Response to Review of "Extreme temperature and precipitation response to solar dimming and stratospheric aerosol geoengineering" by D. Ji et al.

We first thank the referee for his/her insightful comments, which helped us clarify and greatly improve the paper. In the reply, the referee's comments are in *italics*, our response is in normal and changes to the text are shown in blue.

Anonymous Referee #2

General Comments: In this manuscript, the authors analyzed the extreme values of climate indicators under 2 different solar radiation management scenarios G1 and G4. They took extreme index by ETCCDI and applied it on temperature and precipitation. The authors tried to find the differences and similarities on the global impact of two SRM experiment. And also tried to analysis the differences among the model.

This manuscript is novel and further complete the understanding of SRM. The structure is also well organized. I recommend the manuscript for publication though some of the comments still should be fixed or rephrased.

Specific Comments:

1. The significant regions in Fig. 2c and 4c,f,j need further descriptions on calculation process;

Reply: Yes. We've revised the previous Figure 2 and Figure 4. In our new Figure 1 and Figure 4 (we reorder some paragraph, previous Fig.2 is labelled as Fig. 1 now, please refer to our replies to Referee #1), we show the normalized results. We normalize the values of each grid from the differences of G1-abrupt4xCO2 according to the global average of G1-abrupt4xCO2, same for G4-rcp45. With these normalized results, we present the difference between normalized G1-abrupt4xCO2 and G4-rcp45 instead of the ratio between non-normalized G1-abrupt4xCO2 and G4-rcp45 to avoid large unrealistic values. In Figure 6, 7 and 8, we also show the differences of zonally normalized results in several single figures instead of ratios between non-normalized fields. We define all normalization methods in Section 2: Data and methods as the following:

2.3 Normalization methods

There are large differences in forcing between the G1 solar dimming and G4 stratospheric aerosol injection geoengineering schemes. The mean and extreme climates under the two type geoengineering are quite different as will be shown below. To aid the comparisons, we adopt the following normalization methods to compare spatially relative effectivities between solar dimming and stratospheric aerosol injection.

The normalized global spatial effects of solar dimming or stratospheric aerosol injection are defined as the grid mean difference relative to the global mean difference:

$$< \mathrm{X}^{\mathrm{geo}} - \mathrm{X}^{\mathrm{ref}} > = \frac{\overline{\mathrm{X}}^{\mathrm{geo}}_{\mathrm{grid}} - \overline{\mathrm{X}}^{\mathrm{ref}}_{\mathrm{grid}}}{|\overline{\mathrm{X}}^{\mathrm{geo}}_{\mathrm{global}} - \overline{\mathrm{X}}^{\mathrm{ref}}_{\mathrm{global}}|}$$

where the operator $<>$ denotes the normalized grid value, X is TXx, TNn, Rx5day or other climate field, an overbar denotes the average of each grid cell or the global average, the absolute operator $||$ in the denominator of the right term preserves the sign of the geoengineering anomaly. The superscript "geo" represents geoengineering experiments of G1 solar dimming or G4 stratospheric aerosol injection, the superscript "ref" represents the reference experiments of abrupt4×CO2 or rcp45.

To normalize zonal mean difference in the climate extreme indices relative to the global mean difference, we use a similar formula:

$$< \mathrm{X}^{\mathrm{geo}} - \mathrm{X}^{\mathrm{ref}} >= \frac{\overline{\mathrm{X}}^{\mathrm{geo}}_{\mathrm{zonal}} - \overline{\mathrm{X}}^{\mathrm{ref}}_{\mathrm{zonal}}}{|\overline{\mathrm{X}}^{\mathrm{geo}}_{\mathrm{global}} - \overline{\mathrm{X}}^{\mathrm{ref}}_{\mathrm{global}}|}$$

where the operator $<>$ denotes the normalized zonal mean, an overbar denotes the zonal or global average, the absolute operator $||$ in the denominator of the right term preserves the sign of the geoengineering anomaly.

