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Key Points:

- Reducing the incoming solar radiation is often used to emulate injecting SO₂ in the stratosphere, but produces different surface outcomes
- Solar reduction matched to the pattern produced by the aerosol optical depth results in better surface climate matching between the methods
- Including the stratospheric heating produced by the aerosols produces further improvements and highlights key physical mechanisms at play

Supporting Information:

- Supporting Information S1

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Is Turning Down the Sun a Good Proxy for Stratospheric Sulfate Geoengineering?

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Abstract Deliberately blocking out a small portion of the incoming solar radiation would cool the climate. One such approach would be injecting SO₂ into the stratosphere, which would produce sulfate aerosols that would remain in the atmosphere for 1–3 years, reflecting part of the incoming shortwave radiation. The cooling produced by the aerosols can offset the warming produced by increased greenhouse gas (GHG) concentrations, but it would also affect the climate differently, leading to residual differences compared to a climate not affected by either. Many climate model simulations of geoengineering have used a uniform reduction of the incoming solar radiation as a proxy for stratospheric aerosols, both because many models are not designed to adequately capture relevant stratospheric aerosol processes, and because a solar reduction has often been assumed to capture the most important differences between how stratospheric aerosols and GHG would affect the climate. Here we show that dimming the sun does not produce the same surface climate effects as simulating aerosols in the stratosphere. By more closely matching the spatial pattern of solar reduction to that of the aerosols, some improvements in this idealized representation are possible, with further improvements if the stratospheric heating produced by the aerosols is included. This is relevant both for our understanding of the physical mechanisms driving the changes observed in stratospheric-sulfate geoengineering simulations, and in terms of the relevance of impact assessments that use a uniform solar dimming.

Plain Language Summary Injecting SO₂ in the stratosphere has been proposed as a method to temporarily cool the planet by partially reflecting the incoming solar radiation. To assess the eventual side-effects of this method, some climate model simulations have simply reduced the solar constant in the model rather than simulating the actual aerosols that would be produced. We show here what the limits of emulating stratospheric sulfate injection this way are, and what are the physical causes behind the differences from simulations where stratospheric aerosols are simulated.

1. Introduction

The possibility of injecting SO₂ in the stratosphere to mitigate some of the negative effects of anthropogenic global warming has been discussed for decades, starting with Budyko (1978) and notably by Crutzen (2006). Despite model simulations showing that it would be effective at offsetting many aspects of climate change (e.g., P. J. Irvine & Keith, 2020; Kravitz et al., 2017), deploying stratospheric sulfate (SS) injections would come with drawbacks of its own, and many studies have explored the possible side effects of this method, both in the stratosphere (Pitari et al., 2014; Tilmes et al., 2008) and at the surface (Jiang et al., 2019; Jones et al., 2018). When comparing two climates with similar global surface temperatures (or other globally defined metrics, Lee et al., 2020), where one is engineered with stratospheric aerosols and the other has lower CO₂, they would differ because aerosols and GHG do not affect the climate system via the same pathways: while the aerosols reduce solar radiation (shortwave; SW) at the surface, the increasing CO₂ concentrations trap more outgoing longwave radiation (LW) emitted by the planet. Moreover, the spatial and seasonal dependence of the two forcings are also different (Ban-Weiss & Caldeira, 2010; Govindasamy et al., 2003; Jiang et al., 2019), since CO₂ is a well-mixed gas with relatively uniform radiative effect in both space and season, while the insolation varies strongly with latitude and season, and the spatial distribution of stratospheric aerosols also varies due to the stratospheric circulation and injection location (Tilmes et al., 2017). The net results of these effects on the surface are that while the global mean temperature could be successfully reduced through stratospheric sulfate injections, the combination of stratospheric aerosol and increased

CO₂ forcing would lead to residual differences such as regional changes to the hydrological cycle (Cheng et al., 2019; Jones et al., 2018; Simpson et al., 2019). These changes, however, would very likely be smaller in magnitude than those produced by climate change itself (P. J. Irvine & Keith, 2020; MacMartin et al., 2019). Another important difference is to be found in the stratosphere, where the sulfate aerosols would absorb some near-infrared radiation and heat the air locally, resulting in changes to stratospheric dynamics (Aquila et al., 2014; Niemeier & Schmidt, 2017; Niemeier et al., 2020; Richter et al., 2017; Visioni, MacMartin, Kravitz, Lee, et al., 2020), chemistry (Tilmes, Richter, Mills, et al., 2018; Visioni, Pitari, Aquila, Tilmes, et al., 2017), and upper tropospheric clouds (Kuebbeler et al., 2012; Visioni, Pitari, Di Genova, et al., 2018). Furthermore, the stratospheric heating may also affect the surface climate due, for instance, to shifts in the atmospheric circulation (Simpson et al., 2019).

Globally, the differential impact of longwave and shortwave radiative effects has been considered to be the main reason for the surface climate differences, and so reducing the solar constant rather than actually simulating the aerosols has been a widely used simulation technique (Kravitz, Caldeira, et al., 2013). While this simplification clearly would not capture impacts such as changes in ozone (Tilmes et al., 2008) or different ratio of direct/diffuse light (Kravitz et al., 2012), it does capture the simultaneous reduction of SW radiation and increase in LW radiation. Due to the uncertainties in our understanding of stratospheric sulfate microphysics and interaction with radiation, and to the lack, in some models, of a proper representation of stratospheric circulation, this simplification has also allowed more climate models to perform similar simulations (Kravitz, Caldeira, et al., 2013). Many studies have thus used a uniform reduction of the solar constant (solar dimming, SD) as a proxy to simulate the effects of stratospheric sulfate geoengineering, looking at its consequences on surface processes, for instance on the hydrological cycle (Guo et al., 2018; P. Irvine et al., 2019; Ji et al., 2018; Russotto & Ackerman, 2018a, 2018b; Smyth et al., 2017) and vegetation (Dagon & Schrag, 2019; Gienke et al., 2015). Some recent studies aiming to generally evaluate Solar Radiation Management (SRM) techniques in the framework of Integrated Assessment Modeling have also used SD climate simulations as a proxy for any SRM method (Harding et al., 2020; Low & Schfer, 2019; Oschlies et al., 2017; Tavoni et al., 2017).

However, reducing solar irradiance instead of simulating the stratospheric aerosols would only be a good proxy if the differential SW and LW effects dominate the surface climate impacts, as this approximation does not include stratospheric warming caused by the absorption of LW radiation by the sulfate aerosols (Kleinschmitt et al., 2018; Niemeier & Schmidt, 2017; Richter et al., 2017), nor does it capture differences in the spatio-temporal distribution of the aerosols (Dai et al., 2018; Visioni et al., 2019). Furthermore, the impact of aerosols on the ratio of direct to scattered incident light would lead to changes in downwelling radiation at the surface, in turn affecting ecosystems. Previous studies have already compared the two methods and highlighted some of the differences in the surface response (Ferraro et al., 2015; Kalidindi et al., 2015; Niemeier et al., 2013; Xia et al., 2017), finding generally lower changes in the hydrological cycle when performing SD simulations compared to SS ones. However, these previous comparisons have always equated SD with a global decrease in the solar constant and SS with equatorial injections aimed at managing globally averaged quantities, either temperature or radiative forcing. Furthermore, earlier models oftentimes used either nonfully interactive or prescribed aerosols (Kalidindi et al., 2015; Xia et al., 2017) to simulate SS.

In recent years it has been shown that by combining injections at different latitudes it is possible to devise SS strategies capable of managing more than just global surface temperature (Kravitz et al., 2017). The ability of SS to be tailored to more precisely modify the distribution of the radiative forcing in order to minimize projected side effects (Dai et al., 2018; Lee et al., 2020; MacMartin et al., 2017) is therefore another important difference compared to SD.

In light of this, we reconsider in this work the simulated physical differences between SS and SD simulations. Together with simulations more similar to those analyzed in the past (equatorial injections and spatially uniform reduction in the solar constant), we consider here also a set of SS simulations designed to maintain, through multiple injection locations, the global surface temperature together with the interhemispheric and equator-to-pole gradients of temperature (Tilmes, Richter, Kravitz, et al., 2018). We also consider a new set of SD simulations designed to achieve similar objectives through a nonspatially-uniform reduction in the solar constant (similar to Kravitz et al., 2016). Finally, we also include one more set including a 3×3 SD reduction while superimposing the stratospheric heating that would be produced by the aerosols

Table 1

Summary of the Simulations Analyzed in This Study, With a General Description of the Method Used to Maintain Surface Temperatures at 2010–2030 Levels. 1 × 1 and 3 × 3 Indicate the Climate Objectives (First Number) and the Degrees of Freedom That Need to Be Modified in Order to Achieve Those Goals (Second Number) (See for Further Explanation Kravitz et al., 2016)

Sim. name	Description
1 × 1 SD	Uniform solar dimming to maintain global mean temperature
1 × 1 SS	Stratospheric sulfate aerosols injected at the equator to maintain global mean temperature
3 × 3 SD	Solar dimming in three independently adjusted patterns (globally uniform, linear with sine of latitude, and quadratic with sine of latitude) to maintain global mean temperature, the interhemispheric temperature gradient, and the equator-to-pole temperature gradient
3 × 3 SS	Stratospheric sulfate aerosol injection at four independent locations (30°S, 15°S, 15°N, and 30°N) to maintain global mean temperature, the interhemispheric temperature gradient, and the equator-to-pole temperature gradient
3 × 3 SDH	As in 3 × 3 SD but with the stratospheric heating patterns from 3 × 3 SS superimposed

in the analogous SS simulations. A similar experiment has been performed in Simpson et al. (2019), with heating rates from stratospheric aerosols imposed for 20 years in the period 2010–2030. In our case, the simultaneous presence of the stratospheric heating and of the nonuniform solar dimming allows for a more direct comparison between the sets of experiments, given the ability to maintain similar temperature gradients compared to the SS simulations. By cross-comparing these five sets (Table 1), we aim to better separate the differences produced by the various factors mentioned above, in particular those driven by differences in the obtained temperature gradients (caused by latitudinal differences in the amount of solar radiation reflected or attenuated) and those driven by the presence of the aerosols themselves, for instance by further isolating the role of the stratospheric heating in the changes observed in the SS simulations.

