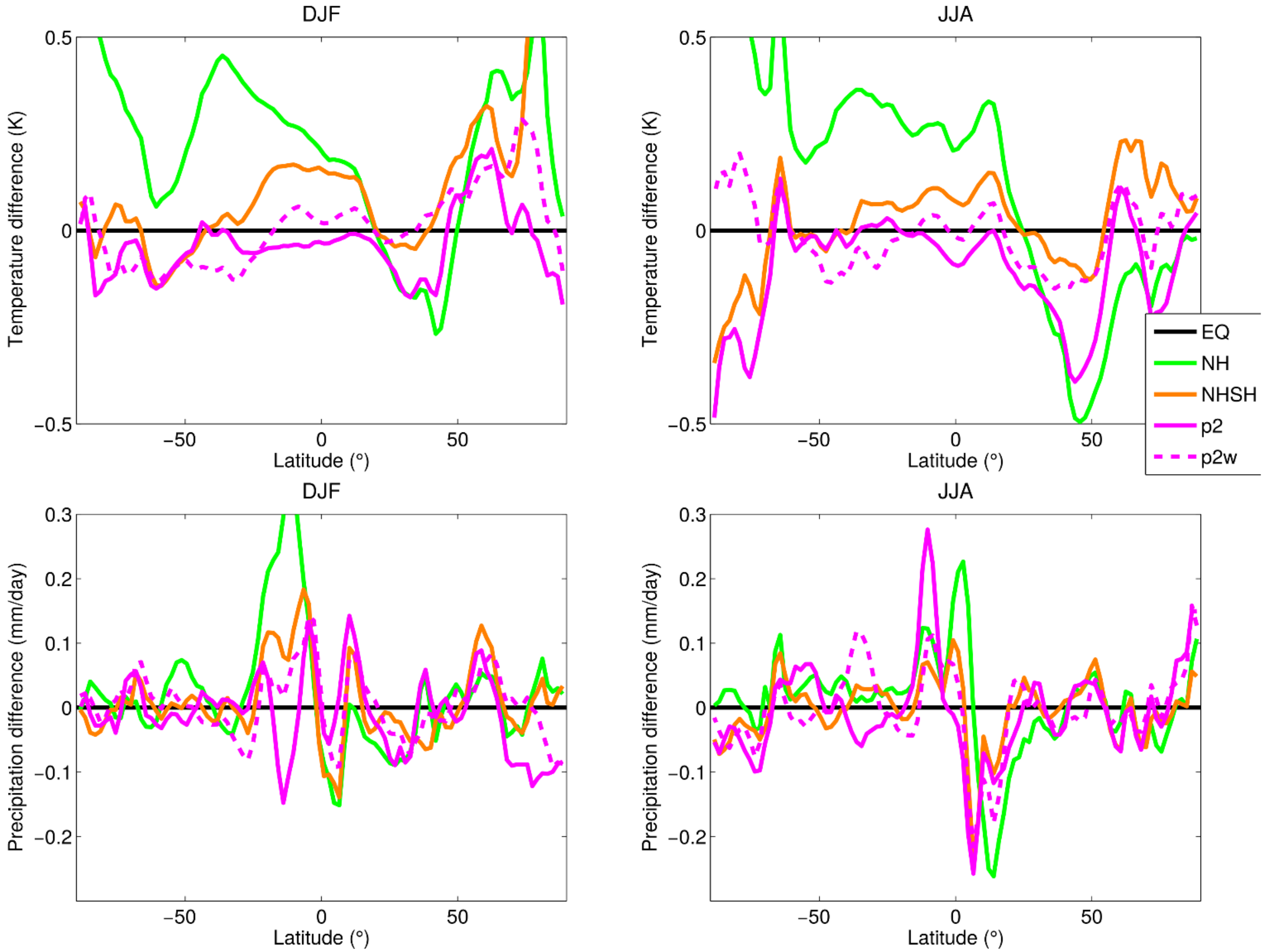

Figure 10~~7~~. The z~~Z~~onal mean anomalies for the temperature in a) December-January-February and b) June-July-August and for precipitation in c) December-January-February d) June-July-August compared to scenario EQ.