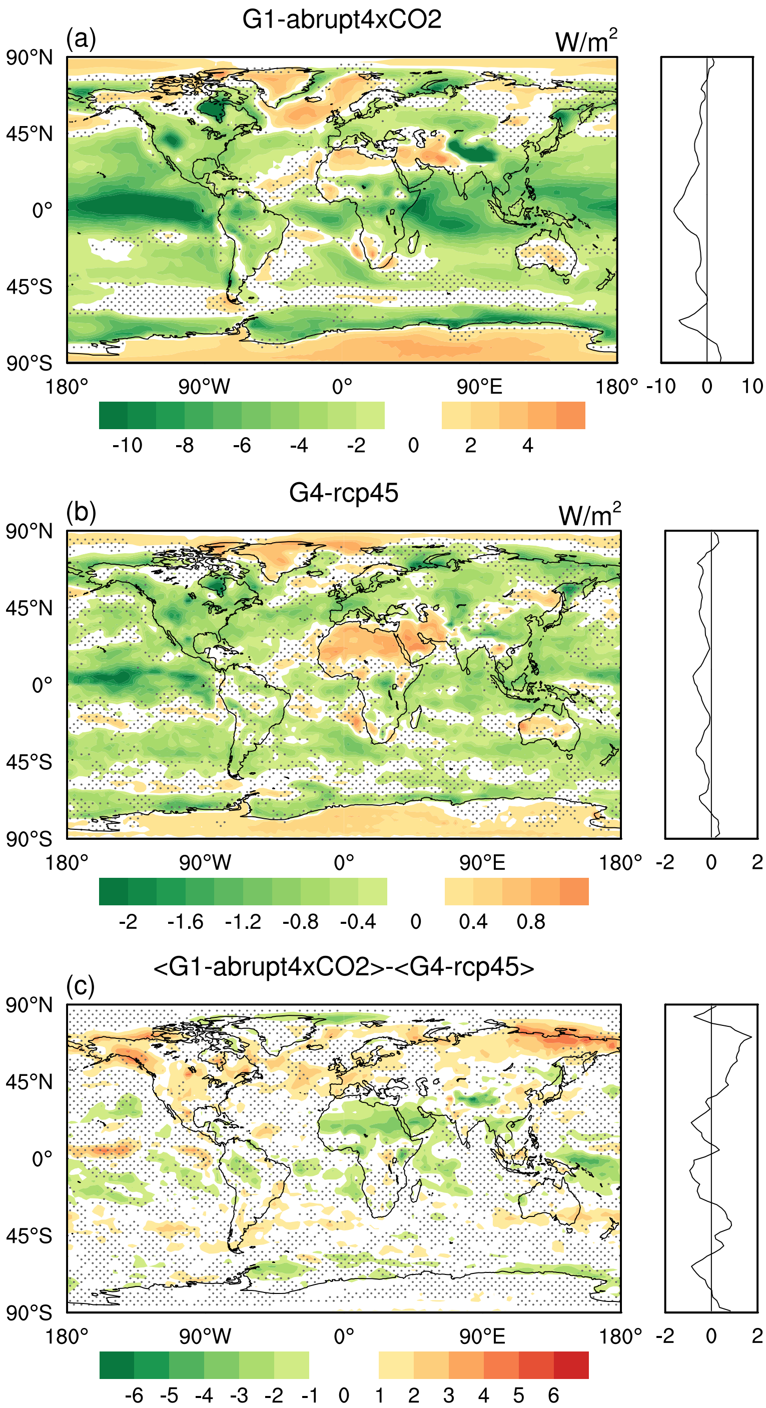

Figure 1: Geographical distributions over the 40-year analysis periods of differences in net radiation flux at TOA between G1-abrupt4×CO2 (top), G4-rcp45 (middle). The bottom panel shows the differences in net radiation flux at TOA between normalized G1-abrupt4×CO2 and G4-rcp45 Stippling indicates regions where fewer than 5 of 6 models agree on the sign of the model response. The right sub-panels show the zonal average of the left sub-panels. Note that all three panels have different scales.