This study is structured as follows: in Section 2 we explain how the five sets of simulations were built, and we expand on how the cross-comparisons can clarify single aspects of the climatic response. In Section 3.1, we compare the simulated results in terms of surface temperature and precipitation and try to understand the physical mechanisms behind them, then try to quantify how well the SD simulations represent the SS ones for some of those quantities in Section 3.2. We then discuss other quantities for which the response is highly different in Section 3.3 for the surface and in Section 3.4 for stratospheric quantities. Finally, we discuss our results in Section 4.

2. Methods

We analyze here five sets of simulations performed with the Community Earth System Model (CESM), with the Whole Atmosphere Community Climate Model (WACCM) as its atmospheric component (Mills et al., 2017), with 70 vertical layers reaching up to 140 km and comprehensive, fully interactive stratospheric chemistry. The model also has a land component (Community Land Model, version 4.5) and coupled ocean (Parallel Ocean Program, version 2, Danabasoglu et al., 2012) and sea ice (Los Alamos Sea Ice Model, CICE4). This configuration of the model has been thoroughly evaluated in Mills et al. (2016), Mills et al. (2017), and compares well with present-day and past observations, both in quiescent conditions and in the period following the 1991 Mt. Pinatubo eruption.

All simulations follow greenhouse gas emissions prescribed under the RCP8.5 scenario, and with either solar dimming or stratospheric SO₂ injections to offset the warming relative to 2020 (calculated as the average over 2010–2030 from a 20-member ensemble of RCP8.5 simulations). The sets termed 1 × 1 aim to keep the global yearly surface temperature (T_0) at the 2010–2030 average, either by means of a uniform reduction of the solar constant (1 × 1 SD) or by SO₂ injections at the equator 5 km above the tropopause (1 × 1 SS) (Kravitz et al., 2019). The other sets, termed 3 × 3, aim to keep three surface temperature targets: keeping global yearly surface temperatures and interhemispheric (T1) and equator-to-pole temperature gradients at the 2010–2030 average (T2), either by modifying the solar constant proportionally to constant, linear,

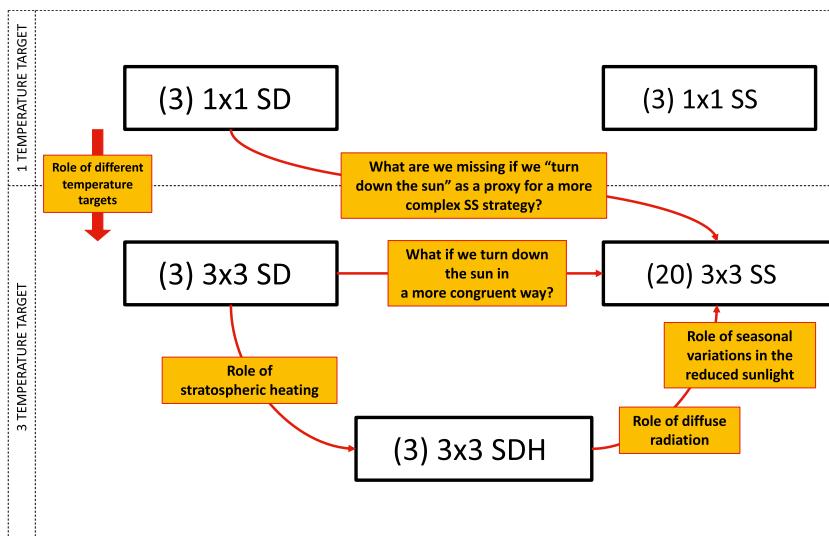


Figure 1. Summary of the simulations employed in this work. The white boxes give the name of these simulations as referred to in this paper and the size of the ensemble, in brackets. The orange boxes represent the key scientific questions that can be answered by comparing different sets of simulations.

and quadratic functions of the sine of latitude (projections of the first three Legendre polynomials onto area-weighted solar reduction) (3×3 SD) (see Kravitz et al., 2016; MacMartin et al., 2013) or by injecting SO₂ at four latitudes (30°S, 15°S, 15°N, and 30°N), 5 km above the tropopause and at the international date line, to achieve an aerosol optical depth (AOD) similar to the desired 3×3 solar reductions needed (3×3 SS) (Tilmes, Richter, Kravitz, et al., 2018). Decisions on the amount of solar reduction or on the amount of SO₂ to inject at each location are taken at the end of each year of simulation by a feedback loop (Kravitz et al., 2017) to ensure that the desired goals are met. Both SS sets have already been described and analyzed in Tilmes, Richter, Kravitz, et al. (2018) and Kravitz et al. (2019).

A final ensemble of simulations tries to maintain the three surface temperature goals with the same method as the 3×3 SD one, but imposes in the stratosphere the same stratospheric heating rates that would result from the stratospheric aerosols in the 3×3 SS simulation in the same period, with a method similar to that described by Simpson et al. (2019) (monthly varying 3D-heating rates above 100 hPa derived from a double call to the radiation scheme with and without the aerosols). The amount of solar dimming needed is then calculated independently from the 3×3 SD ensemble, thus taking into account changes in surface temperatures produced by the stratospheric heating (see Figure S1 and Simpson et al. (2019)). While Simpson et al. (2019) imposed heating that was the same for the entire period, derived from the 2075–2095 period of aerosol injections, in our case the overall magnitude of the heating evolves year-by-year in the same way as the stratospheric heating in the 3×3 SS simulations. This is done in order to have both a more “self-consistent” perturbation year after year and still realistically evolving in magnitude as if the aerosol burden was increased every year. A comparison of the different physical processes that can be investigated by comparing the different sets of simulations is described in Figure 1.

All analyses in this manuscript are for the period 2070–2089, as that 20-year time period has the greatest forcing of all periods simulated and thus the highest signal-to-noise ratio (MacMartin et al., 2019). The SS simulations are started in 2020. The SD simulations are branched off the SS simulations in 2060, substituting the injection of SO₂ with solar reduction (as in Visoni, MacMartin, Kravitz, Richter, et al., 2020). The first 10 years are left out of the analyses to give the system time to relax to the new state, even though all stratospheric aerosols are already removed after the first 2 years without injection. All simulations are compared against the period 2010–2030 (using the entire 20-member ensemble), termed Control in this work.

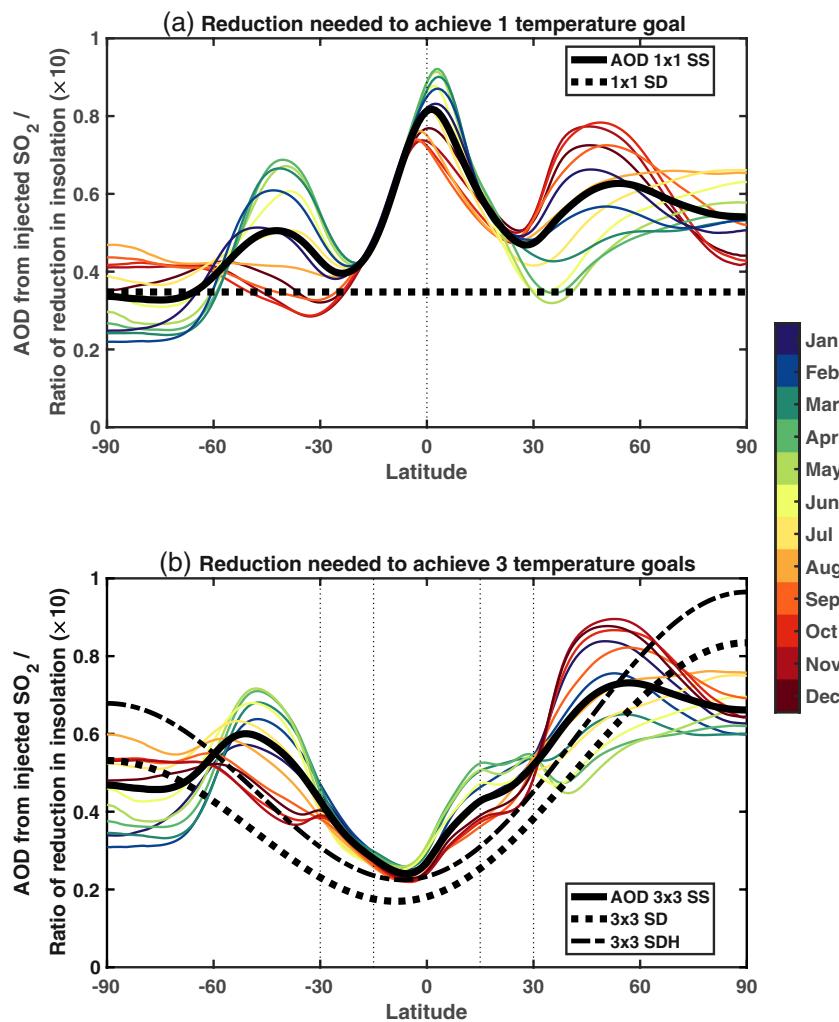


Figure 2. Comparison of stratospheric sulfate AOD obtained through SO_2 injections (SS) or solar dimming (SD) for the five simulations, both averaged over 2070–2089. In panel (a), cases maintaining global mean temperature are shown. In panel (b), cases maintaining global mean temperature, interhemispheric temperature gradient, and equator-to-pole temperature gradient are shown. AOD annual averages are shown in solid black, while solar dimming (expressed as a fraction of incoming solar radiation reduced $\times 10$) is shown in dashed black. Monthly AOD is shown with solid colors (see colorbar). In panel (b), the dash-dotted line shows the solar dimming necessary for the SDH simulations. SO_2 , aerosol optical depth.