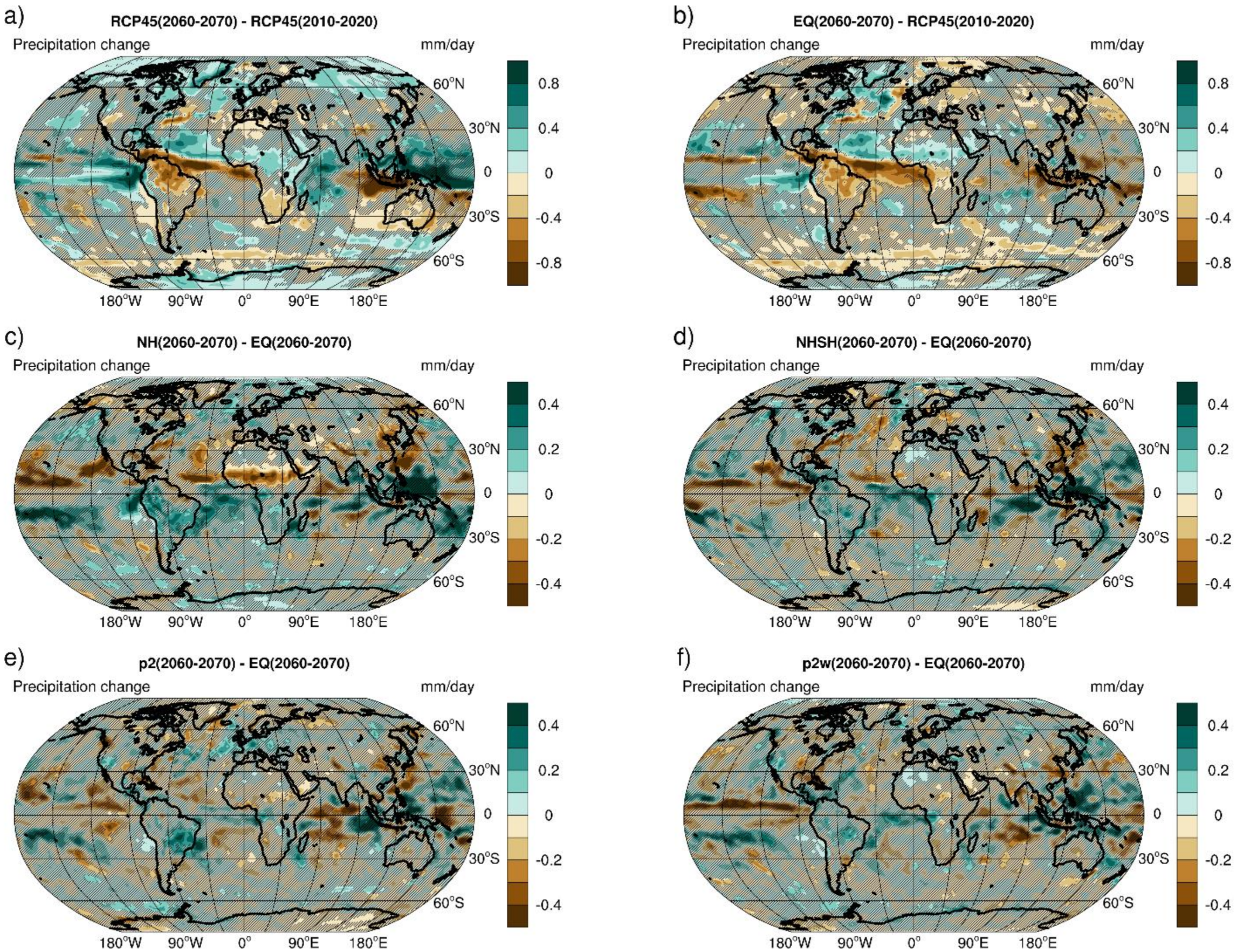

Figure 118. The precipitation anomalies for a) RCP45, b) EQ, c) NH, d) NHSH, e) p2 and f) p2w. Anomalies in a) and b) are presented as the differences between years 2060-2070 and 2010-2020. Anomalies in c) d) e) and f) are presented as the difference to EQ between years 2060-2070. The hatching indicates regions where the change of precipitation is not statistically significant at 95% level.