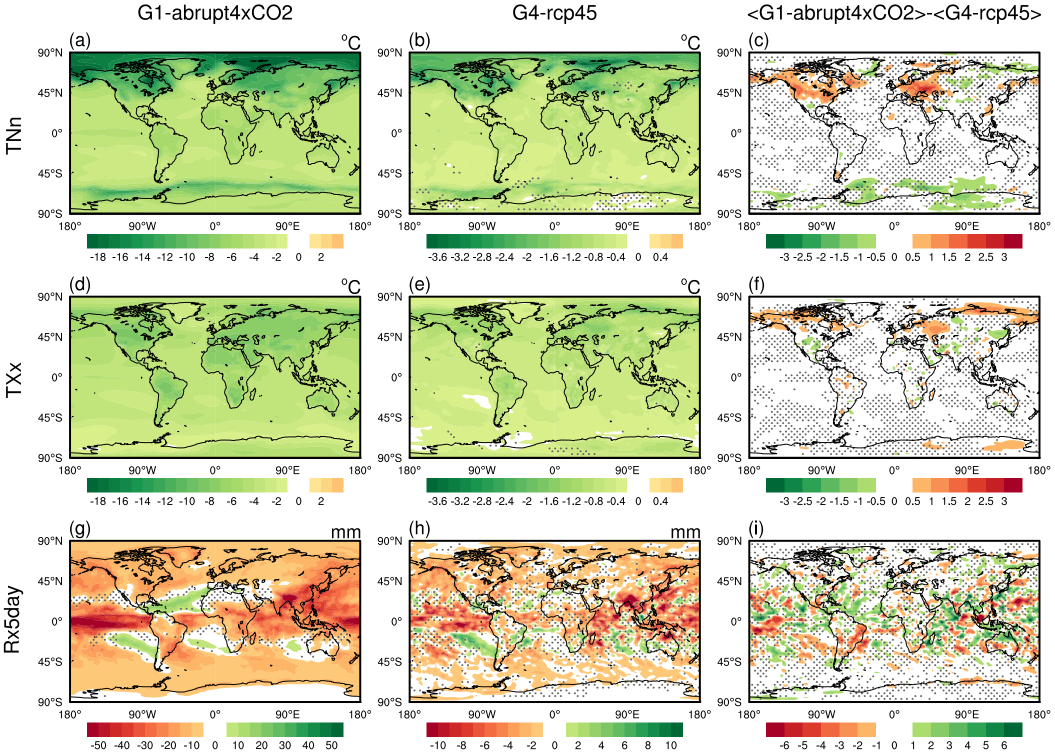

Figure 4: Geographical distributions over the 40-year analysis periods of the differences G1 - abrupt4×CO2 (left column), G4 - rcp45 (middle column), and differences between normalized G1 - abrupt4×CO2 and G4 - rcp45 (right column) for the extreme indices TNn (top row), TXx (middle row), and Rx5day (bottom row). Stippling indicates regions where fewer than 5 of 6 models agree on the sign of the model response. Note that panels have different colour scales.

2. The uncertainty reason present on abstract may not be proper here. Rephrase the word may be better.

Reply: Thanks. We revise the abstract as the following:

We examine extreme temperature and precipitation under two potential geoengineering methods forming part of the Geoengineering Model Intercomparison Project (GeoMIP). The solar dimming experiment G1 is designed to completely offset the global mean radiative forcing due to a CO_2-quadrupling experiment (abrupt4×CO2), while in GeoMIP experiment G4, the radiative forcing due to the representative concentration pathway 4.5 (RCP4.5) scenario is partly offset by a simulated layer of aerosols in the stratosphere. Both G1 and G4 geoengineering simulations lead to lower minimum temperatures (TNn) at higher latitudes, and on land primarily through feedback effects involving high latitude processes such as snow cover, sea ice and soil moisture. There is larger cooling of TNn and maximum temperatures (TXx) over land compared with oceans, and the land-sea cooling contrast is larger for TXx than TNn. Maximum 5-day precipitation (Rx5day) increases over subtropical oceans, whereas warm spells decrease markedly in the tropics, and the number of consecutive dry days decreases in most deserts. The precipitation during the tropical cyclone (hurricane) seasons becomes less intense, whilst the remainder of the year becomes wetter. Stratospheric aerosol injection is more effective than solar dimming in moderating extreme precipitation (and flooding). Despite the magnitude of the radiative forcing applied in G1 being ~7.7 times larger than in G4, and differences in the aerosol chemistry and transport schemes amongst the models, the two types of geoengineering show similar spatial patterns in normalized differences of extreme temperatures changes. Large differences mainly occur at northern high latitudes, where stratospheric aerosol injection more effectively reduces TNn and TXx. While the pattern of normalized differences of extreme precipitation is more complex than that of extreme temperatures, generally stratospheric aerosol injection is more effective in reducing tropical Rx5day, while solar dimming is more effective over extra-tropical regions.

3. On Page 15, Line 1-6, this paragraph are not linked so well with the context. There are also no further analysis on the daily rain types. Further explanation and graphs would be better.

Reply: Thanks. As this is at the end of "3.4 Spatial Response in Extremes", and the tropical precipitation change constitutes a large percentage of global precipitation change, therefore we would like to address how the tropical precipitation change in response to G1 solar dimming and G4 stratospheric aerosol injection in different major rain types. To make it clear, we add the following sentence:

As the tropical extreme precipitation change constitutes a large percentage of global extreme precipitation change in response to two type geoengineering schemes (Fig. 4g, 4h), it is interesting to know how the G1 solar dimming and G4 stratospheric aerosol injection affect major rain types in tropical regions.

Minor comments:

1. P2 L18: Missed ref. Lathan et al. 2. P3 L12: Missed ref. Niemeier et al.

Reply: Thanks. We add missing references, such as Latham (1990), Niemeier et al. (2013), Pitari et al. (2014), Smyth et al. (2017):

Latham, J.: Control of global warming?, Nature, 347, 339–340, 1990.

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

Pitari, G., Aquila, V., Kravitz, B., Robock, A., Watanabe, S., Cionni, I., Luca, N. D., Genova, G. D., Mancini, E., and Tilmes, S.: Stratospheric ozone response to sulfate geoengineering: Results from the Geoengineering Model Intercomparison Project (GeoMIP), J. Geophys. Res.-Atmos., 119, 2629–2653, 2014.

Smyth, J. E., Russotto, R. D., and Storelvmo, T.: Thermodynamic and dynamic responses of the hydrological cycle to solar dimming, Atmos. Chem. Phys., 17, 6439-6453, doi:10.5194/acp-17-6439-2017, 2017.

3. P5 L1: The estimate of CSDI and WSDI is applied on ensemble mean temperature or mean CSDI/WSDI?

Reply: The CSDI and WSDI are calculated for each model firstly, then equal weight is given to each model before calculating multi-model ensemble mean. We clarify this point in "Data and Methods" as following:

Equal weight is given to each model in the analysis, and climate extreme indices are calculated for each model before multi-model ensemble averaging is done.

4. P8 L24-27: It is not clear for me about the relations between different models and the geoengineering impact. Further expression would be better.

Reply: Yes, Thanks for this comment. In the revised manuscript we emphasize the differences between G1 solar dimming and G4 stratospheric aerosol injection, and how each model implements the G4 experiment.

In the "Introduction" section, we add previous studies discussing the differences of the two type geoengineering schemes:

Both methods would cool Earth's surface by reducing sunlight reaching the surface, either by aerosols reflecting sunlight or by artificially reducing the solar constant in climate models. The injected stratospheric aerosols under G4 not only scatter shortwave radiation, also absorb near infrared and longer wavelengths (Lohmann and Feichter, 2005). The differences between stratospheric aerosol injection and solar dimming are influenced strongly by the absorption of longwave radiation by aerosols, this atmospheric heating imbalance could further stabilize the troposphere and lead to stronger precipitation reduction under stratospheric aerosol injection than under solar dimming (Niemeier et al., 2013). That there can be a difference in the mean climate response in reduced solar constant and increased stratospheric sulphate aerosols has been shown (Yu et al., 2015; Niemeier et al., 2013; Ferraro et al., 2014) and we expect that this will also be evident in the temperature and precipitation extremes.