3. Results

All model simulations restore global surface temperature to within 0.17 K of the average in the Control period. In the period 2070–2089 considered in our analyses, that equates to an average cooling of 3.9 K (Tilmes, Richter, Kravitz, et al., 2018) in order to maintain the same temperature as the period 2010–2030. The obtained AOD and solar dimming required to achieve the temperature goals are shown in Figure 2. There are clear differences in the solar dimming patterns that preview some of the observed changes that will be discussed later on. The uniform dimming in the 1×1 SD case implies an overcooling of the tropics and an undercooling at high latitudes (Govindasamy et al., 2003; Kravitz, Caldeira, et al., 2013), resulting in a reduction, for instance, in September sea ice in the Arctic (Table 2) even when global surface temperatures are restored. There are also evident differences with the 1×1 SS case, where the AOD produced by equatorial injections is not latitudinally uniform due to the tropical confinement of the aerosols (Visioni, Pitari, Tuccella, et al., 2018), amplifying even more the tropical overcooling. The increasing fractional solar reduction at higher latitudes compensates for this in the 3×3 cases, either by directly reducing sunlight or by injecting

Table 2

Summary of the Main Results of the Five Simulations, as Departures From the 2010–2030 Period in Control: T_0 , T_1 , and T_2 Represent the Projections of Near-Surface Air Temperatures in the First Three Legendre Polynomial in K; Precipitation (P) and Precipitation-Evapotranspiration Over Land ($\Delta P - E_{land}$) in mm/day

Simulation	ΔT_0	ΔT_1	ΔT_2	ΔP	$\Delta P - E_{land}$	ΔSSI
1 × 1 SD	-0.04	0.29	0.18	-0.09	-0.035	-1.1
1 × 1 SS	0.17	0.07	0.23	-0.14	-0.044	0.7
3 × 3 SD	-0.03	0.02	-0.02	-0.07	-0.041	2.7
3 × 3 SS	0.06	0.04	0.09	-0.12	-0.038	1.5
3 × 3 SDH	-0.10	0.02	-0.02	-0.10	-0.050	2.9

Note. Arctic September Sea ice (SSI) in $10^6 \times \text{km}^2$.

outside the tropics. Over 60° of latitude, however, the 3×3 SS differs further from the SD case due to the dynamical transport barrier there (Visioni, MacMartin, Kravitz, Lee, et al., 2020). Roughly, an AOD of 0.1 equates to a reduction of 1% in incoming solar irradiance (e.g., Hansen et al., 2005). In the 3×3 cases, SDH requires more solar reduction compared to SD. This is due to an increase in stratospheric water vapor resulting from tropopause warming (Tilmes, Richter, Mills, et al., 2018; Visoni, Pitari, & Aquila, 2017) as we show in Figure S1, that in turn warms the surface (Hansen et al., 2005; Simpson et al., 2019).

3.1. Comparison of Simulated Surface Temperatures and Precipitation

In Figure 3, we show the annually averaged surface temperature response in all cases relative to Control. Despite global mean temperature being within 0.17 K of the objective, local differences of up to 1–2 K are present;

however, these differences are much smaller than those due to RCP 8.5 alone. The comparison of the 1×1 SD with both SS simulations highlights that, aside from a few features, simply turning down the sun is not a good analog for how regional temperatures would respond to the stratospheric aerosols. Exceptions include the sign of the tropical overcooling and high-latitude undercooling and the warming over the northern Atlantic Ocean (due to overcompensating the GHG-driven slowing down of the Atlantic Meridional Overturning Circulation (AMOC) in this model (Fasullo et al., 2018)).

These differences are due to various factors. For the 1×1 cases, as shown in Table 2, the magnitude of T_1 and T_2 in the SS case are not captured correctly by the SD case due to the peak in AOD in the tropics that does not resemble the uniform dimming in solar radiation (Figure 2a) (Equatorial injection in this model results in slightly higher AOD in the northern hemisphere than the southern, roughly compensating T_1 even though that was not an objective of the 1×1 SS simulation). For the 3×3 cases, this effect is less pronounced, since the injection locations are chosen so as to have a similar profile to the one actually achieved by the solar dimming (MacMartin et al., 2017). At very high latitudes in both hemispheres, however, some differences are present mostly due to the polar transport barriers (Visioni, MacMartin, Kravitz, Lee, et al., 2020) that reduce the high-latitude AOD. It is likely that a more uniform AOD distribution using more latitudes of injection (see for instance Dai et al., 2018) could produce results more closely resembling those from 1×1 SD: however, some differences would still remain due to the considerable variation across different months of the AOD (Figure 2) compared to the constant dimming produced by the SD cases: as shown by Visoni, MacMartin, Kravitz, Richter, et al. (2020), seasonal variations in AOD can result in notably different surface climates.

Lastly, the other difference between the simulations is the lack of stratospheric heating in the SD simulations. Previous papers point to the substantial lower troposphere warming in the winter (relative to baseline) over the continental northern high latitudes (Europe and Asia), (Jiang et al., 2019; Simpson et al., 2019), and consistent with what has been postulated in the past literature on the Pinatubo 1991 eruption (Robock, 2000; Robock & Mao, 1995), link this at least in part to the stratospheric heating produced by the aerosols. A recent paper by Polvani et al. (2019) has however cast doubts on the physical causal link relating the two, showing that in large ensembles of simulations (one of them performed with WACCM4, a model similar to that used for the simulations in this study) the winter warming over Eurasia does not appear to be a consistent result, being limited to only some members of the ensemble.

Jiang et al. (2019) suggest that shifts in the high-latitude seasonal cycle are partly due to the dynamic effects from the stratospheric heating and partly due to there being more sunlight to reflect in summer than winter, but were unable to quantify the breakdown of the relative importance of these. There they used, however, simulations with a stratospheric heating imposed on top of a 2010–2030 climate, and compared against a geoengineered climate at the end of the century. Here we have the opportunity to expand on previous analyses since we can directly compare simulations with similar temperature gradients and CO₂ concentrations, but different stratospheric responses. In Figure 4a, we show the monthly temperatures over the selected

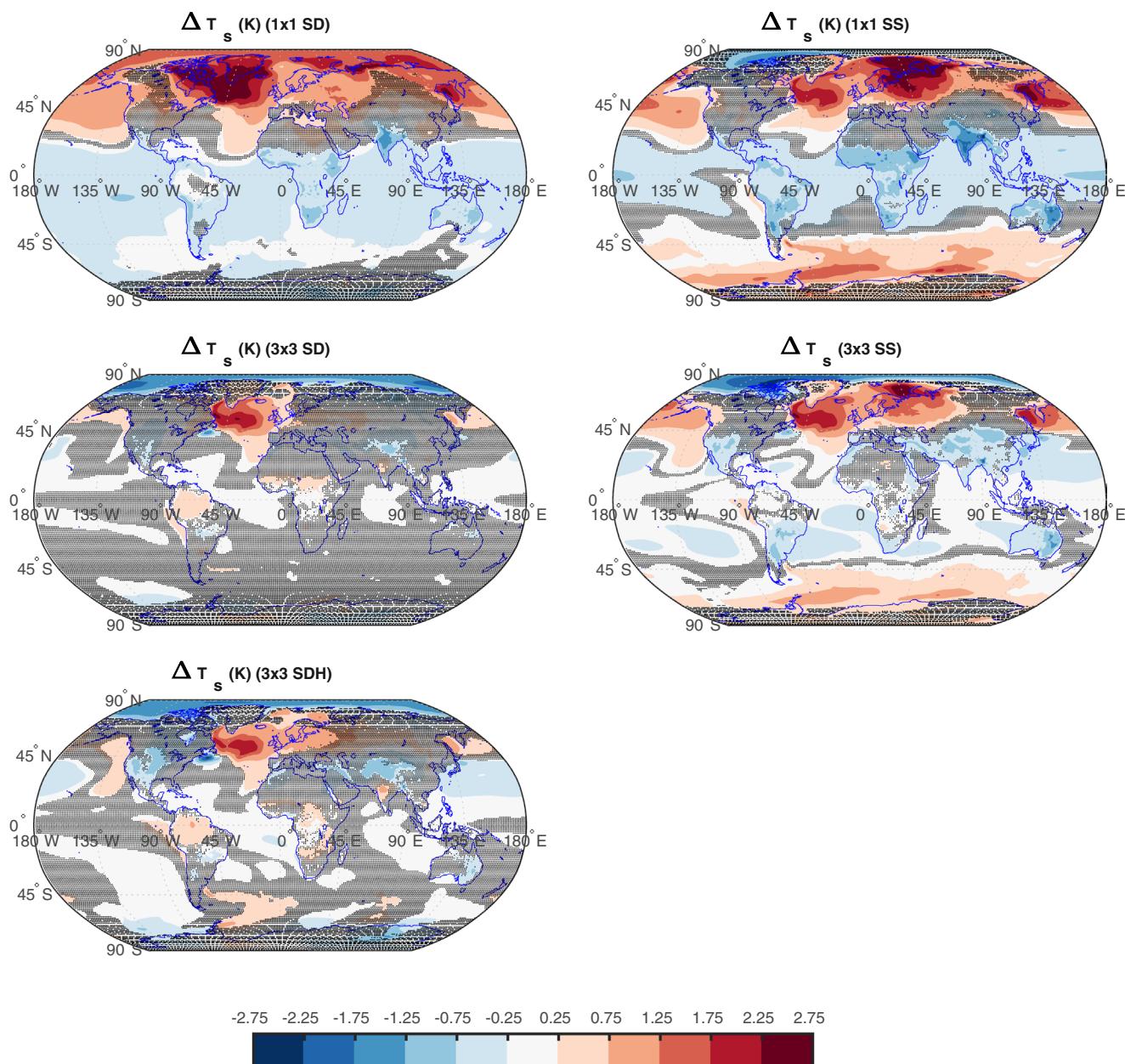


Figure 3. Surface temperature changes for all simulations for 2070–2089 relative to 2010–2030. In the third column, areas are highlighted where surface temperature shows statistically significant (using a two-sided t -test with $p < 0.05$) changes between the simulations with SD and SS. Gray areas indicate regions in all maps where the differences are not statistically different from zero. Differences between the left and right maps are shown in Figure S2.

area for all simulations: in this case, however, the locally enhanced warming over Eurasia is mixed with the different equator-to-pole temperature gradients (T_2): for the 1×1 cases, the warming over high latitudes is primarily due to only keeping global mean temperature constant, which tends to overcool the tropics and undercool high latitudes (Ban-Weiss & Caldeira, 2010; Kravitz et al., 2019). This is further exacerbated in the case of SS since the AOD is mostly concentrated at tropical latitudes. As shown in Russotto and Ackerman (2018b) and Merlis and Henry (2018), the differences in energy transport due to differences in T_2 also lead to a residual polar warming in simulations with uniform solar dimming. Therefore, isolating the contribution of residual warming in winter in particular to this high latitude annual-mean pattern requires looking at seasonal differences with respect to the annual mean (Figure 4b, where we removed the annual

