

We thank editor Valerio Lucarini for pointing out a valuable research article which is now cited in our manuscript.

P15 Lines 470-474 now reads: *"Such effects could be avoided by smaller injection increments, by using a more sophisticated algorithm that could better separate large natural variations in temperature or precipitation from long-term changes or defining geoengineering strategy in advance by using e.g linear response theory (Bódai et al., 2020)."*

Corresponding reference is included in the reference list.

Since our replies to reviewers we found two errors in two of our figures. In revised Fig3. the slope of the fitted lines in legend was referred to by " $\Delta SW/\Delta T$ " even though the figure shows total radiation (SW+LW). This has now changed to " $\Delta F/\Delta T$ ". Another error was in supplementary figure S3, which was included after reviewers comments. X-axes (absorbed radiation) in the figure was turned around. This is now fixed.

We thank Anonymous Referee #1 for 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.

General comments

The authors studied the climate responses to two different geoengineering approaches: sulfur injections and carbon dioxide removal. Using the Gregory regression approach, the authors separated temperature-independent (fast adjustment) and temperature-dependent (slow responses) components and then quantified their contributions to the total precipitation change in an RCP based scenario. The authors also compared the total amount of aerosols needed under various scenarios and the spatial pattern changes. The paper is well written and contributes to our understandings of the hydrological cycle responses to different geoengineering forcing. I would recommend publication after the authors addressed the following comments.

Specific comments

My understanding is that during the simulations using MPI-ESM and CESM, you directly used the "equilibrium" aerosol distributions patterns estimated from mECHAMHAMMOZ under the 1, 2, 3, 4, 5, and 6 Tg(S)/yr emission rates (in Fig.8 you used discrete injected sulfur rates). In the real world, if you change the emission rate of aerosols in year N, it takes time to adjust to a new equilibrium state. Therefore, there is a difference between your simulations and the real-world implementations (maybe it's worth to point out?). Do you have any idea how much the difference could be?

This is true and was briefly mentioned in P7 L195, but we agree that this needs to be discussed more.

Thus in section 2.2 the original sentence :

“An approximation inherent in this approach is that transitory ramp-up and ramp-down periods in the stratospheric aerosol burden with 1 Tg(S)/yr changes in SRM are not taken into account.”
is followed by:

“Thus the simulated SRM changes take place faster than would occur in the real world. For example, the ECHAM-HAMMOZ simulation with 5 Tg(S)/yr injections requires 6 months to achieve 70% of the ultimate steady state aerosol optical depth (AOD) (533nm) after starting from background conditions.. When sulfur injections are suspended in the ECHAM-HAMMOZ simulation, the AOD decreases by roughly by 40% over the course of the first year. However, since the sulfur changes in our ESM simulations are only ± 1 (Tg(S)/yr) and do not usually occur in consecutive years we can assume that neglecting this time lag does not significantly alter our overall results.”

The discussion of regression in Section 3 is good. But in general, I think that the authors could add more information to support their statements and help the reader to better understand. For example, it would be very helpful if the author could show numbers at least for those regression slopes. It’s hard to identify and compare these regression lines with statements in the paper by eyes. Another example is shown in lines 258 to 260: the authors stated that “There was no large difference in surface albedo change between models” and “clear-sky SW absorption was linearly dependent on surface temperature”. Can you remind me where I can find figures or data for such statements?

We have now added the regression slopes to figures 2-4. In addition, we have now added similar regression figures for clear sky shortwave absorption and albedo changes to the supplemental material.

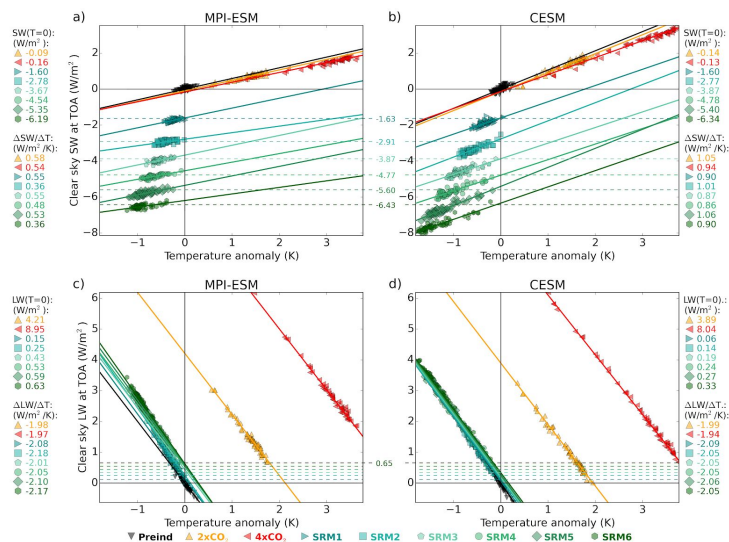


Figure 2: Gregory plots of the...Corresponding radiative forcing (intersection of linear fit and the y-axis (T=0)) in MPI-ESM and in CESM are shown in top and slope of the linear fit in bottom of legends next to the figure...

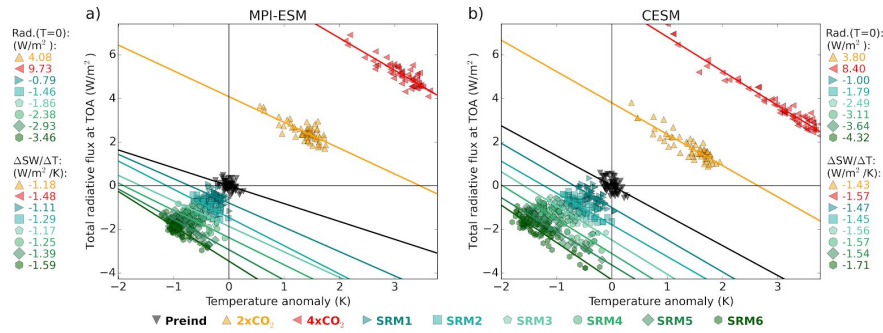


Figure 3: Gregory plots of the...Corresponding all-sky radiative forcing (intersection of linear fit and the y-axis (T=0)) in MPI-ESM and in CESM are shown in top and slope of the linear fit in bottom of legends next to the figure...

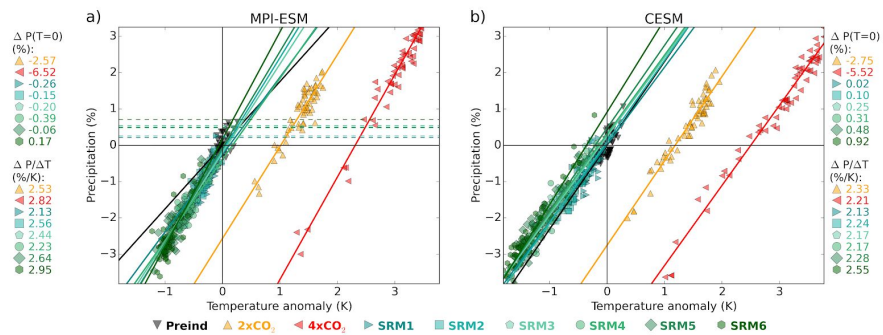


Figure 4: Gregory plots of the...and slope of the linear fit (shown in bottom of the legends) corresponds the slow response due to the temperature change...

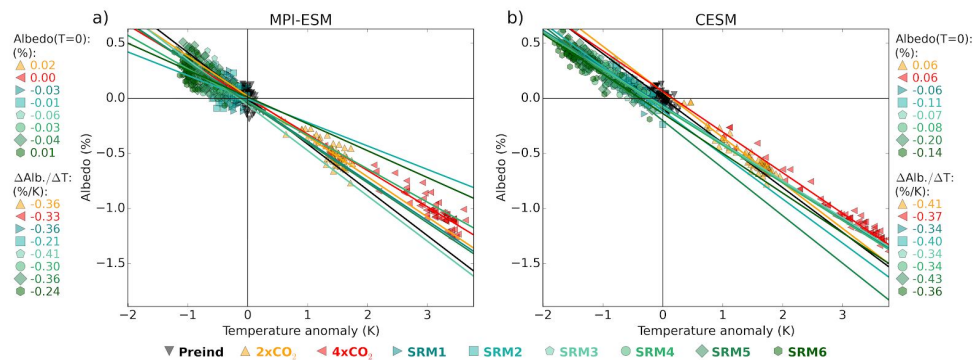


Figure S1: Gregory plots of albedo change for a) MPI-ESM and b) CESM. Markers indicate a single-year global mean value for one ensemble member and solid lines are linear fits. Origin represents zero temperature and albedo anomaly compared to the Preind simulation.

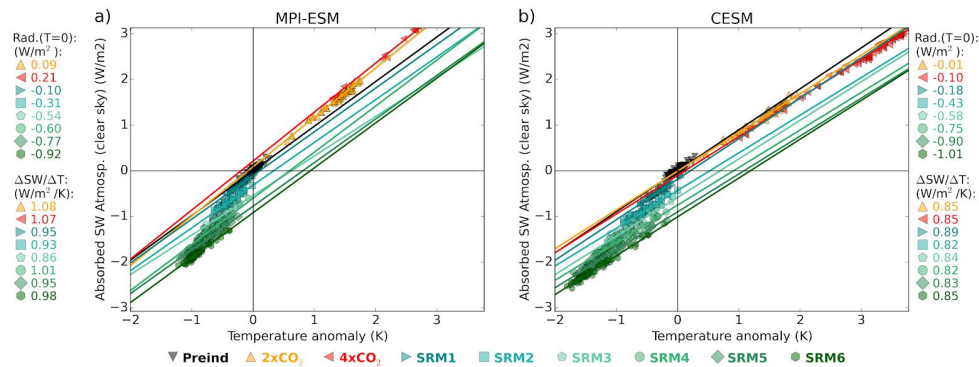


Figure S2: Gregory plots of clear sky atmospheric absorption change for a) MPI-ESM and b) CESM. Markers indicate a single-year global mean value for one ensemble member and solid lines are linear fits. Origin represents zero temperature and atmospheric absorption anomaly compared to the Preind simulation.

For each of the two models, the authors used regression results from three 20-year simulations (preindustrial, 2xCO₂, and 4xCO₂) and applied a logarithmical fit to estimate the coefficient “c” (the fast CO₂ effect to precipitation) (lines 362 to 364). You have only three data points during the curve fit, so I am wondering how good the curve fit is? The fast precipitation response to CO₂ change not only relates to the CO₂ radiative effect but is also partly attributed to the physiological effect. It’s fine to use the logarithmical form (I think the first paper used this relationship is in Cao et al., (2015)), but I think you might want to point it out here.

This is a good comment and we agree that this should be pointed out. Using the logarithmical form requires the assumption that fast response depends linearly on absorbed radiation, but this was not shown or discussed. Based on e.g figure 2 in Samset et al 2016 this dependence is fairly linear, but some deviation occurs which is caused by, as the reviewer pointed out, physiological effects and also sensible heat flux. To address this comment we have now added a figure similar to that in Samset et al 2016, but using data from our simulations:.

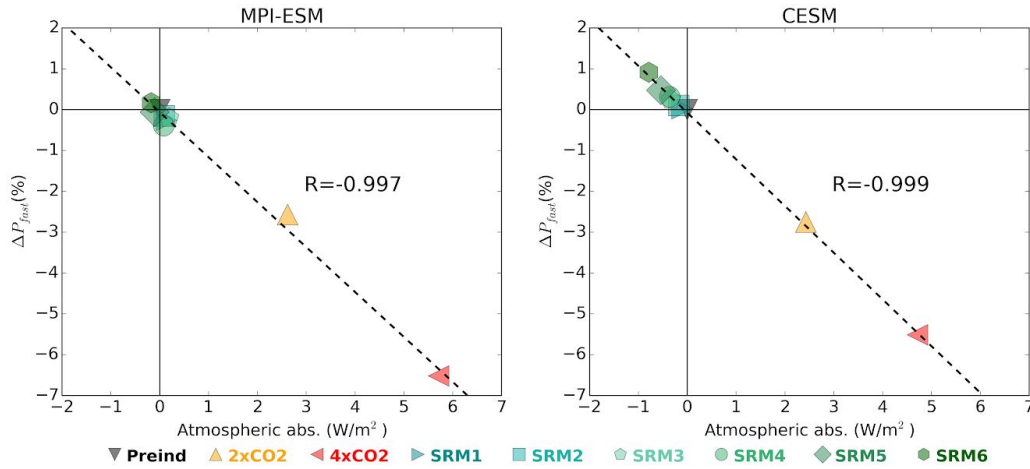


Figure S3. Regression of fast precipitation response versus atmospheric absorption in a)MPI-ESM and b) CESM. R is the Pearson correlation coefficient.

Lines 352-363 have now been rewritten to discuss this further:

“Based on our component analysis simulations we see that the fast precipitation response varies fairly linearly with absorbed radiation (See Fig. 3 in supplementary), but some deviation occurs due to changes to sensible heat flux and physiological responses of vegetation (DeAngelis et al., 2016). This result is consistent with that of Samset et al. (2016) and Myhre et al. (2017). The higher correlations in our simulations compared to Samset et al. (2016) may be due to the use of the fixed Sea Surface Temperature (SST) method to define the fast response in Samset et al. (2016): fast responses quantified with fixed-SST methods include land temperature adjustments.

Radiative forcings are generally assumed to be additive (Marvel et al., 2015). If we assume based on supplementary Fig. S3 that the overall fast response depends only on absorbed radiation, it follows that the fast responses of individual forcing agents are also additive. In Sect. 3.3 we also showed that the slow temperature-dependent component does not depend on the applied forcing. We can thus describe the global mean precipitation change as the sum of the temperature-dependent slow component ($a \times \Delta T$) and all fast components (Fläschner et al., 2016):

$$\Delta P = a \times \Delta T + b(\text{SRM}) + c \times \ln \frac{\text{CO}_2_{\text{preind}} + \Delta \text{CO}_2}{\text{CO}_2_{\text{preind}}} + \text{BG},$$

where a , and c are model-specific coefficients, b is a function of the SRM level, T is the simulated global mean surface temperature, $\text{CO}_2_{\text{preind}}$ is the preindustrial CO_2 concentration, ΔCO_2 is the atmospheric CO_2 change relative to the preindustrial value, and BG is the background fast component, assumed to be the same for all scenarios. Coefficient a is obtained from the scenario-ensemble mean slope in Fig 4 (2.53 %/K for MPI-ESM and 2.27 % for CESM), while b is the fast component (intercept) from simulations of the corresponding SRM scenario (see $\Delta P(T=0)$ values in Fig 4). To calculate coefficient c , we again assume that fast

precipitation response is linearly dependent on absorbed radiation. Radiative forcing due to CO₂ varies logarithmically with concentration (Etminan et al., 2016) and thus the fast precipitation response for CO₂ is also assumed to be logarithmically dependent on CO₂ concentrations (see supplementary material Fig. S4)”

We have also added a figure demonstrating this logarithmical fit to supplementary material (Fig 4).