In the "Results" section 3.1, we add the following to show the impacts of the two type geoengineering schemes on TOA net radiation flux:

The forcing of the G1 solar dimming and G4 stratospheric aerosol injection experiments are quite different, there can be a difference in the mean and extreme climate responses. The multi-model ensemble mean net radiation flux at the top of atmosphere (TOA) is 2.76 Wm^{-2} and 0.004 Wm^{-2} for the abrupt×4CO2 and G1 experiments, and 1.63 Wm^{-2} and 1.27 Wm^{-2} for the rcp45 and G4 experiments during their 40-year analysis periods. Therefore, the G1 solar dimming and G4 stratospheric aerosol injection exert a reduction of 2.76 Wm^{-2} and 0.36 Wm^{-2} for net radiation fluxes at TOA respectively. The differences of mean net radiation flux at TOA over land and ocean between two geoengineering experiments and their reference experiments are show in Table 3. Although the ratio between the global temporally averaged net radiation flux reductions at TOA is a factor of ~7.7, the spatial distribution of net radiation flux changes for the G1 and G4 ensemble means are quite similar, especially the positive TOA net radiation over Greenland, Antarctica, North Africa and West Asia, and the negative TOA net radiation over North America, Central Europe and tropical ocean basins (Figure 1). The entire ensemble shows a large and consistent positive TOA net radiation east of Greenland in the North Atlantic under G1 solar dimming (Figure 1a), the region associated with the overturning part of the Atlantic meridional circulation (AMOC), and which under the G1 forcing was shown to be strongly affected by changes in radiative forcing and air/ocean heat exchange (Hong et al., 2017). However, differences are clearer when we investigate the spatial pattern of normalized effects exerted by the two SRM experiments, although most regions have differences close to zero for normalized solar dimming and stratospheric aerosol geoengineering effects on TOA net radiation (Figure 1c). The G4 stratospheric aerosol injection geoengineering introduces a more effective reduction in TOA net radiation over the Northern Hemisphere, especially over the high-latitude continents, such as northern North America, Siberia and some regions of western Europe. The G1 solar dimming geoengineering introduces a more effective reduction in TOA net radiation over North Africa, northern South America, the Indian Ocean and tropical Western Pacific. In contrast, many other equatorial regions, the Southern Ocean and the Intertropical and South Pacific Convergence Zones display small differences between normalized solar dimming and stratospheric aerosol injection effects.

The G1 solar dimming assumes global uniform solar reduction, while under G4 sulphate aerosols are handled differently among the participating models. GISS-E2-R and HadGEM2-ES adopt stratospheric aerosol schemes to simulate the sulfate aerosol optical depth (AOD), BNU-ESM and MIROC-ESM use the prescribed meridional distribution of AOD recommended by the GeoMIP protocol, CanESM2 specifies uniform sulfate AOD (Kashimura et al., 2017). NorESM1-M specifies the AOD and effective radius which were calculated in previous simulations with the aerosol microphysical model ECHAM5-HAM (Niemeier et al., 2011, Niemeier and Timmreck, 2015). Although a prescribed AOD can be set, difference in assumed particle size for the stratospheric sulfate aerosols (Pierce et al., 2010) and the warming effects of stratospheric aerosol (Pitari et al., 2014) cause difference in the SRM forcing.