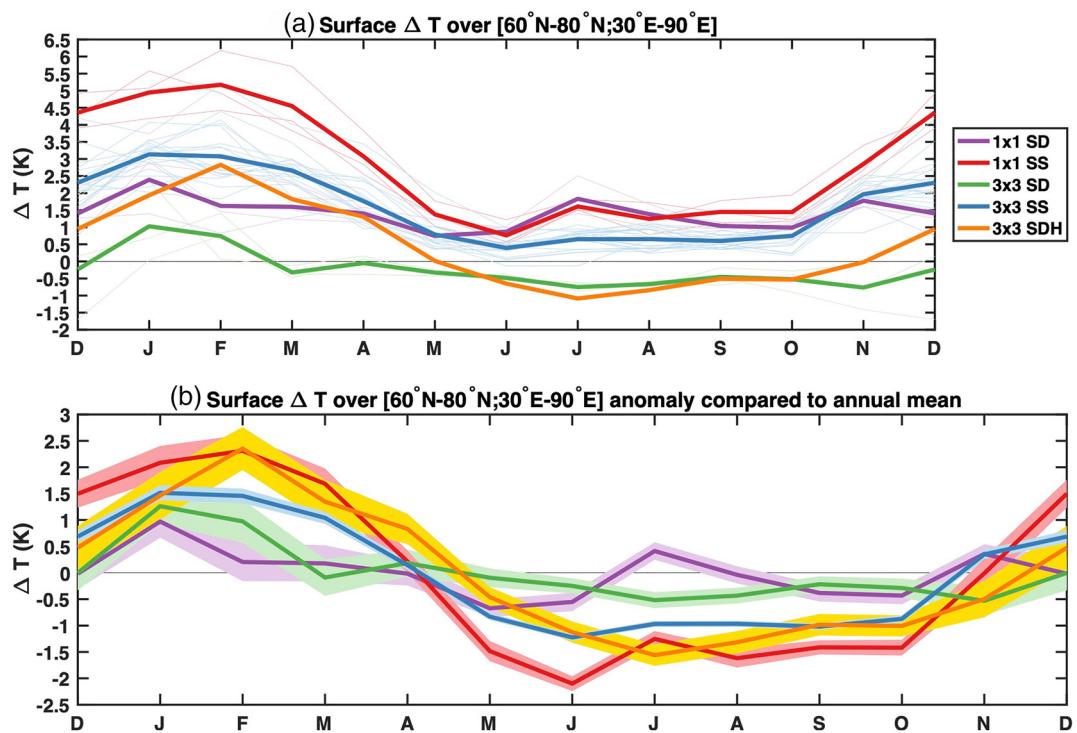


Figure 4. (a) Seasonal cycle of surface temperatures over high northern latitudes for each ensemble (thick lines, see legend) and single ensemble members (thin lines of the same color). (b) Same as (a), but showing the anomaly compared to the annual mean and the shaded curves representing the ensemble variability as ± 1 standard error.

mean temperature calculated in the same area in order to highlight just the seasonal variations) as in Jiang et al. (2019).

Thus we can see that the SD cases both have a moderate warming over DJF relative to the annual mean (0.75 K) whereas the others have a stronger winter warming (1.22 K for 3×3 SS, 1.43 K for 3×3 SDH, and 1.97 K for 1×1 SS). The 1×1 SS and 3×3 SDH cases seem to have similar warming, and both have different warming than the 3×3 SS case. The differences between the 3×3 SS and SDH cases may be explained by looking at the seasonal differences in AOD: as discussed by Visioni, MacMartin, Kravitz, Lee, et al. (2020), for the 3×3 SS case, the high latitude AOD reaches a relative peak compared to the annual average exactly in the months where the winter warming is expected, while for the 1×1 SS case, the AOD results are much more uniform seasonally. From the comparison of the SD and SDH cases, we can observe that the winter warming observed over Eurasia in these simulations can only be partially explained by the stratospheric heating. Over half of the high latitude winter warming compared to the annual mean results from differences between SW and LW forcing which, as Govindasamy et al. (2003) and Jiang et al. (2019) point out, is especially prominent at high latitudes, and that cannot be avoided even if a more careful spatial distribution of the counteracting forcing is applied, as also suggested by Henry and Merlis (2020), who decomposed the vertical structure of the forcing in a single column model and found that inhomogeneities in the two forcings always result in some residual warming at high latitudes. To conclude, the observed differences between the analyzed simulations highlight a complex interplay of factors: the stratospheric heating directly affecting the surface climate through a modification of the North Atlantic Oscillation (Banerjee et al., 2020), the seasonality of the aerosol distribution (that in turn may be dynamically affected by the strengthening of the polar vortex, Visioni, MacMartin, Kravitz, Lee, et al., 2020) and a fundamental difference between the LW and SW radiative forcings; all of these factors indicate that, when assessing the projected potential of stratospheric sulfate geoengineering to mitigate changes in high-latitude ecosystems with the potential to release considerable amounts of carbon (Chen et al., 2020), the inclusion of realistic aerosol behavior is crucial.

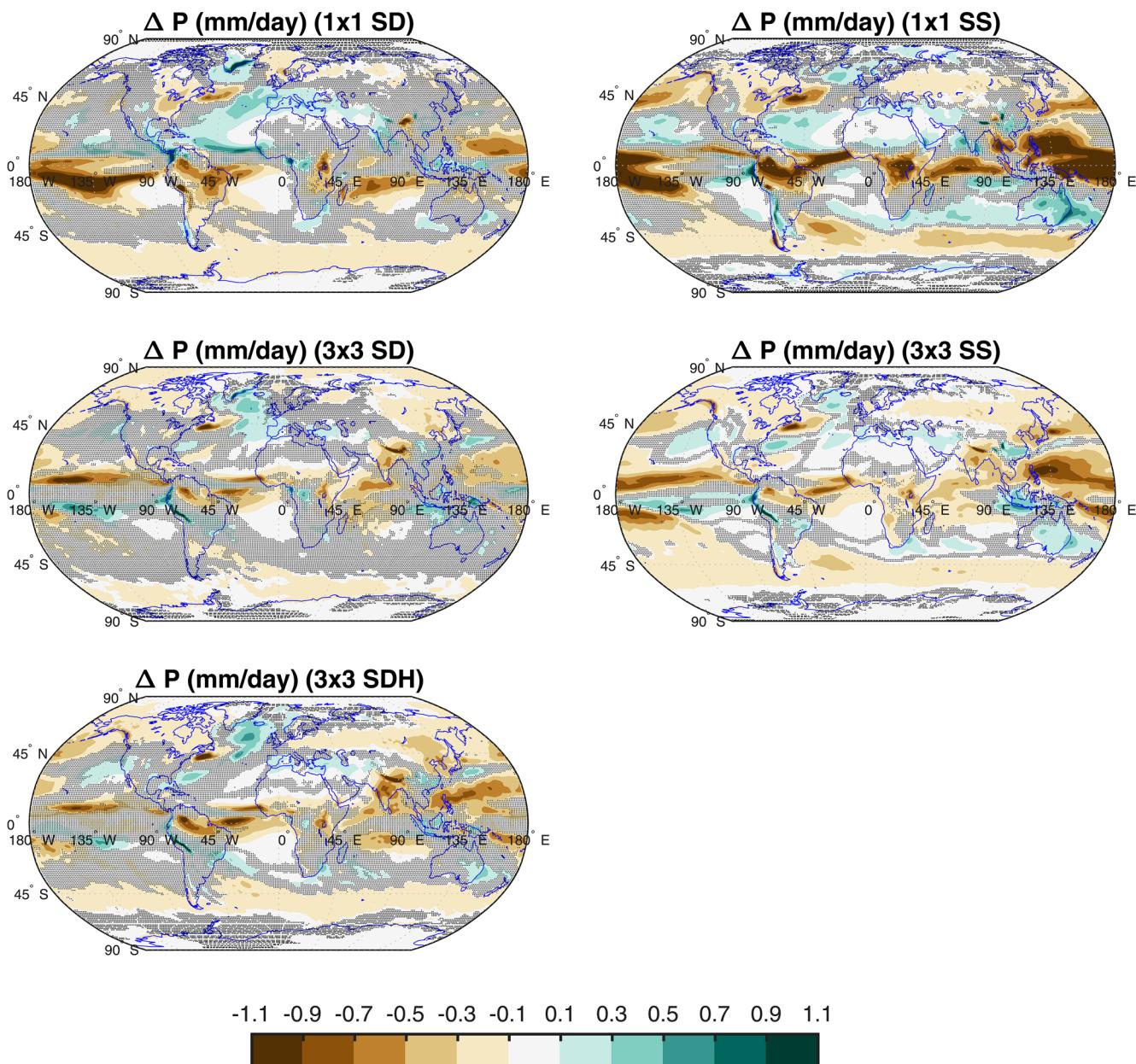


Figure 5. Precipitation changes for all simulations for 2070–2089 relative to 2010–2030. In the third column, areas are highlighted where surface precipitation shows statistically significant (using a two-sided t -test with $p < 0.05$) changes between the simulations with SD and SS. Gray areas indicate regions in all maps where the differences are not statistically different from zero. Differences between the left and right maps are shown in Figure S3.

In Figure 5, we show the same comparison as in Figure 3 but for total precipitation. Results for P-E (precipitation minus evapotranspiration) are reported in the supplementary material (Figure S2). Generally, it is clear that even given the same temperature targets, there are substantial differences in the projected precipitation changes. In particular, both SD cases show reduced changes compared to the SS cases. Unlike for temperature, however, in this case, the SDH case shows further similarities with 3 × 3 SS.