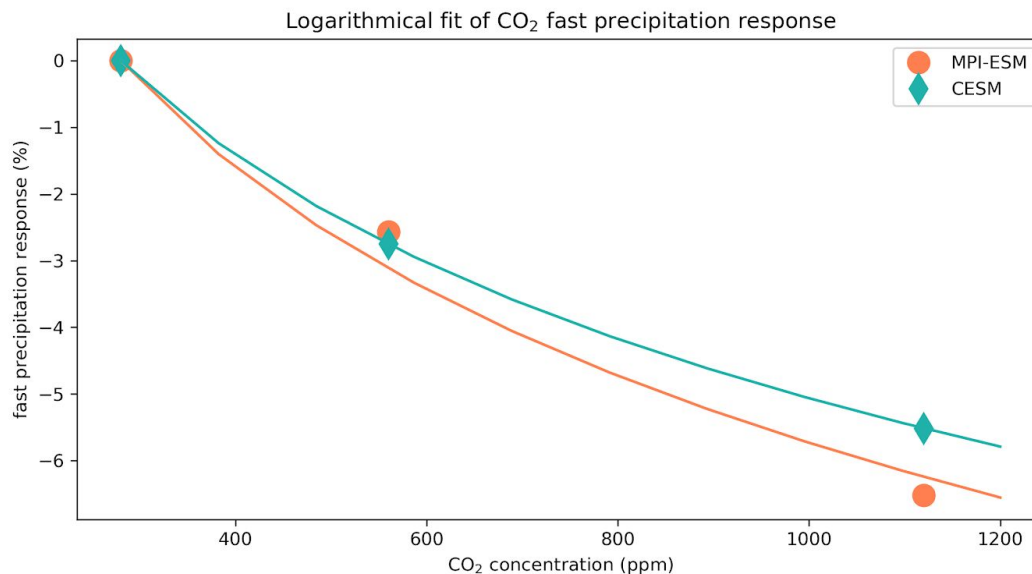


Figure S4. Logarithmical fit of CO₂ fast precipitation calculated from preind, 2xCO₂ and 4xCO₂ scenarios.

Technical corrections

The following technical corrections have been made.

Line 34: Add “increase” to “maintain the global mean temperature increase within 2°C ...”

Line 39: When the author says “a reduction of energy use”, do you mean energy use associated with fossil fuel burning only? Because energy consumption provided by renewables and biofuels will not deteriorate the climate warming target.

We rephrased the sentence to “*would require fast and significant reduction in use of fossil fuels complemented with carbon dioxide removal.*”

Line 47: Missing “)” here: “(Luderer et al., 2018, IPCC 2018)”

Line 67: “. . . SRM would decrease global mean precipitation through the direct radiative effect described above”. The hydrological cycle responses to solar geoengineering depend on magnitudes of geoengineering deployments and which case you are comparing with (the pre-industrial or high-CO₂ world without SRM). I think the statement here should be more specific.

This line is now rewritten:

“One fundamental problem is that compensating GHG-induced warming with SRM would decrease global mean precipitation through the direct radiative effect described above.”

Line 80: add “for” to: “. . . continue to change for decades. . .”

Line 89: “separate” to “separates”, “totally” to “total”

Line 94: “a” to “the”

Line 134: delete “the”

Line 182: what do you mean of “business as usual scenarios” here?

“business as usual scenarios” is changed to “high emission scenario (RCP 8.5)”

Line 196: add “into” to “taken into account”

Line 217: add “as”

Line 224: “were” to “was”

Line 232: Please define “Preind” before using it

Rewritten as:

“First, we calculated the clear-sky shortwave flux and temperature anomaly compared to the stable preindustrial conditions (Preind simulation) for each year individually, and performed a linear regression between the two variables”

Line 293: “warned” to “warm”

Line 294 and 325: the font is different

Line 315: “Fig.1” should be “Fig.6”

Line 324: “2010-2020” should be “2080-2100”

Line 355: there is an additional “a” in Eq. (1)

We thank Tamas Bodai for thorough review, suggestions and comments. Our point by point answers to the comments are presented below. Referee comments are in bold and our replies in body text.

The authors model two geoengineering methods, the Solar Radiation Management (SRM) and Carbon Dioxide Removal (CDR), in two Earth system models, the CESM and the MPI-ESM, and run simulations under several scenarios and analyse the global mean and regional temperature and precipitation responses. The considered scenarios are the following: (1) RCP4.5 (2) RCP4.5 with SRM controlled to approximately maintain present-day global mean temperature throughout the 21st c. (3) RCP4.5 with SRM controlled to approximately maintain present-day global mean precipitation throughout the 21st c. (4) RCP4.5 with an ambitious CDR removing 1% of CO₂ concentration per year They give some evidence in both ESMs that the global mean precipitation response has a global mean temperature-dependent component, which is based on the methodology proposed by Gregory et al. (2004). Besides this the precipitation can respond very fast, at least to the greenhouse co₂ forcing, and this fast response is of opposite sign compared with the temperature-dependent part. To aerosol forcing the fast response is negligible.

This is the reason why there is less precipitation in an SRM scenario when global warming is fully compensated. Conversely, the authors make the point and demonstrate in the models that maintaining global precipitation levels (3) requires less sulfate aerosol injection than maintaining temperature (2). The authors also point out that in the long run, without geoengineering, the temperature-dependent part of the precipitation response will dominate, and so the worst impacts of climate change we would be just yet to see. In the CDR scenario of net CO₂ reduction (4) they find a wetting in both ESMs and an overall very similar precipitation response, however, this turns out to be a coincidence, because the temperature response is not so similar, which drives the precipitation response, and these are the fast response components to other forcing agents that seem to “compensate for” the difference. The ESMs also differ in other aspects. The temperature-dependence of the precipitation is more sensitive in the MPI-ESM - while the fast response (per unit forcing) are surprisingly similar - which is why stronger SRM is needed in MPI-ESM to maintain the temperature (2). The regional responses, both temperature, and precipitation, are very different between the models; it seems hopeless to predict in any location even the sign of the side-effect!!! Although it would not be completely useless to be able to predict at least bounds on the magnitude of the possible change.

The paper is written fairly decently. Although there are some repetitions, and the mathematical symbols and notation should be consistent. I attach an annotated version of the manuscript with corrections, comments, and questions.

These are now corrected based on the referee’s comments in the annotated version.

Overall, I found the paper a very worthwhile read. Even if I had my own experience with the drying under geoengineering and the fast components of the precipitation response, I have not been aware of the link of these two, and I did not know that the slow response can be put down approximately as a temperature-dependent component. The numerical work handling the ESMs was clearly a great effort too. I have just a few perhaps/hopefully minor points to make.

1. Why did you base your four scenarios (1)-(4) on the RCP4.5 emission scenario when it remains within the Paris Agreement as represented in both ESMs, even within 1.5 K warming? I mean why not consider a business as usual scenario when we would much rather need geoengineering?

Actually RCP4.5 does not remain within the Paris Agreement targets (less than 1.5 or 2 K warming compared to the preindustrial era). Figure 6 was misleading in this respect because the plotted temperature anomaly is calculated with respect to 2010-2020 and not with respect to the preindustrial era. We have now included text (“Temperature/precipitation anomalies relative to 2010-2020”) to the y-axis labels to make this point more clear for readers. In addition we now rewrite Line 316 as: *“Under RCP45, the global mean temperature increased by 1.30 K and 1.20 K over the 2010-2020 average in MPI-ESM and CESM, respectively.”*

Likewise, L329-331 now reads: *“Thus, in both ESMs the SRM-PRECI global temperature increase (~1.64 K in MPI-ESM and ~1.27 K in CESM compared to the preindustrial average) stayed within the 2 C target of the Paris Agreement. For CESM, the SRM-PRECI temperature increase also stayed within the 1.5 C Paris target.”*

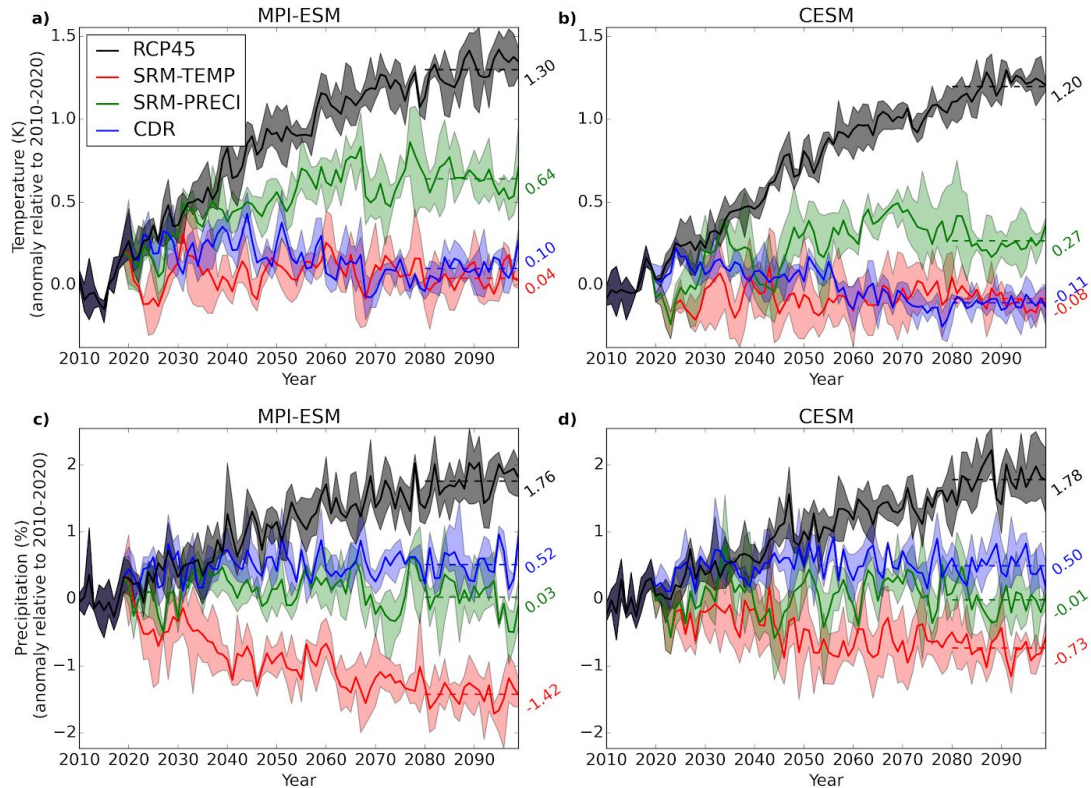


Figure 6: Global mean temperature anomalies in a) MPI-ESM and b) CESM, and global mean precipitation anomalies in c) MPI-ESM and d) CESM. Numbers to the right of each figure indicate the global mean difference between 2080-2100 and 2010-2020. Shaded areas show the maximum and minimum across three ensemble members.

2. Regarding the control method for (2) and (3): You change the forcing level in the ESMs year-to-year, if needed, but is this forcing realistic, would it be consistent with changing the sulfate injection rate year to year? Is there not a transient effect? You wrote that the aerosol model ECHAM-HAMMOZ took 2 years spinup runs.

There is indeed a transient effect which is not taken into account in the simulations. This was mentioned in section 2.2, but is now discussed in more detail as follows:

“An approximation inherent in this approach is that transitory ramp-up and ramp-down periods in the stratospheric aerosol burden with 1 Tg(S)/yr changes in SRM are not taken into account. Thus the simulated SRM changes take place faster than would occur in the real world. For example, the ECHAM-HAMMOZ simulation with 5 Tg(S)/yr injections requires 6 months to achieve 70% of the ultimate steady state aerosol optical depth (AOD) (533nm) after starting from background conditions.. When sulfur injections are suspended in the ECHAM-HAMMOZ simulation, the AOD decreases by roughly by 40% over the course of the first year. However,

since the sulfur changes in our ESM simulations are only ± 1 (Tg(S)/yr) and do not usually occur in consecutive years we can assume that neglecting this time lag does not significantly alter our overall results.”

3. It seems to me that Fig. 7 does not verify that you have a temperature-dependent precip response component. But rather Fig. 4 does. In this respect, a more clear wording is needed at relevant points in the text.

Based on the referee’s comments in the supplement, it appears that we were not sufficiently clear in stating that the temperature-dependent component depends only on temperature and not on the forcing driving the temperature change. This was mentioned on L57 in the introduction and at L309-L310 but is also now articulated more clearly in section 3.3. We have also clarified the rationale for our use of the component-based approach (i.e., in Fig 7). A new figure illustrating the dependence of the fast precipitation response on absorbed radiation has also been included in the supplement. Sect 4.2 it now reads:

“Based on our component analysis simulations we see that the fast precipitation response varies fairly linearly with absorbed radiation (See Fig. 3 in supplementary), but some deviation occurs due to changes to sensible heat flux and physiological responses of vegetation (DeAngelis et al., 2016). This result is consistent with that of Samset et al. (2016) and Myhre et al. (2017). The higher correlations in our simulations compared to Samset et al. (2016) may be due to the use of the fixed Sea Surface Temperature (SST) method to define the fast response in Samset et al. (2016): fast responses quantified with fixed-SST methods include land temperature adjustments.

Radiative forcings are generally assumed to be additive (Marvel et al., 2015). If we assume based on supplementary Fig. S3 that the overall fast response depends only on absorbed radiation, it follows that the fast responses of individual forcing agents are also additive. In Sect. 3.3 we also showed that the slow temperature-dependent component does not depend on the applied forcing. We can thus describe the global mean precipitation change as the sum of the temperature-dependent slow component ($a \times \Delta T$) and all fast components (Fläschner et al., 2016):

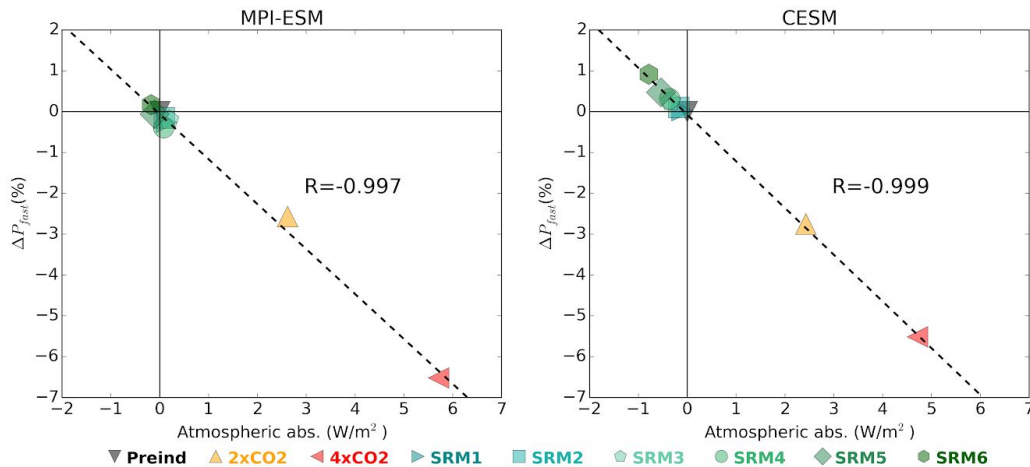


Figure S3. Regression of fast precipitation response versus atmospheric absorption in a) MPI-ESM and b) CESM. R is the Pearson correlation coefficient.