In "Results" section 3.2, we add following to show impacts of two type geoengineering schemes on mean climate states:

The G1 solar dimming and G4 stratospheric aerosol injection geoengineering greatly affected the mean climate states. The annual mean surface air temperatures are 291.0 K and 286.7 K for abrupt4×CO2 and G1 experiments, 288.8 K and 288.3 K for rcp45 and G4 experiments respectively during their 40-year analysis periods. The global hydrological strength is likewise reduced; the annual mean precipitation totals are 1125.8 mm and 1026.9 mm for abrupt4×CO2 and G1 experiments, 1098.4 mm and 1084.3 mm for rcp45 and G4 experiments (Table 3).

5. P12 L2: May be I got missed but I'm not sure what the 'case' indicate.

Reply: In our previous manuscript, the 'case' means the extreme precipitation scales with mean temperature. In the revised manuscript, we largely revise this paragraph as following:

If relative humidity and atmospheric circulation remain relatively unchanged, then intense precipitation amount is governed by total precipitable water in the atmosphere, which the Clausius–Clapeyron relation says scales with mean temperatures (Allen and Ingram, 2002). The global mean precipitation decreases 2.1±0.4% per Kelvin in response to G1 solar dimming, and 2.7±1.0% per Kelvin in response to G4 stratospheric aerosol injection. The GISS-E2-R model contributes a relatively large portion to the spread of scaling between mean precipitation and temperature with a value of 4.5% per Kelvin for G4. If excluding the GISS-E2-R model, the global mean precipitation decreases 2.0±0.4% per Kelvin in response to G1 solar dimming, and 2.3±0.5% per Kelvin in response to G4 stratospheric aerosol injection. The scaling between mean precipitation and mean temperature under G1 and G4 is smaller than 3.4% precipitation change per Kelvin estimated from other coupled models under long-term equilibrium climate in response to doubling CO_2 (Allen and Ingram, 2002). The global mean Rx5day decreases 3.4±1.0% per Kelvin in response to G1 solar dimming, and 4.3±2.6% per Kelvin in response to G4 stratospheric aerosol injection. GISS-E2-R gives global mean Rx5day decreases 9.5% per Kelvin for G4. If excluding GISS-E2-R model, the global mean Rx5day decreases 3.4±1.1% per Kelvin in response to G1 solar dimming, and 3.3±0.6% per Kelvin in response to G4 stratospheric aerosol injection. The scaling of mean precipitation and mean temperature is expected to be much less than the 6.5% per Kelvin implied by the Clausius–Clapeyron relation, as the global-mean precipitation is primarily constrained by the availability of energy not moisture (Pall et al., 2007). The scaling of Rx5day and mean temperature under G1 and G4 is close to, but still weaker than the Clausius–Clapeyron relation, probably because Rx5day is not really an index of the heaviest rainfall events that are expected to be constrained by the Clausius–Clapeyron relation. The Clausius–Clapeyron relation implies the same scaling of extreme precipitation and mean temperatures under both G1 and G4 experiments, which is the case here for five of six models, but not the GISS-E2-R model.

6. P13 L28: Eastern China in Fig4 seems no special around the globe, this part may need further explanation.

Reply: We deleted this sentence. It's more likely a regional feature which is usually not very well represented in the models as suggested by Referee #1.

7. P14 L10-13: The reduction of Rx5day is whether a result from Curry et al., 2014 or from the paper result? Further explanation would be better.

Reply: Here we mean the results from the previous study by Curry et al. (2014). In our study, we also find the reduction of Rx5day under solar dimming and stratospheric aerosol injection geoengineering schemes. Please refer to the revised sentences following this line:

The ensemble means show that Rx5day is strongly reduced over equatorial regions, especially in the equatorial Pacific and southern flank of the Tibetan Plateau (Fig. 4g, 4h). This is due to increased atmospheric stability and suppression of convection under geoengineering (Bala et al.,2008).

8. P15 L1-6: The paragraph may not fully link with the context and there is no graphs or tables to support the statistics.

Reply: The numbers given are from simple calculations of the model precipitation output. We could have put them in a table but it seemed more concise to simply give the statistics as a sentence. The context comes because we are discussing Rx5day throughout the paragraph, and in particular tropical and monsoon rains (that is heavy rain).