On a decadal scale, precipitation changes can be described by changes in total column energy, which can be broken up into column-integrated diabatic cooling and dry static energy flux divergence (Muller & O'Gorman, 2011). Kravitz, Rasch, et al. (2013) used this framework to explain a simulation analogous to 1 × 1 SD, and we adapt that method for the present study to explain the changes in Figure 5, with the caveat that our

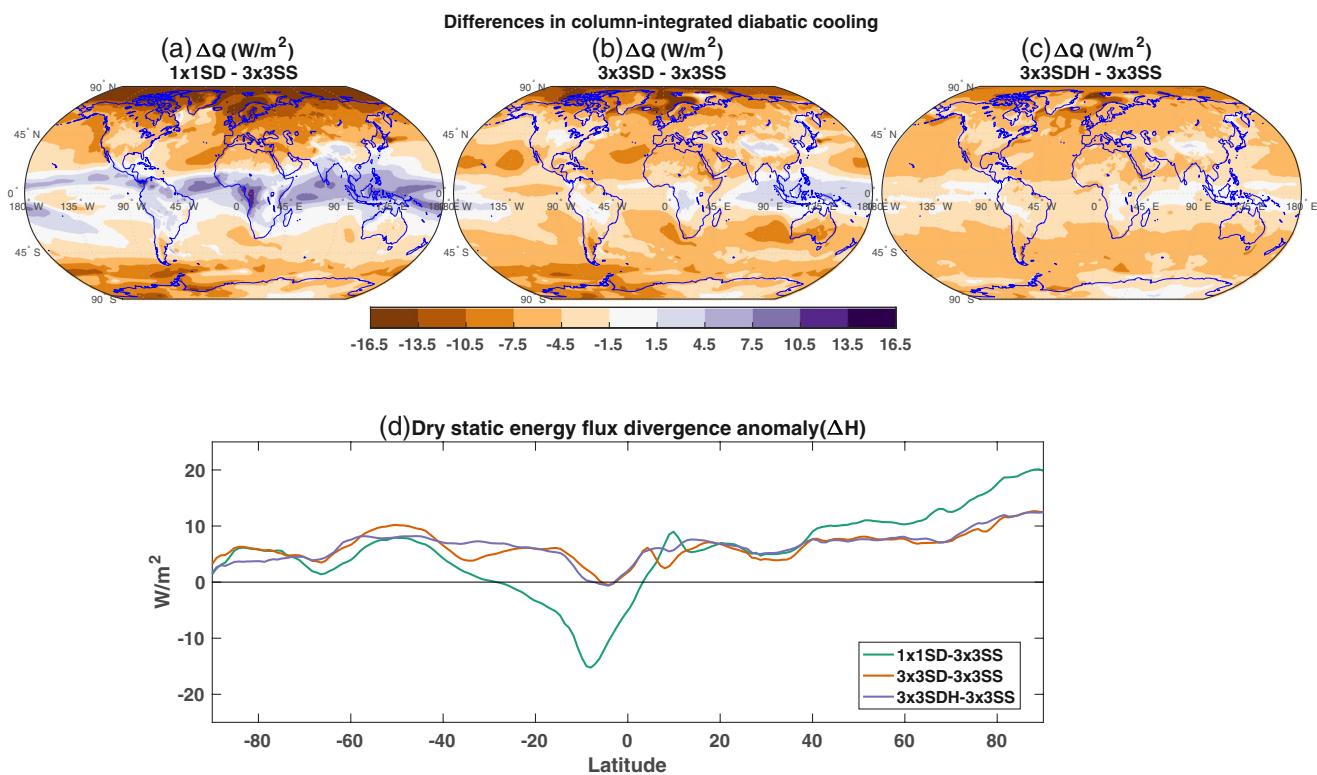


Figure 6. Differences in the column-integrated diabatic cooling (ΔQ , W/m^2) between the 3×3 SS case and the three SD experiments (panels (a–c), 2070–2089 average). (d) Zonal and annual mean differences in the dry static energy flux divergence (ΔH , W/m^2) between the 3×3 SS case and the three SD experiments. See Figure S7 for a comparison of zonal mean precipitation (in W/m^2) and ΔQ . SS, stratospheric sulfate.

period of analyses is not in a perfect steady state. Following the analyses in Kravitz, Rasch, et al. (2013), the differences in the column-integrated diabatic cooling (excluding latent heating), can be calculated as

$$\Delta Q = \Delta RF_{sfc} - \Delta RF_{TOA} - \Delta SH \quad (1)$$

where ΔRF_{sfc} is the net radiative flux at the surface (SW + LW; positive downward), ΔRF_{TOA} is the net radiative flux at the top-of-atmosphere (positive downward), and ΔSH is the change in sensible heat flux (positive upward, as is customary for turbulent fluxes).

Changes in precipitation can then be calculated as

$$L_c \Delta P = \Delta Q + \Delta H \quad (2)$$

where L_c is the latent heat of condensation, ΔQ is the column integrated diabatic cooling, and ΔH is the dry static energy flux divergence (calculated as a residual). In Figures 6a–6c, we show that the SD and 3×3 SS experiments have very different column energy budgets that can help explain some of the differences in surface precipitation shown in Figure 5. The comparison between panels 6a and 6b indicates that a part of the changes in ΔQ are colocated with differences in temperature between the 1×1 and 3×3 cases, especially in the tropical regions, where a uniform solar reduction (or equatorial stratospheric aerosol injections) tends to overcool the tropics and shifts the intertropical convergence zone location. Comparing the results with those for the SDH simulation indicates that part of the precipitation differences between SD and SS simulations can be reduced if the stratospheric heating term is included in the model simulations, due to a more realistic partition of energy in the column. Not all differences can be reduced this way: in Figure 6d, we show that differences in the energy flux divergence term are quite similar between the SD and SDH simulations, implying that some of the observed local changes are due to other processes. For instance, the seasonal dependence of AOD has been shown to affect precipitation regionally and seasonally (i.e., in the

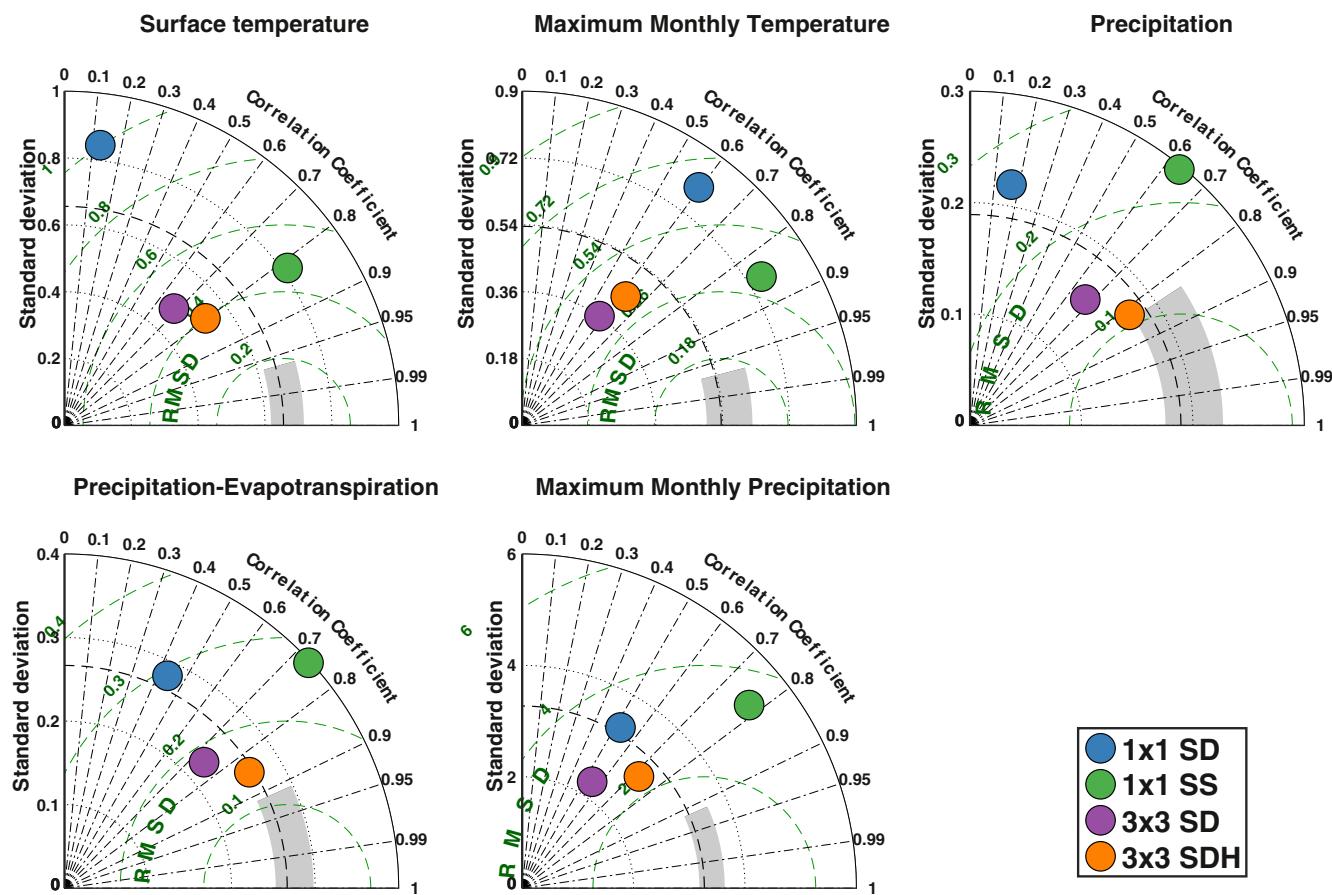


Figure 7. Taylor diagrams for various simulated quantities as compared to the 3×3 SS case. The shaded areas indicate differences indistinguishable from natural variability between a given ensemble and the 3×3 SS ensemble. See text and Figure S8 for further description. SS, stratospheric sulfate.

case of the monsoon season, or over Amazonia, Visioni, MacMartin, Kravitz, Richter, et al., 2020). This can be observed in Figures S5 and S6, where we show the precipitation changes in two of the seasons (DJF and JJA). As an example, over India the magnitude of precipitation changes in JJA is larger in the 3×3 SS simulations than in other seasons, compared to SD and SDH: in this case, differences in cooling over the Tibetan plateau, driven by the seasonal variation of the AOD, would affect the monsoonal circulation, combined with energetic changes in the column produced by the stratospheric heating (Simpson et al., 2018; Visioni, MacMartin, Kravitz, Richter, et al., 2020).