Along similar lines, we feel that inclusion of the BG component in Fig 7 could be misleading in giving the impression that the agreement between total modelled precipitation and the sum of the individual components arises from the BG component. While this is obviously true in the case of RCP 4.5 (from which the BG component is calculated as the residual between equation 2 (previously 1) and modelled precipitation), the same BG component (calculated based on RCP 4.5) is then used as a component in all geoengineering scenarios. Thus in those cases the precipitation agreement referred to above does not arise from the BG component.

To prevent any such confusion, we added a supplemental figure analogous to Fig. 7 but with yearly precipitation differences in the geoengineering scenarios compared to the corresponding year in RCP4.5. Doing the comparison in this way removes the BG component. As this figure shows, the component-based precipitation agrees well with the total modelled quantity in this framework as well.

The corresponding section has been rewritten to make this more clear for the reader:

“Figure 7 shows the precipitation component for each scenario in MPI-ESM and CESM. In general, the precipitation signal as estimated by the fast and slow components via Eq. (2) corresponds well to the actual model quantity in both ESMs for all scenarios. For RCP4.5 this is an obvious result because the BG is derived as the residual between the modelled precipitation and the sum of the individual components for this very scenario. However, the component-based and full precipitation signals also agree well for the other scenarios, even though the BG component is calculated from the RCP45 case. From year-2020 to year-2100 the mean differences between the Eq. (2) results and the actual model quantities were ranged from -0.01% to 0.04% for MPI-ESM and from -0.16% to 0.05% for CESM. Fig. S5 in supplementary material shows the precipitation responses under the geoengineering scenarios as anomalies relative to the RCP4.5 case. The plotted precipitation differences in Fig. S5 are thus

independent of the BG component. We see from this figure that the individual components can be reliably used to understand the drivers of precipitation change for each scenario.”

We choose to include the BG component in figure 7 for the following reasons

- 1) For clarity we wish the modelled precipitation under the individual scenarios to be the same in both figures 6 and 7.
- 2) The BG component shows that there are several other significant fast precipitation components (in the background) which are affecting precipitation in RCP 4.5 scenario
- 3) The BG component was clearly different in same scenario modelled by MPI-ESM and CESM. This is one of the main reasons for the diversity in climate models precipitation results found here.
- 4) We wanted to show and highlight that component-based analyses are not significantly dependent on the background. For example, the precipitation difference between RCP4.5 and CDR can be represented by the fast CO2 component and the temperature-based component for years 2020 and 2100, even though the background atmospheric conditions have changed.

Differing precipitation response between Solar Radiation Management and Carbon Dioxide Removal due to fast and slow components

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10 **Abstract.** Solar Radiation Management (SRM) and Carbon Dioxide Removal (CDR) are geoengineering methods that have
been proposed to ~~mitigate~~~~prevent~~ ~~climate~~ ~~global~~ warming in the event of insufficient greenhouse gas emission reductions.
Here, we have studied temperature and precipitation responses to CDR and SRM with the RCP4.5 scenario using the MPI-
ESM and CESM Earth System Models (ESMs). The SRM scenarios were designed to meet one of the two different long-term
climate targets: to keep either global mean 1) surface temperature or 2) precipitation at the 2010-2020 level via stratospheric
15 sulfur injections. Stratospheric sulfur fields were simulated beforehand with an aerosol-climate model, with the same aerosol
radiative properties used in both ESMs. In the CDR scenario, atmospheric CO₂ concentrations were reduced to keep the global
mean temperature at approximately the 2010-2020 level. Results show that applying SRM to offset 21st century climate
warming in the RCP4.5 scenario leads to a 1.42% (MPI-ESM) or 0.73% (CESM) reduction in global mean precipitation,
whereas CDR increases global precipitation by 0.5% in both ESMs for 2080-2100 relative to 2010-2020. In all cases, the
20 simulated global mean precipitation change can be represented as the sum of a slow temperature-dependent component and a
fast temperature-independent component, which are quantified by regression method. Based on this component analysis, the
fast temperature-independent component of changed atmospheric CO₂ concentration explains the global mean precipitation
change in both SRM and CDR scenarios. Based on the SRM simulations, a total of 163-199 Tg(S) (CESM) or 292-318 Tg(S)
(MPI-ESM) of injected sulfur from 2020 to 2100 was required to offset global mean warming based on the RCP4.5 scenario.
25 To prevent a global mean precipitation increase, only 95-114 Tg(S) was needed and this was also enough to prevent global
mean climate warming from exceeding 2 degrees above preindustrial temperatures. The distinct effects of SRM in the two
ESM simulations mainly reflected differing shortwave absorption responses to water vapor. Results also showed relatively
large differences in the individual (fast versus slow) precipitation components between ESMs.

1 Introduction

30 It is now widely recognized that fast greenhouse gas (GHG) emission reductions, especially for carbon dioxide (CO₂), are
needed if ongoing global warming is to be ~~minimized~~~~slowed down~~. The Intergovernmental Panel on Climate Change (IPCC)

Special Report on Global warming of 1.5 °C (henceforth SR15, IPCC, 2018) brought to wider attention many, ~~partly irreversible~~, risks and partly irreversible negative impacts associated with global mean warming of 1.5 °C above the pre-industrial level (Liu et al., 2018; Schleussner et al., 2016; Seneviratne 2018). The aim of the 2015 Paris Agreement was to
35 maintain the global mean temperature increase within 2 °C of the pre-industrial level, and to pursue efforts to limit the mean increase to 1.5 °C (UNFCCC, 2015). Based on average results of climate models simulations, only one of the Representative Concentration Pathway (RCP) scenarios used in the IPCC Fifth Assessment report (IPCC, 2014) is associated with global mean warming of less than 2 °C; this pathway includes presumptive mitigation after year 2010, which has not taken place (van Vuuren et al., 2007). Millar et al. (2017) and Rogelj et al. (2018) have shown that limiting warming to 1.5 °C is still possible,
40 but would require fast and significant reduction in use of fossil fuels complemented with carbon dioxide removal. would require rapid abandonment of fossil fuel and a reduction of energy use. In addition, air quality legislation will likely lead to decreased cooling from anthropogenic aerosols, which might by itself be enough to increase global mean temperatures over the 1.5 °C target (Hienola et al., 2018).

45 Geoengineering methods have been proposed to prevent dangerous climate warming if CO₂ emissions are not reduced quickly enough (e.g., Caldeira et al., 2013). Such techniques are usually divided into two categories. One is Carbon Dioxide Removal (CDR), whereby CO₂ is removed from the atmosphere—thus addressing the root cause of climate warming (Royal Society, 2009). While these actions will face many political, economic and technical challenges they are most likely needed in some form to avoid 1.5 °C warming (Luderer et al., 2018, IPCC 2018.) The second is Solar Radiation Management (SRM), which
50 aims to increase the shortwave (solar) reflectivity of the atmosphere or Earth's surface. The Paris agreement states that the 2 °C target should be achieved by reaching a balance between anthropogenic GHG emissions and anthropogenic GHG sinks (i.e., CDR) (UNFCCC, 2015). However, challenges related to mitigation and CDR, possible underestimation of future carbon budgets, or new findings in scientific understanding of tipping points could lead to increased interest in using SRM to avoid crossing the Paris Agreement temperature thresholds.

55 Discussions related to SR15 and the Paris Agreement have concentrated mainly on global mean temperature change, rather than on regional variations in temperature changes (Collins et al., 2018; Seneviratne et al., 2018) or on other climate impacts, such as changes in precipitation, that are driven by temperature changes or caused directly by GHG or other forcing agents. On the global scale, precipitation changes can be separated into a surface-temperature dependent slow component, which does
60 not depend on the forcing agent causing the underlying temperature change, and a temperature-independent fast component, which is caused directly by the altered atmospheric radiation absorption (Bala et al., 2009; Myhre et al., 2017; Samset et al., 2016). Changes to the hydrological cycle thus depend not only on the degree of warming but also on the forcing agents and emission changes that are causing the warming. As a result, different emission pathways can lead to different precipitation changes even if they result in similar global mean temperatures. Such hydrologic changes may have a larger impact on human

65 wellbeing than changes in temperature due to impacts on floods, droughts, water resources and ecosystems (Lausier and Jain 2018).

Problems and side effects associated with SRM have been discussed extensively (Robock et al. 2009; Royal Society 2009). One fundamental problem is that compensating GHG induced warming with SRM would decrease global mean precipitation
70 through the direct radiative effect described above. This can be understood as follows. Given a GHG concentration increase, less outgoing longwave (LW) radiation escapes to space, causing surface temperatures to increase until a new equilibrium is achieved. SRM methods aim to offset this temperature increase by reducing incoming shortwave (SW) solar radiation. Thus, even though the total radiative flux may be the same between an increased GHG + SRM scenario and the unperturbed climate, the atmospheric SW and LW radiative fluxes differ. This has been shown in general to lead to a decrease in global mean
75 precipitation (Bala et al., 2008). In general, the suite of climate responses arising from a LW radiation change cannot be fully compensated by modifying SW radiation. Use of SRM thus involves a tradeoff between temperature and precipitation on the global scale.

CDR methods are considered less risky than SRM as these methods remove CO₂ from the atmosphere and thus reduce the
80 atmospheric GHG concentration (Royal Society 2009). However, climate change is not necessarily a reversible process due to factors such as sea and glacier ice melt, sea level rise, and carbon cycle changes (Frölicher and Joos 2010; Wu et al., 2015). In addition, climate does not adapt immediately to a change in radiative forcing. For example, due to ocean thermal inertia global temperatures will continue to change for decades or even centuries after a given radiative forcing perturbation. It is therefore important that CDR scenarios be studied to assess climate responses beyond changes to global mean temperature.

85
In this section 3 of this study, the temperature and precipitation responses to CDR and SRM are simulated with two Earth System Models (ESMs). The mechanisms driving global mean precipitation changes are assessed by separately examining the temperature-dependent slow response and radiatively-induced fast response for differing magnitudes of SRM and CDR. This methodology can be used to better understand impacts of CDR and SRM, ~~and to predict total temperature and precipitation responses if CDR and SRM are used simultaneously.~~
90 Unlike in several previous studies, here, fast and slow responses are quantified by a regression method instead of a fixed sea surface temperature (SST) method (Duan et al., 2018; Myhre et al., 2017; Samset et al., 2016). An advantage of the regression method is that it separates total temperature-dependent and independent responses while in the fixed-SST method land temperature adjustments are included in the temperature-independent fast response. We also study regional disparities in temperature and precipitation responses for both
95 geoengineering techniques, and estimate the SO₂ emission amounts required to keep either temperature or precipitation at present-day levels.

In section 4 we simulate three geoengineering scenarios against the Representative Concentration Pathway 4.5 (RCP4.5) scenario (Thomson et al., 2011). First, we examine two SRM scenarios designed to address two different climate targets: keeping either global mean 1) surface temperature or 2) precipitation at 2010-2020 level via stratospheric sulfur injections. Next, we examine a CDR scenario is designed to keep the global mean temperature at approximately the 2010 level. We used an aerosol-climate model to simulate stratospheric aerosol fields, and two separate ESMs (MPI-ESM and CESM) to simulate the climate response to SRM and CDR.

2 Methods

2.1 Models

This study was conducted using three climate models: one aerosol-climate model with fixed sea surface temperature, and two ESMs. We first simulated stratospheric aerosol fields with the aerosol climate model ECHAM-HAMMOZ. We then implemented the radiative properties of these fields in two ESMs—the Max Planck Institute Earth System Model (MPI-ESM) and the National Center for Atmospheric Research’s Community Earth System Model (CESM)—for simulation of the various scenarios. For each scenario, we run a three-member ensemble with both ESMs.

2.1.1 ECHAM – HAMMOZ

We defined the radiative properties of the aerosol fields resulting from stratospheric injections of sulfur dioxide (SO₂) with the MAECHAM6.1-HAM2.2-SALSA global aerosol-climate model (Bergman et al., 2012; Kokkola et al., 2008; Laakso et al., 2016; Stevens et al., 2013, Zhang et al., 2012). In this model, the ECHAM atmospheric module (Stevens et al., 2013) is coupled interactively with the HAM aerosol module (Zhang et al., 2012). The HAM module calculates the emissions, removal, and radiative properties of aerosols along with the associated gas and liquid phase chemistry. The model includes the SALSA explicit sectional aerosol scheme (Kokkola et al., 2018), which describes aerosols based on number and volume size distributions with 10 and 7 size sections for soluble and insoluble particles, respectively. The model simulates the microphysical processes of nucleation, condensation, coagulation, and hydration. The model was configured as described by Laakso et al. (2017). Simulations were performed at T63L47 resolution, which corresponds approximately to a 1.9° x 1.9° horizontal grid with 47 vertical levels reaching up to ~80 km. The model accurately simulates stratospheric aerosol loads and radiative properties based on observations of the 1991 Mt. Pinatubo eruption (Laakso et al., 2016; Kokkola et al., 2018). It should be noted that this model configuration does not simulate the quasi biennial oscillation at L47 resolution. Hydroxyl radical (OH), which impacts the oxidation of SO₂ to sulfate as well as ozone concentration, is accounted for through prescribed monthly mean fields.

2.1.2 MPI-ESM and CESM

MPI-ESM (Giorgetta et al., 2013) consists of the same atmospheric model (ECHAM6.1) as ECHAM-HAMMOZ, and the MPI-ESM simulations here also employed the same T63L47 resolution as the ECHAM-HAMMOZ simulations described above. MPI-ESM includes the JSBACH active land model (Reich et al., 2013) and the Max Planck Institute Ocean Model (MPIOM) (Junglaus et al., 2012), both fully coupled to the atmospheric module. MPIOM includes the HAMOCC ocean biogeochemistry model (Ilyina et al., 2013). The tropospheric aerosol climatology of Kinne et al. (2013) is used in all scenarios.