3.2. Solar Dimming as a Modeling Analogue for Sulfate Injections

From our analyses, it is clear that generally the outcomes of SD simulations and SS simulations are different: in this section, we try to better quantify these differences to better answer the initial question: is solar dimming a good proxy for stratospheric sulfate geoengineering? As a baseline for comparison, we use our 20 (members) \times 20 (years) 3×3 SS simulations as our best estimate of the forced response (in this model) of an SS strategy that aims to minimize changes in surface climate, and we compare this with the other four simulations (3 members \times 20 years for 1×1 SD, 1×1 SS, 3×3 SD, and 3×3 DH). The metrics we use are surface temperature, precipitation, precipitation minus evapotranspiration, monthly maximum temperatures and monthly maximum precipitation, which have been used previously to define the impacts of geoengineering (P. Irvine et al., 2019), plotted on Taylor diagrams (Figure 7, Taylor, 2001). These kind of diagrams are generally used to evaluate multiple model performances compared to observations on three metrics: the Pearson correlation coefficient, plotted as the azimuthal angle, measures the pattern similarities; the root

mean squared error (RMSE), proportional to the distance from the point on the x-axis defined as our benchmark, measures the overall difference between that benchmark and the other simulations; and the standard deviation σ , as distance from the axis origin, that measures the amplitude of the variations in both simulated and the benchmark values (that lie on the dashed line). The similarity is then evaluated as the distance between the single value for each simulation and the benchmark value that lies on the x-axis. In Figure 7, we also include gray shading that serves as a measure of the differences induced by the natural variability. To construct this metric, we consider the general difference between any random pick of three ensemble members of 3×3 SS simulations (overall, $\binom{20}{3} = 1140$) and plot each of the resulting subsets against the full 20-member ensemble (the operation performed to obtain this is shown in Figure S8). The gray shading can therefore be considered as the effect of sampling a smaller ensemble size: if one of the other simulations approaches this area, we cannot tell whether the residual difference is due to natural variability or differences in physical processes between the simulations. From the results in Figure 7, we conclude that simply turning down the sun produces regional climate results that are highly uncorrelated from those obtained in 3×3 SS simulations. The 3×3 SDH simulation is most similar to the baseline indicating the importance of (1) tailoring the pattern of solar dimming so that the net effect matches the radiative forcing of the aerosols, and (2) including stratospheric heating that would result from the aerosols. This result especially holds for hydrological quantities, indicating that the stratospheric changes produced as a response to stratospheric heating are an especially important component of the climate response to stratospheric sulfate aerosols. For temperature, the differences between 3×3 SD and 3×3 SDH are more marginal, indicating that differences from baseline are predominantly due to the pattern of forcing (see Figure 2).

3.3. Simulation of Other Surface Variables

Taylor diagrams are most effective for quantities that present at least some patterns of similarity to the baseline. There are other quantities where this does not hold, for example incoming solar radiation at the surface, where previous studies looking at ecologically relevant metrics (Dagon & Schrag, 2019) have used solar dimming simulations to predict vegetation changes under geoengineering. In Figure 8, we show some of the differences between SD and SS in 14 locations around the globe (the specific locations are shown in Figure S9: only changes over land are considered in these analyses). We have chosen these locations as some of the largest biomass regions in the world: large forest (Song et al., 2018) in all continents save Antarctica, and the US Corn-belt (Green et al., 2018). We first consider the overall amount of incoming solar radiation at the surface in these zones, and find that differences attributable to both the objectives (1×1 and 3×3) and strategies (SD and SS). In some places, counter-intuitively, the overall amount of incoming solar radiation even goes up compared to the control period, mainly due to local changes in cloud coverage (Figure 9). Differences between SD and SS simulations in this case are associated with very high clouds, and results would be rather different if we consider low-, medium- or high-altitude clouds (see Figures S10–S12), suggesting different mechanisms by which geoengineering, in these simulations, affects cloud coverage. In particular, while low-altitude clouds show very similar changes between SS and SD simulations, medium-altitude clouds present differences that are resolved (at mid and low latitudes) by including the stratospheric heating term, suggesting their modification is driven mostly by changes produced by the temperature anomalies in the lower stratosphere and not by climate-change driven factors (e.g., Norris et al., 2016). High-altitude ice clouds, that have a strong radiative effect on outgoing longwave radiation at mid-latitudes (Fusina et al., 2007), show the highest differences. Contrary to previous research (Kuebbeler et al., 2012; Visioni, Pitari, Di Genova, et al., 2018) with different models that showed how these changes are also driven by the vertical temperature gradient, here the main cause of the changes seems to be the aerosols themselves. While it has already been suggested that this might be due to incorrect parametrizations in CESM1(WACCM) (Schmidt et al., 2018), further investigation is warranted.

Similarly, large differences are present when considering the changes in the ratio of direct incoming solar radiation compared to the total: the portion of sunlight arriving directly, versus that arriving diffused might be very important when considering the effects on different kinds of vegetation and ecosystems (Gu et al., 2003; Mercado et al., 2009): in this case (Figure 8b), large differences are not only present between SS and SD cases, but even among different strategies for similar methods (e.g., differences between 1×1

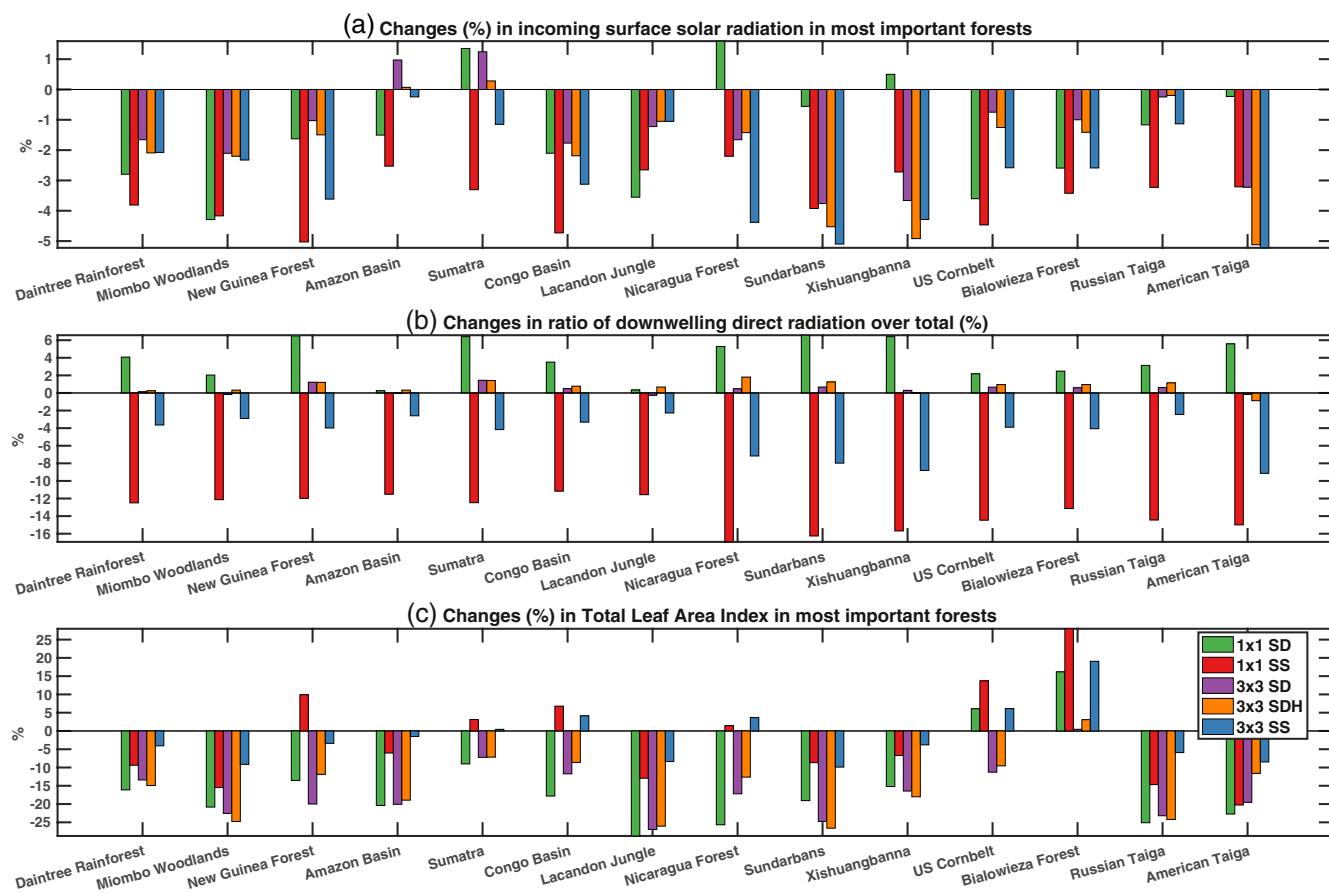


Figure 8. (a) Changes in incoming solar radiation over land in 14 locations with some of the largest forests (see Figure S9 and text) for all five experiments in the period 2070–2089 compared to 2010–2030 in RCP8.5. (b) Changes in the portion of incoming solar radiation over land arriving directly as a fraction of the total incoming solar radiation for all five experiments in the period 2070–2089 compared to 2010–2030 in RPCP8.5. (c) Simulated changed in Total Leaf Area Index in those locations for all five experiments compared to the 2070–2089 period in RCP8.5.

SS and 3×3 SS). For the 3×3 SD and 3×3 SHD experiments, changes in this ratio are very small, as the changes in cloud coverage are also mostly negligible in large parts of the planet (Figure 9) for these experiments. On the other hand in the 1×1 SD experiment, the model projects a small increase in direct incoming solar radiation in most areas, due to the more significant decrease in cloud coverage over most of the considered areas. Similarly, in the SS experiments, the presence of the aerosols reduces the amount of direct incoming solar radiation due to scattering from the aerosols themselves, but the magnitude of these changes is remarkably different: this is due both to a different distribution of the aerosols (see Figure 2 and Kravitz et al., 2019), that are much higher in the 1×1 SS experiment at low latitudes and to a difference in the simulated cloud response, as 1×1 SS predicts a larger increase in medium-altitude clouds compared to 3×3 SS (Figure S11). An example of how changes in radiation could affect our understanding of the impacts of geoengineering is given in Figure 8c, where changes in Leaf Area Index (LAI) are shown against the same time period (2079–2089) in RCP8.5 (to account for changes in LAI produced by increasing CO₂ concentrations, that are the main driver of LAI changes, unlike the first two panels). LAI is determined dynamically in the land model in CESM, and responds to changes in temperature and hydrology together with changes in photosynthesis and respiration dependent on the incoming solar radiation. For this reason, the various experiments project different vegetation responses depending on the geoengineering strategy, sometimes also with different sign: for instance in the Congo Basin, the SS experiments project a modest increase in LAI compared to RCP8.5 while the SD experiments project a large decrease (especially for the 1×1 case). Overall, it is hard to directly link the changes in LAI in the interactive land model simply to the changes in incoming solar radiation, given the contribution of other factors, such as the CO₂ increase,

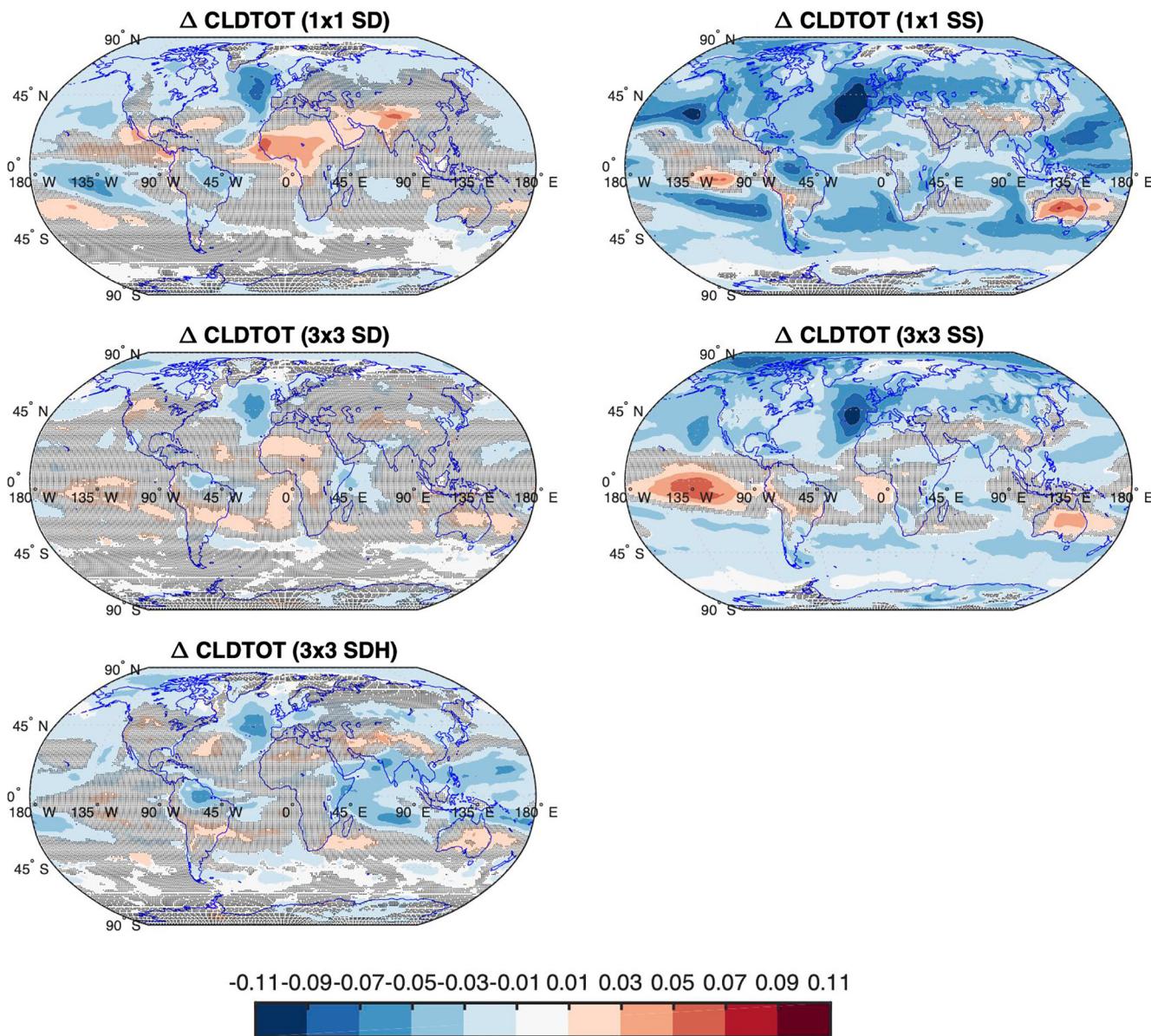


Figure 9. Simulated total cloud fraction differences (dimensionless) in the five geoengineering experiment against the Control 2010–2030 period. Gray areas indicate regions in all maps where the differences are not statistically different from zero (using a two-sided t -test with $p < 0.05$).

different regional temperatures, and changes in their seasonal cycle, precipitation and more, and given the feedback of these changes themselves on some of those factors (for instance, the link of plant transpiration and local hydrology). But in light of the importance of understanding ecosystem changes in the context of stratospheric sulfate geoengineering, this suggests that future studies aiming to do such assessments should take great care to use simulations where the aerosols are present in a realistic distribution.

A correct representation of the changes in cloudiness would be important not just for the radiation effects on ecosystems: the importance of clouds in the surface radiative budget of continental ice sheets (McIlhatten et al., 2017; van Kampenhout et al., 2020) indicates that, in order to assess the ability of SG to limit sea level rise (P. J. Irvine et al., 2018) and restore continental glaciers extent, solar dimming simulations as a proxy might produce incorrect results by incorrectly reproducing cloud changes and, partially, high-latitude warming produced by the stratospheric heating.

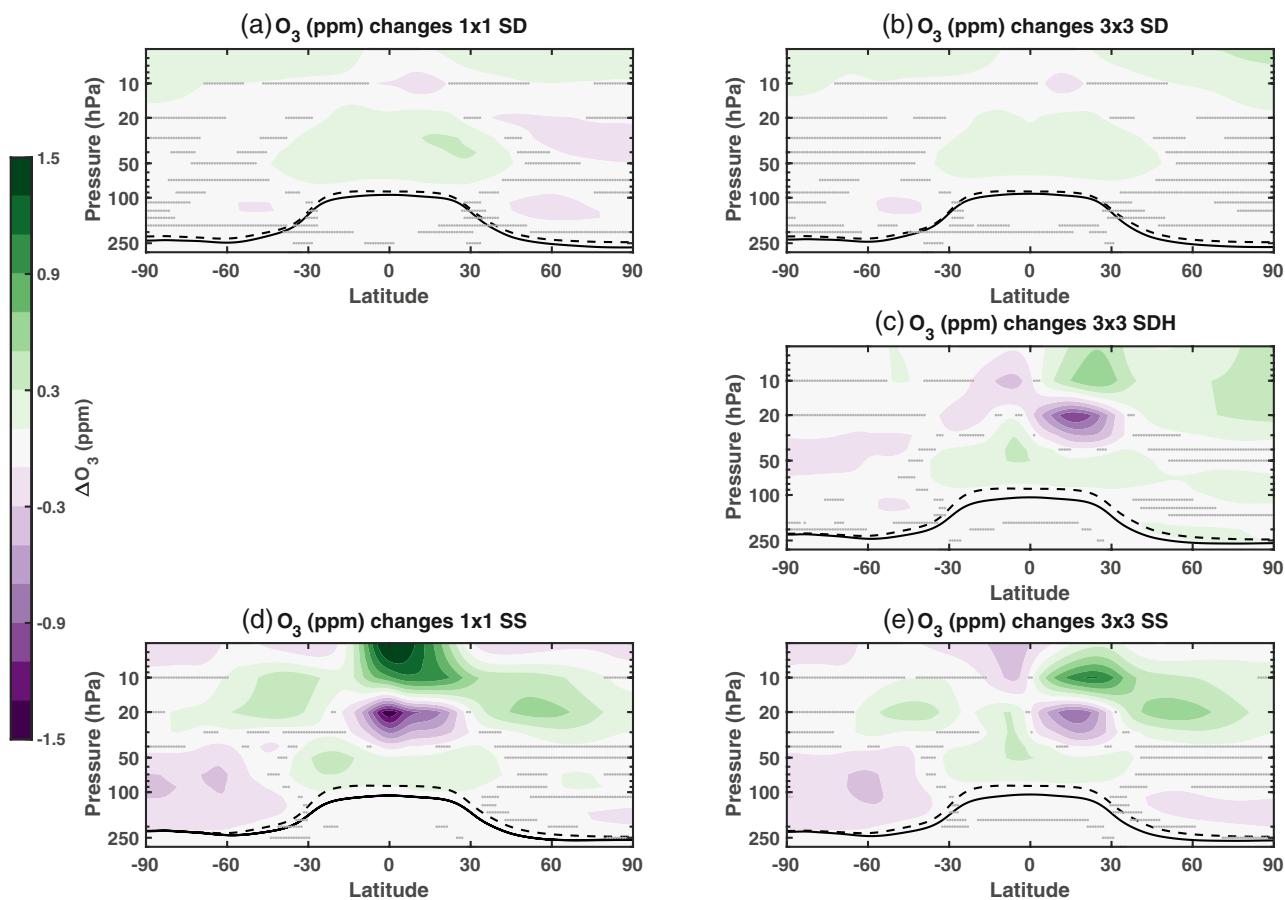


Figure 10. Changes in stratospheric ozone concentrations (ppm) compared to the same period (2070–2089) in RCP8.5. Average tropopause height for RCP8.5 (continuous black line) and the geoengineering simulations in the panels (dashed black line) are also shown. Hatched areas indicate regions in all maps where the differences are not statistically different from zero (using a two-sided t -test with $p < 0.05$).

3.4. Simulation of the Stratospheric Response

As we've shown in the previous sections, the stratospheric response is an important component in correctly capturing the climate response to sulfate injections. In the case of some surface variables, this happens because of dynamical changes in the circulation (Figure S13). Previous works have shown that stratospheric chemistry would also be impacted by the sulfate aerosols (Tilmes, Richter, Mills, et al., 2018; Vattioni et al., 2019; Visioni, Pitari, Aquila, Tilmes, et al., 2017) but in most cases, these changes (such as in the concentration of N_2O and CH_4) are also due to modifications of stratospheric dynamics. The effects of SS on stratospheric ozone may however vary due to different causes other than dynamical changes (Pitari et al., 2014; Tilmes et al., 2008; Tilmes, Richter, Mills, et al., 2018), for instance by the direct increase in Surface Area Density (SAD) resulting in changes in heterogeneous chemistry (Richter et al., 2017), both in the tropics and at higher altitudes. These changes might be important to project changes in surface UV (Madronich et al., 2018), with consequent human impacts (Eastham et al., 2018).