CESM version 1.2.2 (Hurrell et al., 2013) consists of the Community Atmospheric Model (CAM4) which is used with horizontal resolution of $0.9^\circ \times 1.25^\circ$ and 26 vertical levels up to 40 km (finite volume grid). It is coupled to the Parallel Ocean Program (POP2) ocean model, the Community Land Model (CLM4) and Community Ice Code (CICE4) sea ice model.

2.1.3 Implementing prescribed aerosol fields in ESMs

To examine the effects of solar radiation management by stratospheric sulfur injections we implemented prescribed sulfate fields in ~~the~~ ESMs as described by Laakso et al. (2017). First, we used ECHAM-HAMMOZ to ~~the~~ simulate aerosol fields resulting from gaseous SO_2 injections. These simulations include a 2-year spin-up period followed by a 5-year steady-state period. From this 5-year period, mean stratospheric values for aerosol optical depth (AOD), single scattering albedo (SSA), and the asymmetry factor (ASYM) were archived as monthly output in 14 SW bands plus 16 LW bands for (absorption) AOD. We then implemented these fields in the two ESMs as prescribed zonal and monthly mean fields. ECHAM-HAMMOZ and MPI-ESM share the ECHAM atmosphere model, which itself uses the Rapid Radiative Transfer Model. Because the same resolution (T63L47) was employed for both ECHAM-HAMMOZ and MPI-ESM, the only differences in aerosol radiative properties between the models was caused by zonal and monthly averaging of the radiative properties (however, the total AOD did not vary between the two). In the case of CESM, aerosol fields from the ECHAM-HAMMOZ simulations had to be interpolated horizontally to $0.9^\circ \times 1.25^\circ$ and to 26 vertical levels. Because CAM4 uses different wavelength bands than does ECHAM (7 LW bands and 19 SW bands), we interpolated the aerosol optical properties accordingly.

The above implementation ensures that SRM radiative effects are consistent in both ESMs, while also enabling longer-term analyses since computationally expensive aerosol microphysics are prescribed rather than simulated online. The aerosol radiative effects are nevertheless based on explicit simulations of aerosol microphysics and of the resulting aerosol size distribution and spatial-temporal variability. Our methodology is therefore more physically realistic compared to approaches that simply reduce the solar constant or apply idealized zonally homogenous aerosol fields. Realistic simulation of aerosol microphysics is necessary for robust prediction of the associated radiative effects, which depend on the size, properties, and location of the particle. In the stratosphere, particle life times are roughly one year, so that microphysical processes such as coagulation and condensation play a greater role than in the troposphere. As a result of these microphysical processes, radiative

forcing from stratospheric sulfur injections does not increase linearly with the amount of injected sulfur and thus radiative impacts cannot be scaled linearly based on level of the injection level (Niemeier et al., 2015).

160 2.2 Simulations

To simulate SRM stratospheric aerosol fields, we performed six SRM and one control simulation with ECHAM-HAMMOZ. Here, SO₂ was injected continuously throughout the simulation at 20 km altitude between 10 N and 10 S latitudes. Each of the ECHAM-HAMMOZ simulations included injection of 1, 2, 3, 4, 5 or 6 Tg(S)/yr.

165 We divide the ESM simulations into two groups: 1) component analysis simulations, and 2) scenarios. Component analysis simulations are performed to enable subsequent separation of the slow (temperature-dependent) and fast (temperature-independent) responses to the specific forcing agent (~~Gregory et al., 2004~~) based on a regression method (Gregory et al., 2004). In this method, an individual forcing agent (CO₂ or SRM) is added to the steady state climate conditions, and different climate variables are regressed against the global mean surface temperature change. The fast and slow responses for a specific forcing agent is then obtained from the fitted regression line. Specifically, the fast temperature-independent response is derived as the intercept (zero temperature change), while the slow temperature-dependent response is derived as the slope. This analysis is done for three purposes: 1) to evaluate the implementation of the stratospheric aerosol fields across the two ESMs, 2) to quantify differences in radiative forcing and climate sensitivity between models under a specific forcing agent, and 3) to separate the fast and slow precipitation responses of the forcing agents. A total of 9 scenarios are simulated with both ESMs: 175 preindustrial, 6 SRM scenarios with 1, 2, 3, 4, 5, 6 Tg(S) injections, and 2xCO₂ and 4xCO₂ conditions.

All component analysis simulations start from a radiatively balanced climate for pre-industrial conditions. A forcing agent (CO₂ or SRM) is introduced at the outset of the simulation while other conditions are kept pre-industrial levels. We simulated three 20-year ensemble members for each component analysis scenario in Table 1.

180 Scenario simulations were based on RCP 4.5 (Moss et al., 2010; van Vuuren et al., 2011), and included: i) one baseline scenario with no geoengineering (RCP45), ii) two SRM scenarios designed to keep global mean surface temperature (SRM-TEMP) or precipitation (SRM-PRECI) at 2010-2020 mean values, and iii) one CDR scenario designed to keep global mean surface temperature at the 2010-2020 mean value (CDR). In each case, three ensemble members were simulated for years 2010-2100.

185 In the RCP 4.5 scenario, radiative forcing stabilizes several decades before the end of the simulations (year 2100), leading to warming clearly below that seen ~~in business as usual scenarios~~ high emission scenario (RCP 8.5), but above the targets defined in the Paris Agreement. For the SRM-TEMP and SRM-PRECI scenarios, the global mean temperature or precipitation was kept close to the 2010-2020 mean via changing level of controlled stratospheric sulfur injections.

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In practice, the SRM-TEMP and SRM-PRECI scenario objectives were achieved by adjusting the aerosol loading as needed based on the continuous SO₂ injection simulations from ECHAM-HAMMOZ (Sect. 2.1.3). Specifically, the SRM was controlled annually based on mean temperature or precipitation values from the two preceding years, as follows:

195 If $(X_{\text{year-1}} + X_{\text{year-2}})/2 > X_{2010-2020} + A$ then $\text{SRM}_{\text{year}} = \text{SRM}_{\text{year-1}} + 1 \text{ Tg(S)/yr}$.

If $(X_{\text{year-1}} + X_{\text{year-2}})/2 < X_{2010-2020} - A$ then $\text{SRM}_{\text{year}} = \text{SRM}_{\text{year-1}} - 1 \text{ Tg(S)/yr}$, _____ (1)

where X₂₀₁₀₋₂₀₂₀ is the global mean temperature (SRM-TEMP) or precipitation (SRM-PRECI) for 2010-2020 based on RCP45.
X_{year-1} + X_{year-2} are the corresponding global mean value temperature (for SRM-TEMP) or precipitation (for SRM-PRECI) in
200 the two preceding years. A two year running window of two preceding years is used to avoid undue influence from natural variability in global mean temperature or precipitation. Use of a longer window is suboptimal because the temperature or precipitation change the year following an SRM adjustment then does not carry sufficient weight for the subsequent evaluation. This can lead to overly large temperature or precipitation changes before the need to act is recognized.

~~while X₂₀₁₀₋₂₀₂₀ is the corresponding global mean value for 2010-2020 based on RCP45.~~

205 ~~An approximation inherent in this approach is that transitory ramp-up and ramp-down periods in the stratospheric aerosol burden with 1 Tg(S)/yr changes in SRM are not taken account.~~

The A parameter is a thresholdboundary value and set to 0.2 K in SRM-TEMP, which based on our test simulations is generally larger than natural variability. For SRM-PRECI A is defined to correspond to a 0.5% change in the global mean precipitation
210 in the model. If both of the above conditions are false, the stratospheric sulfur injections are maintained at the previous year's level. SRM simulations are initialized with 1 Tg(S)/yr injections at year 2020. ~~A two year running window is used to avoid undue influence from natural variability in global mean temperature or precipitation. Use of a longer window is suboptimal because the temperature or precipitation change the year following an SRM adjustment then does not carry sufficient weight for the subsequent evaluation. This can lead to overly large temperature or precipitation changes before the~~
215 ~~need to act is recognized.~~

~~An approximation inherent in this approach is that transitory ramp-up and ramp-down periods in the stratospheric aerosol burden with 1 Tg(S)/yr changes in SRM are not taken into account. Thus the simulated SRM changes take place faster than would occur in the real world. For example, the ECHAM-HAMMOZ simulation with 5 Tg(S)/yr injections requires 6 months to achieve 70% of the ultimate steady state aerosol optical depth (AOD) (533nm) after starting from background conditions..~~
220 ~~When sulfur injections are suspended in the ECHAM-HAMMOZ simulation, the AOD decreases by roughly by 40% over the course of the first year. However, since the sulfur changes in our ESM simulations are only ±1 (Tg(S)/yr) and do not usually occur in consecutive years we can assume that neglecting this time lag does not significantly alter our overall results."~~

In the CDR scenarios, CO₂ removal was likewise initialized at year 2020. Here, the annual CO₂ increase based on RCP4.5 was counteracted by a 1% annual removal of the atmospheric CO₂ concentration. This process was continued until year-2070, when radiative forcing is stabilized in the RCP4.5 scenario. Accounting for both RCP4.5 emissions and CDR, the total atmospheric CO₂ concentration is then reduced yearly by 0.3 - 0.6 % between 2020-2070 (Fig. 1). Removing 1% of atmospheric CO₂ in 2020 corresponds to negative emissions of approximately 8.7 GtC/yr. As carbon cycle feedbacks (i.e., outgassing from natural carbon sinks) lower the efficiency of CDR (Tokarska and Zickfeld, 2015), the actual amount of sequestered carbon would in reality need to be even higher than this. Achieving such high negative emissions in 2020 would be virtually impossible. The rate required is higher than the maximum estimated sustainable potential of the highest-potential negative emission technologies (Fuss et al., 2018), without even considering competition between the methods. Among SR15 scenarios pursuing the most aggressive CDR, the median carbon sequestration rate for the primary employed method (bioenergy with carbon capture and storage) reaches ~4 GtC/yr in 2100 (Rogelj et al., 2018). Thus, the CDR scenario employed here should be considered as an idealized high-end carbon removal scenario, and we do not speculate how CDR could be achieved and do not study impacts of any specific CDR technology. All non-CO₂ GHG concentrations and other forcings in the CDR scenario are the same as in RCP4.5.

3. Fast and slow components of radiation and precipitation

Fast and slow components of radiation and precipitation ~~were~~ quantified from the component analysis simulations by regressing ~~variables of interest~~~~studied variable~~ against temperature. These simulations were 20 year long. In each case, three ensemble members were simulated. Simulations were initiated in stable preindustrial conditions. In addition, ~~studied~~ forcing agent (CO₂ or SRM) were included, which causes radiative imbalance and results in warming or cooling. Then, annual global mean values were regressed against temperature to separate temperature-dependent and independent responses.

3.1 Evaluating the implementation of stratospheric sulfur aerosol fields in MPI-ESM and CESM

We evaluated the stratospheric aerosol implementation by comparing clear-sky aerosol radiative forcing in the two ESMs with that in ECHAM-HAMMOZ. The ECHAM-HAMMOZ simulations were performed with fixed sea surface temperatures, with aerosol radiative forcing calculated based on the change between a scenario with stratospheric sulfur injection and the control simulation. To calculate the corresponding radiative forcing in the ESMs, a regression (Gregory) method was used (Gregory et al., 2004) (Fig. 2), which also provides the climate feedback parameter which can be used to analyse different responses in two ESMs. First, we calculated the clear-sky shortwave flux and temperature anomaly compared to the stable preindustrial conditions (Preind simulation) for each year individually, and performed a linear regression between the two variables~~First, we calculated the clear sky shortwave flux and temperature anomaly compared to the Preind simulation for each year individually and made a linear regression between the two variables.~~ Then, we obtained a radiative forcing as the clear-sky

shortwave flux anomaly of the linear regression line at zero temperature anomaly (i.e., when the climate system has not yet
255 adjusted to the forcing).

The SW radiative forcing in both ESMs was in good agreement with that in ECHAM-HAMMOZ (dashed lines). Radiative
forcings were slightly smaller (*i.e. less negative*) in MPI-ESM than ECHAM-HAMMOZ, likely due to differing background
conditions (preindustrial in MPI-ESM versus year-2000 in ECHAM-HAMMOZ, and thus more extensive ice cover in the
260 MPI-ESM simulations). The zonal distribution of radiative forcing also agrees well between the models (not shown).
Stratospheric aerosols absorb some LW radiation, and the LW radiative forcing in MPI-ESM agrees well with that in ECHAM-
HAMMOZ. However, CESM exhibits 37% (on average) weaker LW radiative forcing than ECHAM-HAMMOZ. This is
probably due to the different radiative transfer models in CESM-CAM4 (9 LW radiation bands) and ECHAM-HAMMOZ (16
LW radiation bands). However, LW radiative forcing was small compared to the SW forcing, and this underestimation does
265 not significantly affect the results or conclusions of this study. ~~Since~~*Because* LW radiative forcing (warming effect) is weaker
while SW radiative forcing (cooling) is stronger in CESM than in MPI-ESM, SRM resulted in slightly more clear-sky cooling
in CESM.

We see in Fig. 2 that SW radiative forcing does not increase linearly with the amount of injected sulfur. This is because more
270 sulfur condenses onto existing particles, and small particles coagulate more efficiently with larger particles, when the sulfate
burden is increased. This leads to lower particle numbers and larger particle sizes per unit sulfur injected (Heckendorn et al.,
2009; English et al., 2012; Niemeier and Timmreck, 2015). Conversely, Fig. 2 shows that the LW radiative forcing increased
quite linearly with the amount of injected sulfur as shown, as also demonstrated by Niemeier and Timmreck (2015).

275 Earth's outgoing radiation ~~is following linearly changes in is a linear function of~~ temperature (Koll and Cronin 2018), an effect
apparent in Fig. 2 c and d. However, SW radiation also changes as a function of temperature and we found that this change is
fairly linear. The resulting feedback was positive, amplifying cooling in the SRM scenarios and amplifying warming in the
case of a CO₂ increase. The radiative fluxes in Fig. 2 are clear-sky, and this SW feedback is thus caused mainly by ice cover
and albedo changes along with changes in atmospheric absorption. The SW feedback was much larger in CESM (all-scenario
280 average of 0.96 W/m²K) than in MPI-ESM (0.50 W/m²K). There was no large difference in surface albedo change between
models (*supplementary Fig. S1*). However, clear-sky SW absorption (net clear-sky SW flux at top of the atmosphere (TOA) -
net clear-sky SW flux at surface) was linearly dependent on surface temperature by 0.98 W/m²K in MPI-ESM and 0.85 W/m²K
in CESM (*supplementary Fig. S2*). We attribute this to *atmospheric shortwave response of* the change in atmospheric water
vapor due to the temperature change ~~, which then contributes to atmospheric shortwave absorption.~~ The differing model
285 response likely originates from the distinct radiation schemes and spectral resolutions in MPI-ESM and CESM. This argument
is supported by Fildier and Collins (2015), who likewise derived a larger SW absorption response to temperature in MPI-ESM
compared to models that include CAM4.

Overall, we find that the clear-sky aerosol radiative forcings in the two ESMs are in good agreement with ECHAM-HAMMOZ. However, the same stratospheric sulfur fields yielded 8% weaker (on average) total (SW+LW) clear-sky radiative forcing in MPI-ESM than in CESM.

3.2 Differences in Effective Radiative Forcings in MPI-ESM and CESM

Figure 3 shows Gregory plots for the total TOA all-sky (clouds also taken into account) radiative forcing ~~with clouds also taken into account~~. In this case, the total SRM radiative forcing was 22% weaker in MPI-ESM than in CESM. On the other hand, the radiative forcing due to increased CO₂ concentrations was larger in MPI (orange and red markers in Fig. 3), but the difference was relatively small and is explained by different cloud radiative forcings between models. The impact on SW radiation was larger than it was on LW radiation. The overall result is that the same stratospheric sulfur injection led to larger and faster cooling in CESM than in MPI-ESM (Fig. 3). During the 20-year simulation period, stratospheric sulfur injections of 6 Tg(S)/yr (SRM6) led to slightly over -1 K global mean cooling (left-most green hexagon in Fig. 3a) in MPI-ESM but closer to -2 K in CESM (Fig 3b). Global mean warming after 20-year 2xCO₂ and 4xCO₂ simulations was consistent between the models. However, there was a nearly 2 x larger radiative imbalance in MPI-ESM compared to CESM by the end of the simulations. If these simulations reached radiative equilibrium, the climate would presumably therefore be warmer in MPI-ESM than in CESM.

3.3 Temperature-independent fast and temperature-dependent slow precipitation responses

Precipitation responses can be divided into a temperature-independent fast response, which takes place immediately when some forcing agent is introduced, and a slow response caused by the temperature change and subsequent feedbacks (Myhre et al., 2017). Because of climate (e.g., ocean) inertia, precipitation will change slowly along with temperature even in the case of abrupt radiative forcing changes. Here, we separately quantified these fast and slow responses based on the regression method described earlier. Results are shown in Fig. 4. Fast response was obtained by intersection of fitted line and the y-axis (T=0), and slope of the linear fit shows the slow response due to the temperature change. Fast responses are mainly driven by changes in atmospheric absorption (Samset et al., 2016). A change in absorbed radiation modifies the amount of energy transferred between the TOA and surface. This energy transfer is then largely compensated by a change in latent heat flux (evaporation), in turn changing precipitation. Changes in CO₂ concentration affect LW atmospheric absorption while SRM primarily modifies SW reflection ~~and is affecting relatively less to how much radiation is absorbed~~.

Figure 4 shows that an atmospheric CO₂ increase led immediately to a decrease in global mean precipitation. However, this CO₂ increase simultaneously warmed the climate, which eventually led to a precipitation increase. After 2-5 years, this temperature-dependent slow component exceeded the immediate radiative component, and global mean precipitation was then larger than in the absence of a CO₂ increase. On the one hand, stratospheric sulfur aerosols (SRM1-6) also absorb some

320 radiation (Fig. 2b), but on the other hand, relatively ~~much~~ more solar radiation is reflected and thus less is absorbed by the
background atmosphere. We therefore saw only a small total temperature-independent increase in global mean precipitation
for most SRM cases. Overall increasing CO₂ decreases precipitation via the fast component and increases precipitation via
the slow temperature component (Fig. 5). Fast precipitation impacts were significantly larger for CO₂ changes than for SRM
(shown in legends in Fig 4.), and therefore the fast precipitation component of SRM was omitted in Figure 5 for clarity.

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As Fig. 4a shows, the fast precipitation responses in MPI-ESM differed from those in ECHAM-HAMMOZ, despite the fact
that the same atmosphere model was used in both cases. This may result from differing background conditions between the
models, land temperature change in ECHAM-HAMMOZ with fixed SST, or noise of in the yearly mean values of MPI-ESM
simulations.

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Based on the scenarios examined here, the average global precipitation change scales with global mean temperature with a
proportionality coefficient of 2.54 (SD 0.27) %/K in MPI-ESM and 2.26 (SD 0.13) %/K in CESM. These values are robust for
temperature changes caused by CO₂ and SRM forcings. Our results thus support prior findings that the slow precipitation
response is not dependent on the forcing agent (Kvalevåg et al., 2013).

335 **4. Results from simulated scenarios**

In the scenario runs (Table 1), the years 2010-2100 were simulated for RCP45 and for geoengineering the RCP4.5 climate via
SRM or CDR. Results are discussed below.

4.1 Change in global mean temperature

340 Global mean temperature and precipitation anomalies relative to 2010-2020 are shown in Fig. 6+. Under RCP45, the global
mean temperature increased by 1.30 K and 1.20 K over the 2010-2020 average in MPI-ESM and CESM, respectively. These
changes were slightly below the CMIP5 multi-model mean of 1.35 K (Knutti and Sedláček, 2012). During the same period,
global mean precipitation increased by 1.76-1.78 % under RCP4.5, also below the CMIP5 multi-model mean (2.66 %).

In the SRM-TEMP scenario, the global mean surface temperature was kept close to the present-day value via stratospheric
345 sulfur injections. This reduced global mean precipitation in both ESM simulations (Fig. 6). The reduction was significantly
larger in MPI-ESM (-1.42 %) than in CESM (-0.73 %). These differences are explored in Sect. 5. Given the SRM-TEMP
results, it is not surprising that when global mean precipitation is maintained at the 2010-level in the SRM-PRECI scenario,
the climate warms. SRM-PRECI warming in MPI-ESM is 0.64 K over 2010-2020 -level, substantially larger than was seen in
CESM (0.27 K). This is consistent with the disparate model results for SRM-TEMP.

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Overall, in both models, the majority of the global mean climate warming seen in RCP45 was compensated in SRM-PRECI. Based on GISTEMP data, the global average temperature in 2010-2018 was approximately 1 K warmer than in the pre-industrial era (defined as 1880-1900) (GISTEMP Team, 2019; Lennsen et al., 2019). Thus, in both ESMs the SRM-PRECI global temperature (~1.64 K in MPI-ESM and ~1.27 K in CESM compared to the preindustrial average increase) stayed within
355 the 2 C target of the Paris Agreement. For CESM, the SRM-PRECI temperature increase also stayed within the 1.5 C Paris target.

The CDR scenario led to a 0.10 (MPI-ESM) and -0.11 (CESM) K change in global mean temperature by the end of the century (2080-2100) compared to present-day (2010-2020). There was thus no significant difference in global mean temperature
360 between the CDR and SRM-TEMP scenarios at the end of the century. The largest difference in global mean temperature between these scenarios was seen immediately after the onset of geoengineering, when the CDR temperature was larger than in SRM-TEMP. Under CDR, the global mean temperature only starts to decrease post-2040. This is because CDR acts ~~more~~ slowly atmospheric CO₂ to reduce global temperatures whereas ~~that does similar cooling can be gained with~~ stratospheric sulfur injection ~~much faster~~ (Royal Society 2008). In the CDR scenario, CO₂ removal was suspended in year-2070, when
365 atmospheric CO₂ concentrations have returned to their 1976 levels. The global mean temperature at that time was close to the present-day value, and did not change significantly through the end of the century (when the rate of change in atmospheric CO₂ matches that seen in RCP 4.5). Thus, even this very optimistic CDR scenario is insufficient for cooling the climate to pre-21st century levels. However, our CDR scenario only reduced CO₂ concentrations, with other GHGs and aerosol concentrations following RCP 4.5.

370 **4.2 Change in global mean precipitation**

Although the global mean surface temperature in the CDR scenario was the same at the end of the century (2080-2100) as at the beginning of the century (2010-2020), the global mean precipitation was over 0.5 % larger in both ESMs. In Sect. 3.3, we showed that the precipitation impacts of SRM and CO₂ can be separated into a temperature-independent fast component and a temperature-dependent slow component. Here we use that framework to examine precipitation responses across the different
375 geoengineering scenarios. Precipitation is also affected by non- CO₂ GHGs, tropospheric aerosols, and land-use changes, all of which can induce their own temperature-independent fast components. For our purposes this can be assumed to be the same across all scenarios.

Based on our component analysis simulations we see that the fast precipitation response varies fairly linearly with absorbed radiation (See Fig. S3 in supplementary), but some deviation occurs due to changes to sensible heat flux and physiological responses of vegetation (DeAngelis et al., 2016). This result is consistent with that of Samset et al. (2016) and Myhre et al. (2017). The higher correlations in our simulations compared to Samset et al. (2016) may be due to the use of the fixed Sea
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Surface Temperature (SST) method to define the fast response in Samset et al. (2016): fast responses quantified with fixed-SST methods include land temperature adjustments.

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Radiative forcings are generally assumed to be additive (Marvel et al., 2015). If we assume based on supplementary Fig. S3 that the overall fast response depends only on absorbed radiation, it follows that the fast responses of individual forcing agents are also additive. In Sect. 3.3 we also showed that the slow temperature-dependent component does not depend on the applied forcing. We can thus describe the global mean precipitation change as the sum of the temperature dependent slow component ($a \times \Delta T$) and all fast components (Fläschner et al., 2016):

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$$\Delta P = a \times \Delta T + b(\text{SRM}) + c \times \ln \frac{\text{CO}_2 \text{ preind} + \Delta \text{CO}_2}{\text{CO}_2 \text{ preind}} + \text{BG}, \quad (24)$$

where a , and c are model-specific coefficients, b is a function of the SRM level, T is the simulated global mean surface temperature, $\text{CO}_2 \text{ preind}$ is the preindustrial CO_2 concentration, ΔCO_2 is the atmospheric CO_2 change relative to the preindustrial value, and BG is the background fast component, assumed to be the same for all scenarios. Coefficient a is obtained from the scenario-ensemble mean slope in Fig 4 (2.53 %/K for MPI-ESM and 2.27 % for CESM), while b is the fast component (intercept) from simulations of the corresponding SRM scenario (see $\Delta P(T=0)$ values in Fig 4). To calculate coefficient c , we again assume that fast precipitation response is linearly dependent on absorbed radiation. Radiative forcing due to CO_2 varies logarithmically with concentration (Etminan et al., 2016) and thus the fast precipitation response for CO_2 is also assumed to be logarithmically dependent on CO_2 concentrations (see supplementary material Fig. S4) where a, b, c are model specific coefficients, T is simulated global mean surface temperature, $\text{CO}_2 \text{ preind}$ is the preindustrial CO_2 -concentration, ΔCO_2 is the atmospheric CO_2 change relative to the preindustrial value, and BG is the background fast component, assumed to be the same for all scenarios. Coefficient a is obtained from the scenario ensemble mean slope in Fig 4, while b is the fast component (intercept) from simulations of the corresponding SRM scenario. The fast precipitation response varies linearly with absorbed radiation (Myhre et al., 2017). Radiative forcing due to CO_2 varies logarithmically with concentration (Etminan et al., 2016). Thus, the fast precipitation response for CO_2 is logarithmically dependent on CO_2 concentrations. We calculated the fast precipitation response for three different CO_2 concentrations: preindustrial, $2 \times \text{CO}_2$, and $4 \times \text{CO}_2$. The coefficient c can then be calculated from a logarithmical fit of the fast response versus CO_2 concentration across these three scenarios. This approach yields c values of 4.5 (%) for MPI-ESM and 4.0 (%) for CESM. Finally, we calculated the BG component as the 5-year running mean residual between the first three right-hand-terms of the right hand side of Eq. (24) and the modelled precipitation (ΔP in Eq.(2)) based on the RCP45 scenario. Note that if Eq. (24) is used only to study precipitation difference change between modelled scenarios, the BG component is not needed (see supplementary material Fig. S5). However here we also wish to examine precipitation changes relative to 2010-2020, and the BG term is thus included here.

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415 Figure 7 shows the precipitation component for each scenario in MPI-ESM and CESM. In general, the precipitation signal as estimated by the fast and slow components via Eq. (2) corresponds well to the actual model quantity in both ESMS for all scenarios. For RCP4.5 this is an obvious result because the BG is derived as the residual between the modelled precipitation and the sum of the individual components for this very scenario. However, the component-based and full precipitation signals also agree well for the other scenarios, even though the BG component is calculated from the RCP45 case. From year -2020 to year-2100 the mean differences between the Eq. (2) results and the actual model quantities were ranged from -0.01% to 0.04% for MPI-ESM and from -0.16% to 0.05% for CESM. Fig. S5 in supplementary material shows the precipitation responses under the geoengineering scenarios as anomalies relative to the RCP4.5 case. The plotted precipitation differences in Fig. S5 are thus independent of the BG component. We see from this figure that the individual components can be reliably used to understand the drivers of precipitation change for each scenario. Figure 7 shows the precipitation component for each scenario in MPI-ESM and CESM. In general, the precipitation signal as estimated by the fast and slow components via Eq. (1) corresponds well to the actual model quantity in both ESMS for all scenarios. From year 2020 to 2100 mean error in results between Eq. (1) and actual model quantity were 0.01%, 0.04%, and -0.01% with MPI-ESM and 0.16%, 0.12%, and 0.05% with CESM in SRM-TEMP, SRM-PRECI, and CDR, respectively. These individual components can therefore be used to understand the drivers of precipitation change for each scenario.

430 Figures 7a and b show that the precipitation increase in RCP45 would be roughly twice as large if only the slow component were operative. However, the fast radiative component reduced global mean precipitation increase by over 1% in both ESMS. This fast component related to increasing atmospheric CO₂ (plus other GHG and absorbing aerosol) probably also explains why the increase of observed global mean precipitation ~~to date~~ has not increased significantly ~~to date~~, despite the fact that climate has warmed (Allan et al., 2014).

435 Under the SRM-TEMP scenario (Fig. 7 c and d), the global temperature change (and thus the slow precipitation component) was small, as is the fast precipitation component due to sulfate aerosols. However, the fast component due to CO₂ was as large as in RCP45. This fast (radiative) component from CO₂ is the main reason that SRM generally leads to a decrease in global mean precipitation when used to fully offset GHG-induced warming. On the other hand, in the SRM-PRECI scenario (Fig. 7 e and f) the climate was cooled to the point that the temperature-dependent slow component balances the fast radiative components (CO₂, SRM and background), so that the net precipitation change was close to zero.

445 The CDR scenario led to a slight increase in global mean precipitation, despite no significant net change in global mean temperature. Figures 7 g and f show that this was also explained by the fast radiative component of CO₂. As in SRM-TEMP the slow temperature-dependent component was small. However, atmospheric CO₂ concentrations were much lower by the end of the century, reducing atmospheric absorption and thus increasing global precipitation compared to 2010-2020.