Chemical ozone destruction due to increased SAD, especially in the polar regions, is mostly tied to changes in ozone-depleting substances (Morgenstern et al., 2018) that are projected to strongly decrease in the coming decades (Dhomse et al., 2018). Therefore, the relative contributions of chemical versus dynamical ozone destruction depend on the decade of analyses. In our analyses toward the end of the century, the predominant effect in the tropical regions in the mid-stratosphere is driven by dynamical circulation changes, as can be observed in the comparison between Figures 10c and 10e, advecting ozone-poor air from lower to higher altitudes due to an increase in vertical velocities and an acceleration of the Brewer-Dobson circulation and by an increase in stratospheric water vapor that modifies the HO_x cycle-mediated ozone loss

(Richter et al., 2017; Tilmes, Richter, Mills, et al., 2018). At high latitudes, on the other hand, the SAD-induced changes result in a delay of the predicted recovery under baseline conditions (as discussed in Tilmes et al., 2008) that is not observed in the SDH case in Figure 10e.

4. Conclusions

Simulations with climate models are our main instrument for understanding the possible changes to the Earth System that would be produced by using geoengineering to counteract the effects of increases in GHGs. Properly simulating the projected regional effects is crucial in order to inform policy-makers and the general population about the possible outcomes.

Even without considering geoengineering, there are uncertainties in the projected local changes under climate change, although with improvements in climate models, these uncertainties are decreasing (Christensen et al., 2007; Matte et al., 2019). For solar geoengineering, our assessment of local changes does however depend on more factors than for climate change: aside from the uncertainty in specific physical processes (Kravitz & MacMartin, 2020), these factors include (i) the desired level of cooling (P. Irvine et al., 2019; MacMartin et al., 2019; Tilmes et al., 2020); (ii) the specific technique simulated (i.e., the method chosen to reduce surface temperatures, Gasparini et al., 2020; Niemeier et al., 2013), and (iii) within the same technique, the specific strategy deployed (Kravitz et al., 2019; Visioni, MacMartin, Kravitz, Richter, et al., 2020). There is thus a compound of different kinds of uncertainties (those listed, and those we do not know we do not know about) that result in challenges in clearly determining—and communicating—what effects geoengineering would have locally.

This is made even more challenging if the term “solar geoengineering” is used improperly to conflate different things, and in particular, stratospheric sulfate injections in all its forms and a global reduction in the incoming solar radiation (i.e., the G1 experiment described in Kravitz et al., 2011). On one hand, the use of the latter to simplify the former is understandable, considering the challenges in correctly simulating stratospheric dynamics and stratospheric sulfate interactions (Kravitz & MacMartin, 2020; Timmreck et al., 2018). In this work, we have shown, however, that the climate outcomes in the two cases present large difference. In this work we have focused on analyzing some of the key variables often used to evaluate climate engineering projections: surface temperatures, the hydrological cycle, minimum and maximum yearly temperatures, stratospheric ozone, clouds and incoming solar radiation at the surface. In particular, we have shown that while both methods can reduce globally averaged surface temperatures and other globally defined climate metrics, depending on the method and on the choices of targets large regional differences are observable in the annually averaged surface temperatures. Partially these differences can be reduced if the reduction in the solar constant is performed in a way as to more closely resemble the shape of the stratospheric optical depth resulting from the sulfate injections, but we show that in high-latitudinal regions the effect of the stratospheric heating is a contributor to the surface response. The effect of the stratospheric heating is even more evident for precipitation changes, due to its contribution to the partitioning of the energy budget in the vertical column. For other variables that might be relevant for a comprehensive assessment of the effects of sulfate geoengineering on ecosystems, such as the changes in diffuse radiation at the surface, the overall effect is tied to both the actual presence of the aerosols and to the changes in cloud coverage that, at least in this model, appear to be sensitive to the different temperature gradients, to the stratospheric heating and to the aerosols themselves: for this reason, simulations that do not include the physical response of the aerosols might not be suitable for impact assessments.

Overall, our results confirm and strengthen previous observations related to the changes that would be produced by the presence of stratospheric aerosols, and highlight the need to include these processes whenever the surface impacts of sulfate geoengineering are to be determined. We can summarize the main differences between a top-of-the-atmosphere solar constant reduction and the presence stratospheric aerosols by identifying three mechanisms that largely explain those differences:

1. The aerosols do not produce a uniform reduction in the incoming solar radiation (both latitudinally and temporally, Figure 2). Especially if the deployed injection strategy has particular goals resulting in a particular aerosol distribution (e.g., the strategy described in Tilmes, Richter, Kravitz, et al., 2018), the

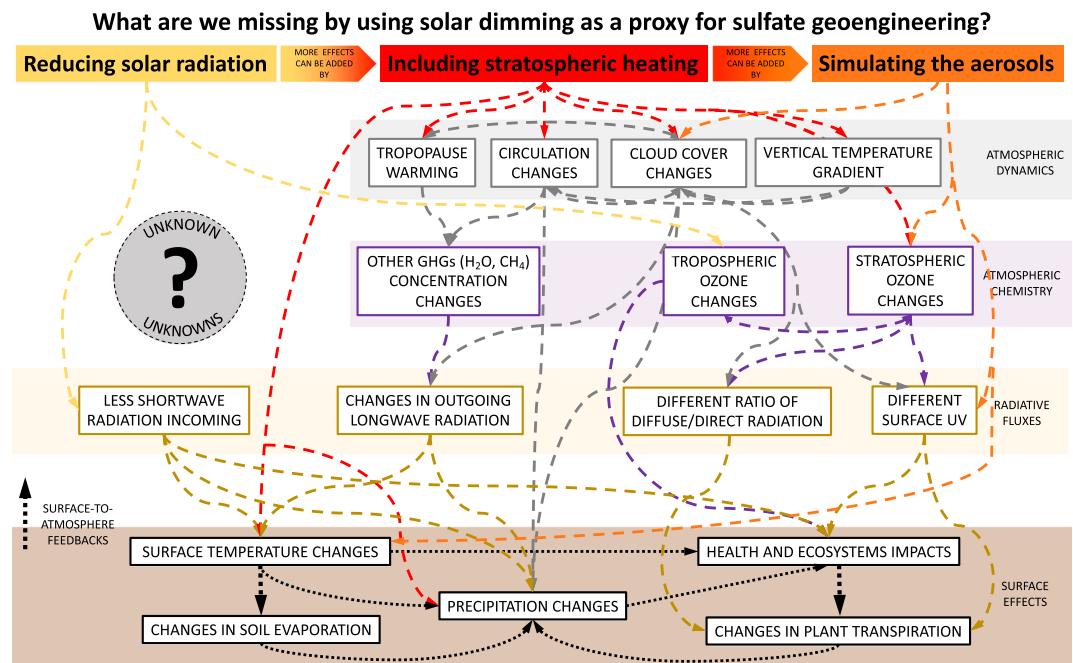


Figure 11. Infographic of the most important studied effects produced by solar geoengineering on the various components of the climate system. The three different ways in which climate models can simulate the effects of the injection of stratospheric sulfate are shown on top, going from the least to the most complex representation: solar dimming, adding the stratospheric heating on top of the solar dimming or directly simulating the aerosols. All three are then connected to the effect of their presence on various components of the Earth System (divided in atmospheric dynamics, atmospheric chemistry, radiative fluxes, and direct surface effects) through arrows that highlight some of the important interactions (recognizing that ultimately, everything is influenced by everything else).

comparison with a uniform solar dimming produces widely different results, both in regional temperatures and precipitations. This is mainly due to differences in the resulting temperature gradients, that produce shifts in the climate response (as discussed, for different SS strategies, in Kravitz et al., 2019). Because of this, these discrepancies can be reduced if the solar constant is dimmed not uniformly, but in a way resembling the distribution of the simulated aerosols, in order to have the same temperature gradients that SS experiment is designed to maintain

2. The aerosols produce a localized stratospheric warming that results in various changes at the surface and in the upper atmosphere. Even if the same surface temperature gradients are maintained between experiments, quantities such as precipitation and P-E still show differences when the sun is dimmed compared to when the aerosols are simulated. In our simulations, combining solar dimming with stratospheric heating helps further reduce the differences with the 3×3 SS strategy
3. The aerosols scatter part of the incoming sunlight, modifying the ratio of direct to diffuse radiation, possibly modifying the projected changes on vegetation and evapotranspiration. Stratospheric aerosols affect stratospheric chemistry (principally ozone), and also ultimately result in the deposition of sulfate at the surface that might have environmental effects (albeit those have been projected to be small, see Kravitz et al., 2009; Visoni, Slessarev, et al., 2020)

These points are summarized in Figure 11, highlighting both the causes of the simulated changes and the interconnections in the climate system that result in changes at the surface; in the figure, we also include effects not directly analyzed in this study but discussed in referenced works.

Are the produced changes in the surface climate significant? This is a question that depends on the amount of cooling provided by the geoengineering and thus on the amount of injected SO_2 . In the simulations analyzed here, we use the RCP8.5 scenario, that has very high emissions throughout all the century and that result in around 4 degrees of warming in the 2070–2089 period. This can therefore be considered an “extreme” scenario, resulting in the need of very high injection amounts producing a considerable perturbation

in stratospheric temperature. Considering a peak-shaving scenario where a limited deployment is aimed at remaining below an otherwise dangerous temperature threshold (MacMartin & Kravitz, 2019; Tilmes et al., 2020) are projected to result, very likely, in some of these changes being indistinguishable from the normal climate variability (MacMartin et al., 2019).

In the last years, however, the topic of the impacts of climate engineering has gathered more and more interest not only from climate scientists but also from the broader scientific community, interested in impacts both on human activities (Tavoni et al., 2017) and on the environment and ecosystems. Because of this, a proper, robust assessment of all possible side effects is becoming crucial. While this mainly requires tackling uncertainties in our physical knowledge and shortcomings in our climate simulations (Kravitz & MacMartin, 2020), the importance of recognizing the shortcomings of using solar dimming as a proxy for stratospheric sulfate geoengineering cannot be ignored.

Data Availability Statement

Data from the simulations used in this work are available at <https://doi.org/10.5065/D6JH3JXX> (for the 3 × 3SS, 1 × 1SS, and RCP8.5 simulations) and <https://doi.org/10.7298/z8c9-3p43> (for all other simulations).

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