Although the global mean precipitation response was approximately the same in both ESMs in RCP45 and CDR, a closer look at the underlying drivers shows that only the radiative component of CO₂ was consistent across models. The temperature-dependent response differs between ESMs, driving divergent precipitation impacts. This was resulted from slightly different temperature response and hydrological sensitivity between ESMs. In RCP4.5 temperature-dependent slow component was 32% larger in the end of the simulation (2080-2100) with MPI-ESM than in CESM simulation. In CDR magnitude of the slow component was the same between models (0.28% in MPI-ESM and -0.24% in CESM at the end of the simulation), but the sign was different. However, this effect was compensated by differing non-CO₂ background responses, which also changed over the course of the simulated century. Figure 7 shows that this BG response is very different between the models and even have a different sign. In MPI-ESM non-CO₂ fast components were causing 0.48% decrease on precipitation at the end of the simulation (2080-2100) compared to the beginning (2010-2020) while in CESM non-CO₂ forcings were increasing precipitation by 0.23%. Thus, it is merely fortuitous that the net precipitation response was similar between models in the CDR and RCP45 scenarios.

The BG radiative components impacting precipitation include a range of factors including non-CO₂ GHG (methane, nitrous oxide, ozone, CFCs etc), tropospheric and background stratospheric aerosols, and land-use change—with differing treatments between models. Radiative transfer modeling also differs between the ESMs. As shown in Sect. 3.1-3, radiative forcing and (particularly) atmospheric absorption—and thus latent heat flux and precipitation—in the ESMs responded differently to the various forcing agents. Thus, it is not surprising that the BG precipitation component, which is affected by several different forcing agents, also differs between models.

5. Sulfur injections

Figure 8 shows the amount of sulfur required to keep global temperature or precipitation at current levels through the end of the 21st century. All scenarios started with injections of 1 Tg(S)/yr in year-2020, and the amount of required sulfur then increased along with the RCP4.5-driven warming. In all cases, more sulfur was needed to compensate for RCP4.5 warming than for the associated precipitation increase (see cumulative injection amount on right-hand axes). As shown in Sect. 4.2, the fast, CO₂-driven radiative component partly offsets the temperature-driven precipitation component caused by global warming. Thus, in the SRM-PRECI scenario, the sulfur aerosol only needs to compensate for the (already partly offset) precipitation effect of changing temperatures, rather than for the total temperature change (as is the case in SRM-TEMP).

Based on these simulations, in a total of 107-113 Tg(S) and 95-114 Tg(S) was required to prevent a simulated precipitation increase between years 2020 and 2100 in MPI-ESM and CESM, respectively (scenario SRM-PRECI). These 80-year totals are slightly larger than the amount of SO₂ emitted each year in the mid 1970s, when annual emissions were roughly 75 Tg(S)/yr (Smith et al., 2011). Global sulfur emissions have since decreased; however, China alone emitted over 100 Tg(S) SO₂ between

480 2006 and 2008 (Li et al., 2017). However, the lifetime of aerosols derived from surface emissions is on the order of days, and the cooling impact is therefore much smaller than in the case of stratospheric injection. In the SRM-PRECI scenario, yearly injections are 3 Tg(S)/yr or less, with the exception of occasionally higher injections for one MPI-ESM ensemble member.

Figure 8 reveals significant differences in injection amounts between the two ESMs. In CESM, preventing global mean warming (under RCP4.5) through year-2100 requires a total of 163-199 Tg(S). This was less than twice the amount required to prevent an increase in global precipitation. However, simulations with MPI-ESM suggest that preventing global mean warming via SRM would require 292-318 Tg(S), 50-100% more than in CESM and approximately 3x the amount required to stabilize global mean precipitation in scenario SRM-PRECI. Maximum yearly injections reached 6 Tg(S)/yr in MPI-ESM but only 3 Tg(S)/yr in CESM. These differences are mostly explained by the model responses to sulfate aerosols shown in Sect. 3: the all-sky forcing for a given amount of sulfur was significantly (22-33 %) larger in CESM than in MPI-ESM.

Figure 8 also shows some limitations of the climate-control algorithm used here. At times the change in SRM injection amount was too large, leading to an overly-strong climate response. In some cases the ensuing compensatory change in injection amount then overshoots the desired climate response in the opposite direction. This led to rapid fluctuations between SRM levels, as seen for example between years 2070-2080 in MPI-ESM ensemble member 2 for the SRM-PRECI scenario. Such effects could be avoided by smaller injection increments, ~~or by~~ using a more sophisticated algorithm that could better separate large natural variations in temperature or precipitation from long-term changes or defining geoengineering strategy in advance by using e.g linear response theory (Bódai et al., 2020). We also noted that the introduction of 1 Tg(S)/yr in 2020 led to an overly-large precipitation response for all simulations under scenario SRM-PRECI. However, the above effects do not affect the overall results and conclusions shown here.

6. Regional climate responses

While the SRM-TEMP and CDR scenario simulations led to similar global mean temperatures by the end of 21st century, the regional responses were quite different. Figures 9 a and b map the temperature difference between these two scenarios in both ESMs for the last 20 years of the 21st century. We see that the SRM-TEMP scenario led to cooler tropics and warmer high latitudes than the CDR scenario in both ESMs. These regional discrepancies have been demonstrated in prior studies (Kravitz et al., 2013; Laakso et al., 2017) and point to a fundamental problem with the SRM approach. Aerosols primarily affect incoming SW radiation, while GHGs affect LW thermal radiation, and the meridional gradient is steeper for SW than for LW radiation. Consequently, compensating for a global mean LW change by modifying SW radiation leads to zonally-dependent differences. This issue can be reduced by concentrating the SRM injections in mid and high latitudes, or via seasonal adjustment of the sulfur injection area (Laakso et al., 2017). Overall, however, the temperature differences over land between

scenarios were rarely statistically significant (indicated by hatching in Fig. 9, [10% and 20% of land area in MPI-ESM and CESM respectively](#)).

515 Figures 9 c and d compare the SRM-TEMP scenario to present-day climate (2010-2020). In MPI-ESM, the regional SRM-TEMP versus present-day temperature differences were significantly larger than those between SRM-TEMP and CDR at the end of the century. However, this was not the case in the CESM simulations. It should be kept in mind that comparing years 2080-2100 from the SRM-TEMP scenario with 2010-2020 (as present-day) is a somewhat arbitrary choice, and that the comparison reflects not only geoengineering impacts but also climate change under RCP4.5. In addition, even though the global mean temperature was similar between these two periods, the climate was relatively stable in 2080-2100 but was 520 warming in 2010-2020 climate. The regional patterns seen in Fig. 9 c) and d) thus depend to a degree on the choice of reference years, and not only the impacts of geoengineering.

Regional temperature anomalies for other scenarios are provided in the supplement (Fig. [S62](#)). Overall, RCP45 led to larger warming at high latitudes than at low latitudes when compared to CDR for years 2080-2100. The corresponding regional 525 patterns in SRM-PRECI were similar to those in RCP45 but with reduced magnitude. Nevertheless, warming in SRM-PRECI relative to the CDR scenario was statistically significant almost everywhere in both models.

Figure 10 shows the relative precipitation differences between the SRM-PRECI and CDR scenarios in boreal winter (DJF) and summer (JJA) in 2080-2100. Globally, CDR led to 0.5% more precipitation than SRM-PRECI in both models. However, this 530 precipitation change was not regionally or seasonally homogeneous. A key conclusion is that these changes were rarely statistically significant (hatching in Fig. 10) and that there was often not good agreement between models.

Both models did show broadly similar responses over tropical oceans, especially over the Eastern Pacific and Atlantic. This was probably caused by an Intertropical Convergence Zone (ITCZ) shift due to the zonal temperature difference between 535 SRM-PRECI and CDR (SRM-PRECI led to more warming in high versus low latitudes compared to CDR). Generally, the responses seen in Fig. 10 were larger in MPI-ESM than in CESM, likely due to the significantly warmer climate in MPI-ESM under SRM-PRECI. Supplemental Figures [S73](#) and [S84](#) show that when comparing temperature in SRM-PRECI and CDR, simulations with MPI-ESM led to much greater warming in DJF and (especially) JJA over Europe, Australia and South America when compared to CESM. Figure 10 shows that the corresponding precipitation responses were also significantly 540 different over these areas. Precipitation responses for the other studied scenarios are shown in the supplement (Figs. [S95](#) and [S106](#)). As with the results in Fig. 10, spatial features of these precipitation responses were rarely statistically significant. To increase confidence in how SRM and CDR would affect regional precipitation distributions, longer simulations or larger ensemble sizes are necessary.

7. Discussion and conclusions

545 Here, we have studied different scenarios in which global mean warming and precipitation changes are compensated by solar
radiation management (SRM) or carbon dioxide removal (CDR) during the 21st century. We carried out simulations using two
Earth System Models, MPI-ESM and CESM, with SRM based on stratospheric aerosols first simulated with the aerosol-
climate model ECHAM-HAMMOZ. SRM was used for two scenarios in which the magnitude of sulfur injections was
controlled to maintain global mean temperature or precipitation at year 2010-2020 levels in the RCP4.5 scenario. Additionally,
550 an idealized CDR scenario (also based on RCP4.5) was performed that included 1%/yr removal of atmospheric CO₂. We
examined the resulting global mean precipitation changes ~~mechanistically~~ by dividing the response into temperature-dependent
and temperature-independent components. These model-specific components were defined based on a regression method using
simulations with fixed climate conditions, and that included a constant SRM treatment or an abrupt change in atmospheric
CO₂ concentrations.

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Our work supports prior studies in showing that the ratio of the global precipitation change to the global temperature change
for SRM is larger than for an atmospheric CO₂ perturbation (e.g. Bala et al., 2008). Thus, less sulfur was needed to compensate
for the global mean precipitation change under RCP4.5 than to compensate for the corresponding temperature. Our results
showed that maintaining global precipitation at the same level from 2010 to 2100 required a total of 107-113 Tg(S) (with MPI-
560 ESM) and 95-114 Tg(S) (with CESM). However, preventing an increase in global mean temperature required 292-318 Tg(S)
(with MPI-ESM) and 163-199 Tg(S) (with CESM). To give perspective to this: Keeping global precipitation at current levels
through 2100 would thus require roughly the same amount of sulfur as the estimated surface emissions of China alone between
1996-2005 (121 Tg(S), Smith et al., 2011) <http://sedac.ciesin.columbia.edu/data/set/haso2-anthro-sulfur-dioxide-emissions-1850-2005-v2-86/data-download>. This simultaneously reduced global mean warming by 50% and 78% based on the MPI-
565 ESM and CESM simulations, respectively (compared to the 2010-2100 RCP4.5 temperature increase in the absence of SRM).

While completely preventing global mean warming in this century (in RCP4.5) would require much more sulfur than
preventing a change in global precipitation, the total sulfur required was comparable to that emitted globally at the surface
from anthropogenic sources during the first five years of the 21st century (274 Tg(S), Smith et al., 2011). However, maintaining
570 a constant global mean temperature in this way led to a significant reduction in global mean precipitation (-1.42% with MPI-
ESM and -0.73% with CESM) compared to present-day climate. Our component analysis showed that this precipitation
decrease was caused by the temperature-independent radiation component resulting from the CO₂ increase in the RCP 4.5
scenario. Under RCP4.5 without SRM, this component was overridden by the temperature-dependent effect on precipitation
from global warming. When this temperature component was compensated by SRM, the CO₂ component remains and global
575 mean precipitation decreases. It should be noted that this is the case for all SRM methods and not only for stratospheric
aerosols. SRM itself had only a small temperature-independent fast effect on precipitation.

In the CDR scenario, the annual CO₂ increase based on RCP4.5 was counteracted by a 1% annual removal of the atmospheric CO₂ concentration until year 2070. This was found to slow down warming significantly and to return the global mean temperature to its present-day (2010-2020) value. The atmospheric CO₂ budget is currently increasing at roughly 4 GtC/yr. In our CDR scenario, 8.7 GtC/yr of CO₂ was removed ~~yearly at~~ after year-2020. Our scenario should be considered as an idealized high-end CDR scenario as achieving this high CO₂ removal rates in a few years would not be feasible due to technological, economic, social, and political ~~constraints~~ issues. The results highlight the challenge in substantially slowing global warming, and suggest that entirely preventing global-mean warming during this century solely via CDR without significant cuts in CO₂ emissions is probably not achievable.

Even though global mean temperature at end of the CDR simulation was the same as at the beginning, global mean precipitation increased (~0.5 %) in both ESMs. To date, we have not seen as large increase in global mean precipitation as would be expected only based on the temperature increase (Allan et al., 2014). This is because the fast radiation-driven precipitation effect is largely compensating the slower temperature-dependent component from warming. However, over time, the temperature component will dominate, and a significant increase in global mean precipitation is expected. If atmospheric CO₂ is removed as in the CDR scenario, the temperature component is prevented from increasing, but simultaneously a positive fast CO₂ precipitation component is induced by the reduction of CO₂, increasing global mean precipitation. It is thus difficult to prevent an increase in global mean precipitation via GHG reduction. However, global precipitation changes are also driven by the fast radiative components of aerosols and non-CO₂ GHGs, and future precipitation will depend on how these emissions evolve over time.

RCP45 and CDR scenarios led to a similar global mean precipitation response between the two ESMs. However, regression analysis revealed that this was fortuitous. The precipitation response to changing temperature and CO₂ concentrations differed between the ESMs, but these differences were masked by offsetting background (BG) effects related to other GHGs and tropospheric aerosols. Large differences in the primary drivers of precipitation change can therefore exist between ESMs even when the ESMs predict similar net changes. A more detailed component analysis, with BG effects separated into relevant subcomponents, is therefore needed. The Precipitation Driver Response Model Intercomparison Project (PDRMIP) may help address this issue (Myhre et al., 2017).

Similar component analyses as done here on the global scale (Sect. 4.2) can in principle be performed regionally. However, for regional analyses (e.g., applying Eq. (24) for a single model grid box), the dry static energy flux divergence of the atmosphere needs to be taken into account (Richardson et al., 2016). This term depends on the neighbouring grid boxes and is not linear or independent from other components. Because of this and natural variability, regression analyses to quantify the fast and slow precipitation components either regionally or for individual grid boxes will be subject to noisier data than in the

global case. However, preliminary analyses reveal regions where the approach appears promising, and we therefore recommend further evaluation of this potential in subsequent work.

615 Overall, this study shows that global mean temperature-independent fast and temperature-dependent slow precipitation
responses caused by CDR and SRM can be quantified by the regression method. When these components are known, the
global mean precipitation change can be presented as the sum of the temperature-dependent slow component and all fast
components. Our results show that the fast responses of CO₂ have a major role in the resulting precipitation impacts, when
CO₂ induced global warming is slowed down by geoengineering. If global warming is prevented by stratospheric sulfur
injections while atmospheric CO₂ concentration still increases, the global mean precipitation is decreased due to the fast
620 response of increasing atmospheric CO₂. On the other hand, less sulfur is required to keep the global mean precipitation stable,
because the fast precipitation response to increased CO₂ is the opposite of the slow precipitation response resulting from
warmer climate. Without SRM, temperature response overruns CO₂ fast response (as in RCP45). Also in our CDR scenario,
the global mean precipitation increase was explained by the positive fast precipitation response to reduced CO₂. As we showed
here, separating precipitation to fast and slow response is a useful method to analyse differing precipitation responses between
625 different geoengineering techniques. This framework can thus help to understand and anticipate temperature and precipitation
responses in different time scales and geoengineering scenarios, where SRM and CDR are used potentially simultaneously. In
principle, this method can also be used to study precipitation response in any scenario, if the temperature change and forcing
agents are known.

630 Code and data availability. The data from the model simulations and implemented model codes are available from the authors
upon request.

Author contributions. AL designed the research, performed the experiments, carried out the analysis and prepared manuscript.
All author contributed ideas, interpretation and discussion of results and to writing the paper.

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Competing interests. The authors declare that they have no conflict of interest.

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Component analysis simulations (Preindustrial)	20 years with fixed background conditions
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Preind	Fixed preindustrial conditions
2×CO ₂	Atmospheric CO ₂ concentration = 570 pm
4×CO ₂	Atmospheric CO ₂ concentration = 1140 pm
SRM1-6	Continuous 1-6 Tg(S)/yr sulfur injections (10 N - 10 S, 20km)
Scenarios (RCP 4.5)	years: 2010 - 2100 with RCP 4.5 scenario in background
RCP45	Representative Concentration Pathway 4.5 W/m ²
SRM-TEMP	Temperature kept at 2010-2020 level by SRM
SRM-PRECI	Precipitation kept at 2010-2020 level by SRM
CDR	In addition to yearly change in atmospheric CO ₂ concentration in RCP 4.5, 1%/yr CO ₂ is removed from atmosphere

Table 1. Simulations

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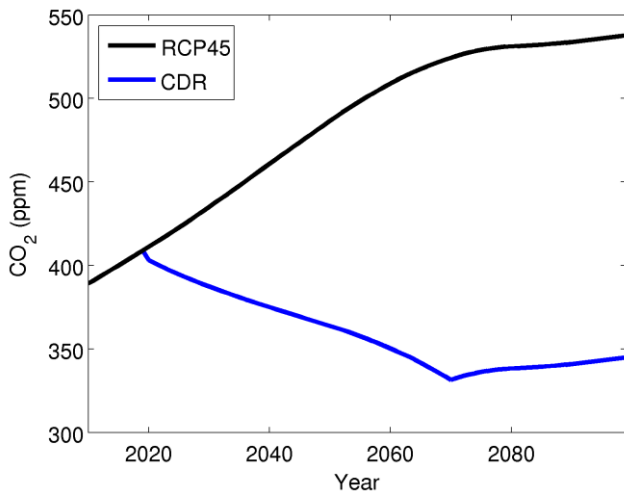
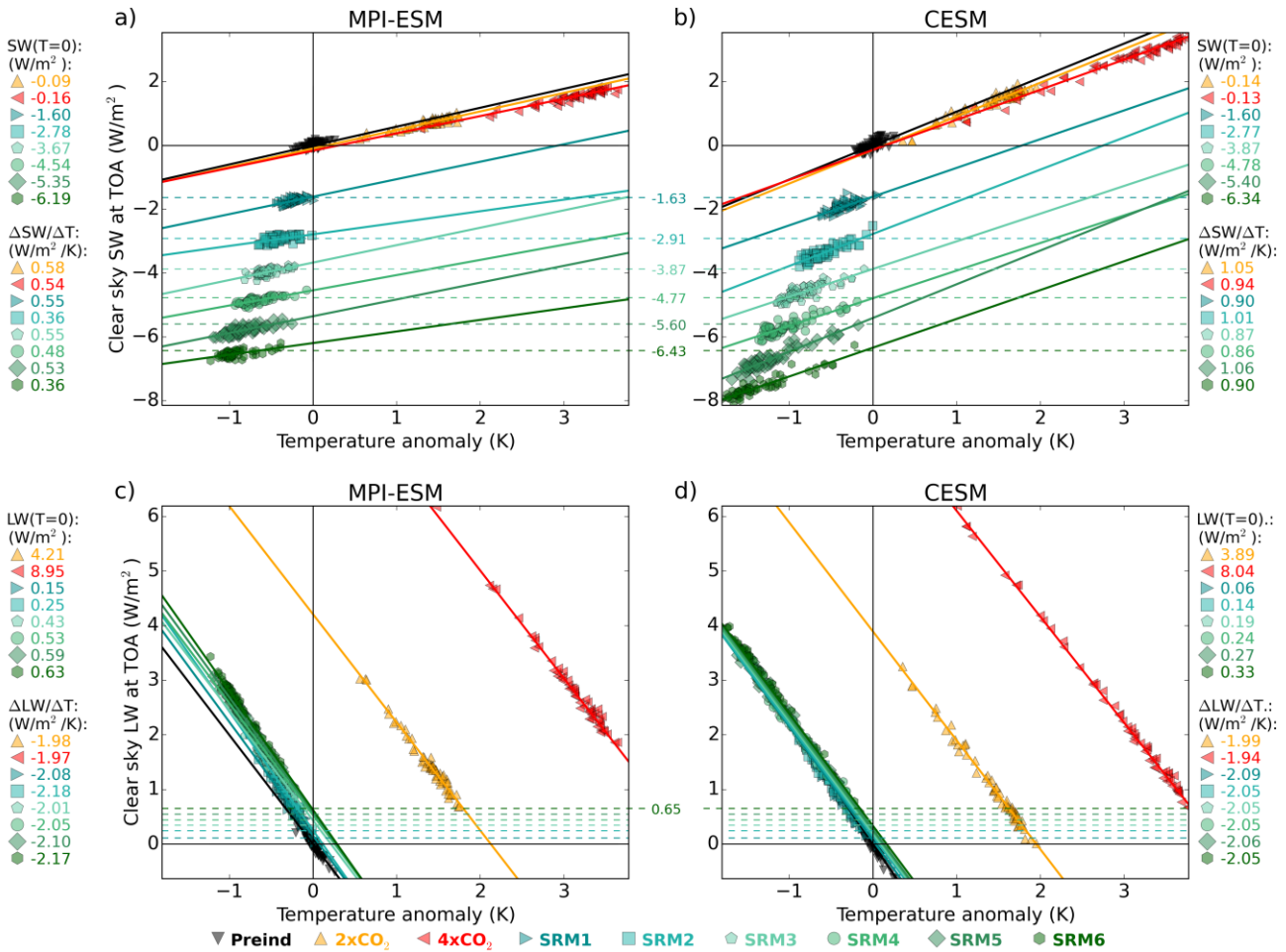
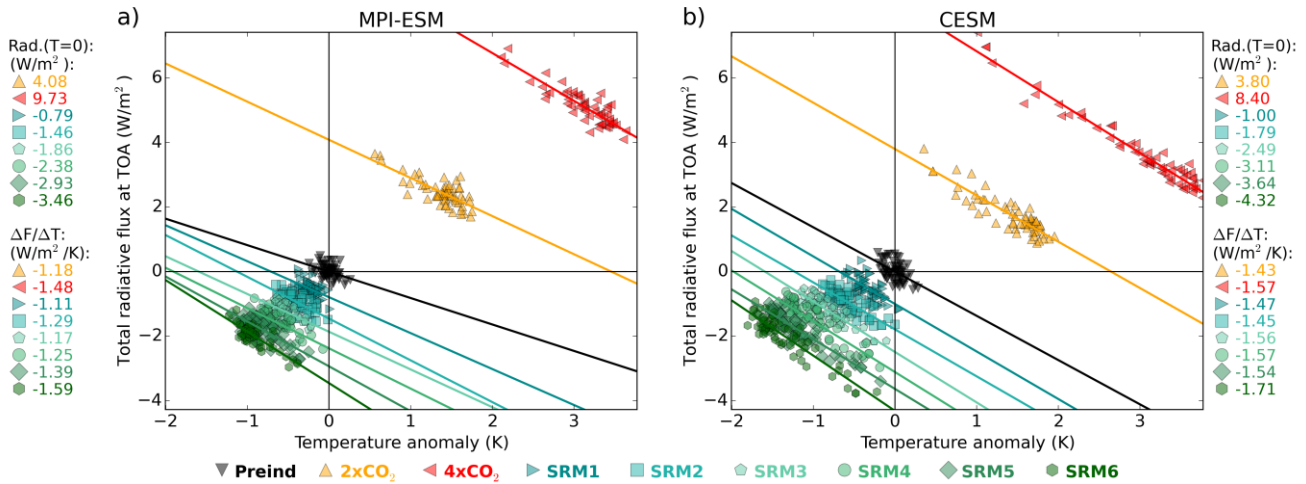


Figure 1: Atmospheric carbon dioxide concentration in scenarios RCP45 and CDR.



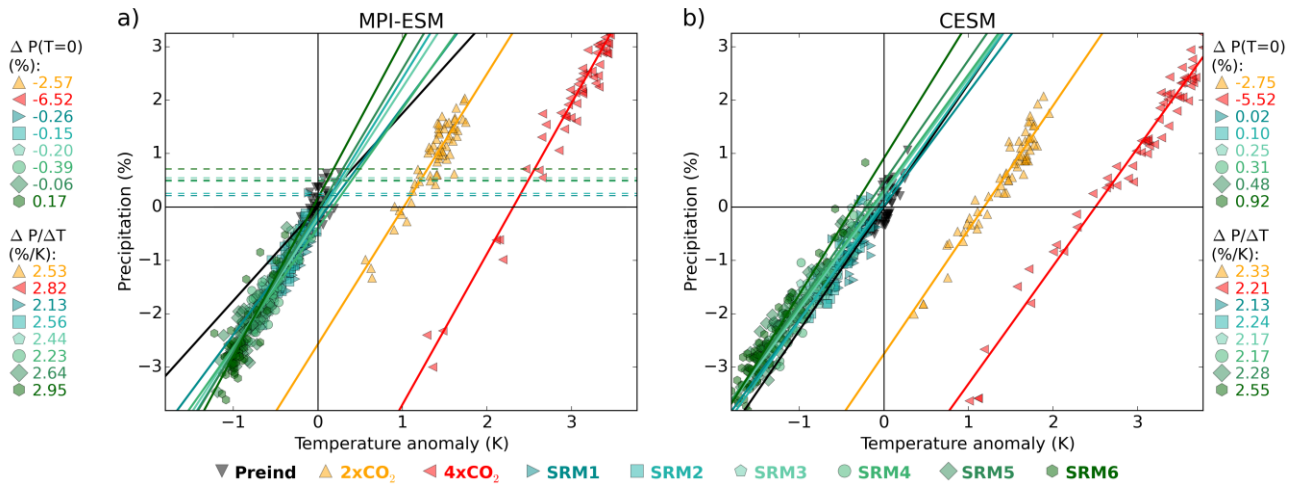
885 **Figure 2: Gregory plots of the shortwave radiative flux change (clear-sky conditions) with a) MPI-ESM and b) CESM, and of the longwave radiative flux change (clear-sky conditions) with c) MPI-ESM and d) CESM. Markers indicate a single-year global mean value in one ensemble member and solid lines are linear fit lines. Dashed lines show aerosol clear-sky radiative forcing in ECHAM-HAMMOZ, with numerical values shown in the middle. Corresponding radiative forcing (intersection of linear fit and the y-axis (T=0)) in MPI-ESM and in CESM are shown in **top and slope of the linear fit in bottom of legends** next to the figure. Origin represents zero temperature and clear-sky radiative flux anomaly compared to Preind simulation.**



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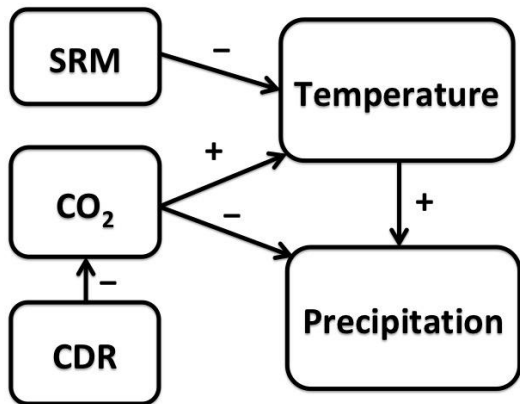
Figure 3: Gregory plots of total all-sky radiative flux change at the top of the atmosphere for a) MPI-ESM and b) CESM. Markers indicate a single-year global mean value for one ensemble member and solid lines are linear fits. Corresponding all-sky radiative forcing (intersection of linear fit and the y-axis (T=0)) in MPI-ESM and in CESM are shown in **top and slope of the linear fit in bottom** legends next to the figure. Origin represents zero temperature and clear-sky radiative flux anomaly compared to Preind simulation.

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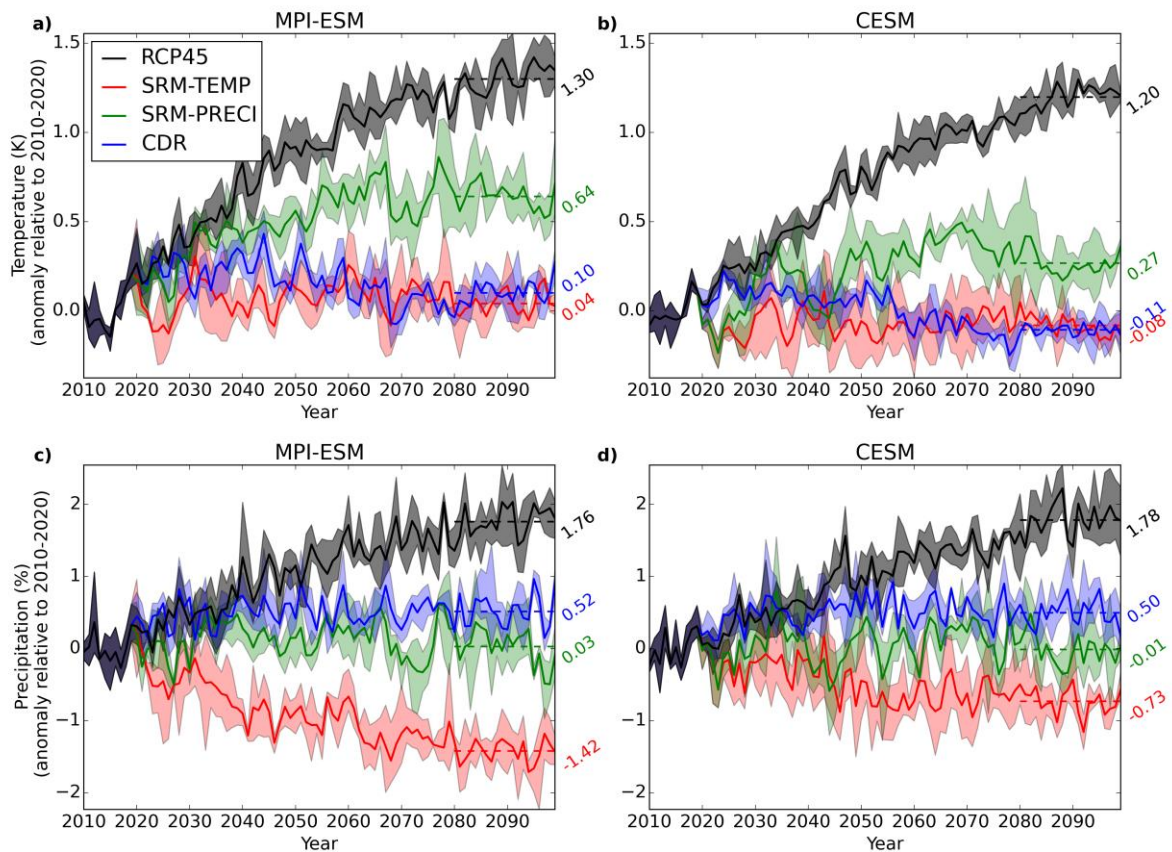


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Figure 4: Gregory plots of global precipitation changes under increased CO₂ (orange and red) and SRM scenarios with differing sulfur injection amounts (blue to green) for a) MPI-ESM and b) CESM. Each markers indicates a single-year global mean value for one of three ensemble members and solid lines are linear fits. Origin represents zero temperature and precipitation anomaly compared to Preind simulation. Fast precipitation response is obtained from intersection of linear fit and the y-axis (T=0) (shown in **top of the** legends next to the figure), and slope of the linear fit (**shown in bottom of the legends**) corresponds the slow response due to the temperature change. Dashed lines show (fast) precipitation responses for the corresponding scenarios in ECHAM-HAMMOZ (simulations with fixed SST).



905 **Figure 5:** A schematic presentation of fast radiatively-induced and slow temperature-induced components of SRM and CDR. Plus and minus signs indicate the direction of change in the target variable when the driving variable is increasing. If the driving variable is decreasing (e.g., temperature decrease due to SRM), the target variable changes in the opposite direction as indicated (e.g., decrease in precipitation due to decreased temperature). The fast component of SRM is so small compared to that induced by changes in CO₂ concentration that it is omitted for clarity.



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Figure 6: Global mean temperature anomalies in a) MPI-ESM and b) CESM, and global mean precipitation anomalies in c) MPI-ESM and d) CESM. Numbers to the right of each figure indicate the global mean difference between 2080-2100 and 2010-2020. Shaded areas show the maximum and minimum across three ensemble members.

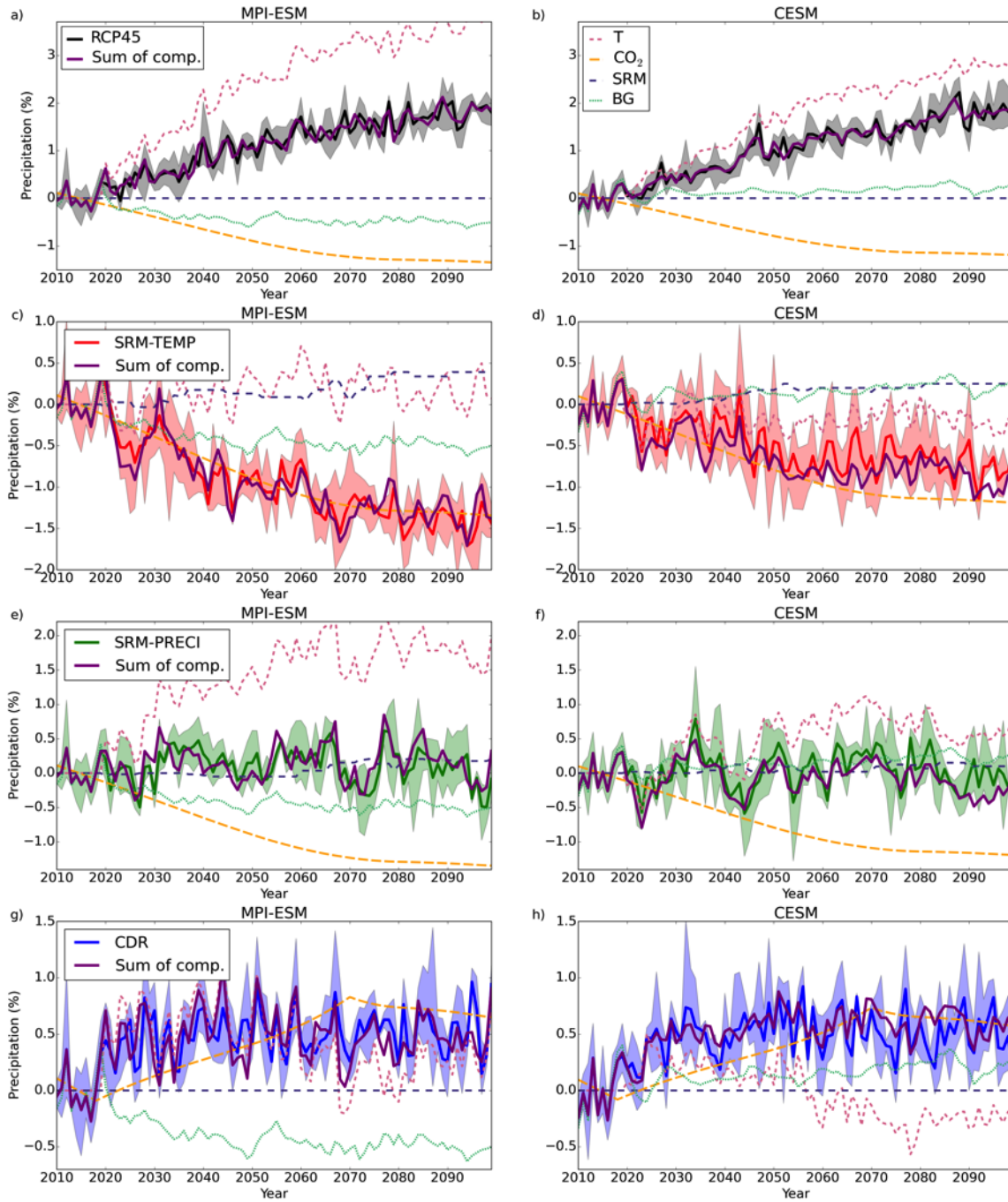
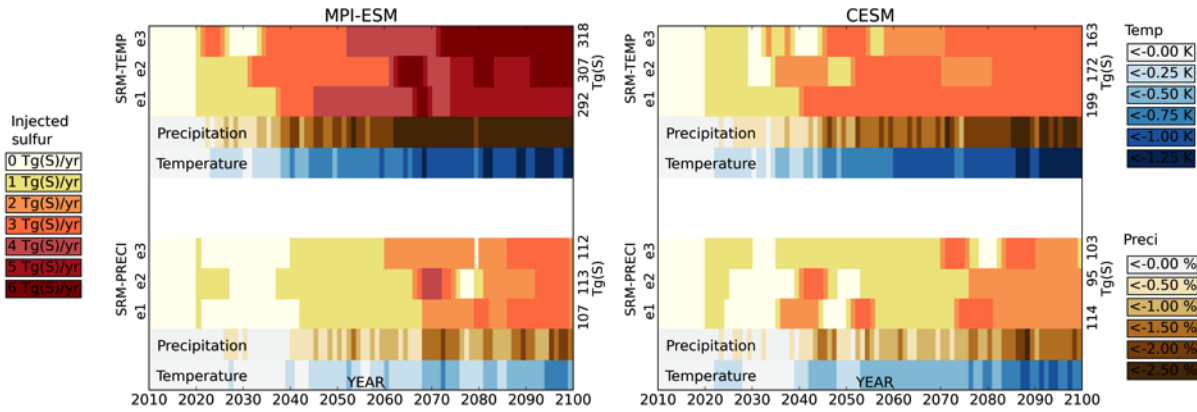
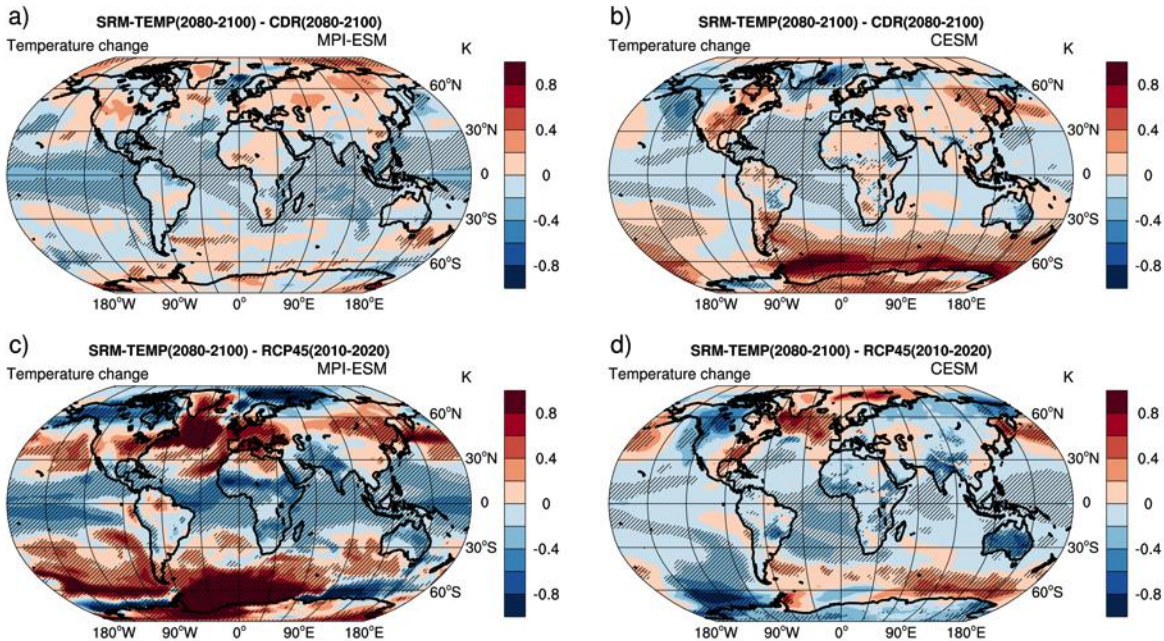


Figure 7: Precipitation components for each of the simulated scenarios. Solid colored lines with shaded areas have the same meaning as in Figures 5 c and d. Dashed colored lines indicate the precipitation change caused by individual component (see legend in panel b) for each scenario and model. The purple solid line shows the sum of all precipitation components (T, SRM, CO₂, and BG).



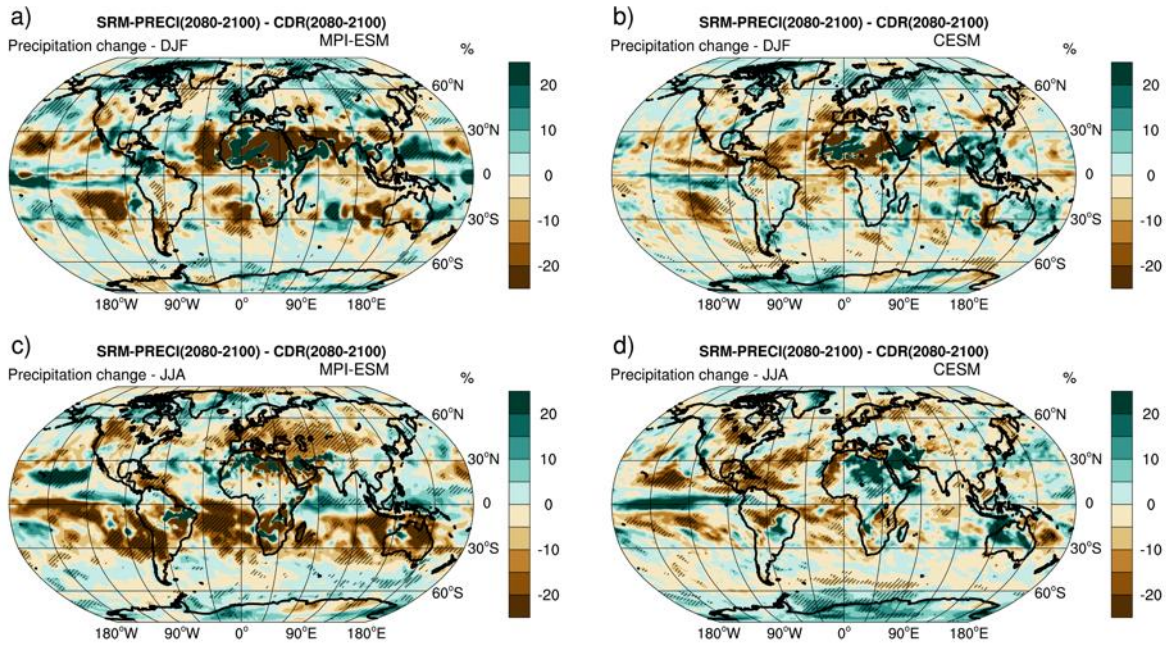
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Figure 8: Yearly sulfur injections in scenarios SRM-TEMP and SRM-PRECI for three ensemble members in MPI-ESM (left) and CESM (right). Also shown are the corresponding global mean precipitation and temperature differences relative to RCP45. The cumulative injection amount for each ensemble member is listed on the right-hand axis.



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Figure 9: Differences in regional temperature patterns between the SRM-TEMP and CDR scenarios for years 2080-2100 in a) MPI-ESM and b) CESM. Also shown are the temperature differences between the SRM-TEMP scenario for years 2080-2100 and present-day climate (RCP45, years 2010-2020), in c) MPI-ESM and d) CESM. Hatching indicates regions where the temperature change is statistically significant at the 95% level, with significance levels estimated using a Student's paired t-test (sample of 20 yearly mean values for 3 ensemble members).



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Figure 10: Relative change in precipitation between the SRM-PRECI and CDR scenarios for a) December-January-February and c) June-July-August in MPI-ESM, along with the corresponding figures for CESM (b and d). Hatching indicates regions where the temperature change is statistically significant at the 95% level, with significance levels estimated using a Student's paired t-test with (sample of 20 yearly mean values for 3 ensemble members).

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