~~Trade-offs of~~How to Combine Solar Geoengineering and Mitigation under Climate Targets?

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Abstract. So far, scientific analyses have mainly focused on the pros and cons of solar geoengineering or solar radiation management (SRM) as a climate policy option in mere isolation. Here, we put SRM into the context of mitigation by a strictly temperature-target-~~-~~based approach. As ~~a~~the main innovation, we present a scheme that extends the~~by which the~~ applicability regime of temperature targets~~ is extended~~ from mitigation-only to SRM-mitigation analyses. ~~HerebyAt this moment, w~~We explicitly account for one major category of side effects ~~a risk-risk comparison ~~of SRM~~ and global warming,~~ while minimizing economic costs for complying with the 2°C temperature target. To do so, we suggest regional precipitation guardrails that are compatible with the 2°C target. Our analysis shows that the value system enshrined in the 2°C target leads to an elimination of most of SRM from the policy scenario if a transgression of environmental targets is confined to 1/10 of the standard deviation of natural variability. Correspondingly, ~~would be almost prohibitive for SRM, while still ~~about half to nearly two-thirds of mitigation costs could be saved, depending on the relaxation of the~~choice of extra room for~~ precipitation criterion. In addition, assuming a climate sensitivity of 3°C or more, in case of a delayed enough policy, a modest admixture of SRM to the policy portfolio might provide debatable trade-offs compared to a mitigation-only future. ~~In addition~~Also, in our analysis which abstains from an utilization of negative emissions technologies, for climate sensitivities higher than 4°C, SRM will be an unavoidable policy tool to comply with the temperature targets. The economic numbers we present must be interpreted as upper bounds in the sense that cost-lowering effects by including negative emissions technologies are absent. However, with an additional climate policy option such as carbon dioxide removal present, the role of SRM would be even more limited. Hence, our results, pointing to a limited role of SRM in a situation of immediate implementation of a climate policy, are robust in that regard. This limitation would be enhanced~~result would hold the more so, once~~ if further side effects of SRM are taken into account in a target-based integrated assessment of SRM.

1 Introduction

Since Paul Crutzen has highlighted solar radiation management (SRM) as a potential climate policy option in addition to adaptation and mitigation (Crutzen (2006)), there is~~ and~~ increasing research on this technique as a measure to counteract anthropogenic~~ally caused~~ global warming (Barrett et al. (2014); Bellamy et al. (2013); Goes et al. (2011); Irvine et al. (2012); Kravitz et al. (2013); MacMartin et al. (2014); Moreno-Cruz and Keith (2013); Schmidt et al. (2012); Shepherd (2009); Wigley (2006)). The bulk of analyses focuses on the pros and cons of SRM ~~as such, i.e.~~ in mere isolation. However, ~~this researchit needs to be complemented by~~ an integrated analyses is needed to allow decision-making on~~to reflect that the society might take decisions on~~ SRM~~ in view ofgiven alternative~~ taking into account more conventional policy options such as adaption or mitigation.~~-~~

In a non-welfare-optimal setting, Smith and Rasch (2013) studied the role of SRM in conjunction with mitigation for a limited set of pre-defined mitigation scenarios inspired by the Representative Concentration Pathways (RCP)~~-inspired mitigation scenarios in order~~ to meet a pre-defined temperature target. A few studies have performed an integrative analysis comprising both SRM and a stylized representation of mitigation in a Cost~~-~~-Benefit Approach (CBA) which is arguably~~as~~ the most prominent welfare-optimal approach (Bahn et al. (2015); Emmerling and Tavoni (2018); Goes et al. (2011); Heutel et al. (2016); Heutel et al. (2018); Moreno-Cruz and Keith (2013)). However, because the economic costs of SRM ~~are presently~~have been assumed to be ~~relatively~~ low compared to mitigation, any ~~meaningful~~ assessment should consider the inclusion of side effects of SRM~~ in the integrated analysismust include a risk-risk trade-off between impacts from SRM against impacts from global warming as the dominant effect~~. ~~The e~~ Earlier studies presented trade-off results for stylized impact assumptions within the standard economic paradigm of ~~cost benefit analysis~~CBA~~,. This~~which is, as much as possible, in ~~-~~line with standard economic axioms. ~~But, at the same time~~Nevertheless, some studies suggest that~~ it is challenging to~~ directly recommending climate policy through only ~~cost benefit analysis~~CBA is challenging~~,~~ due to the presence of deep uncertainty about global warming impact functions (Ekholm (2018); Kolstad et al. (2014); Kunreuther et al. (2014)). ~~They would~~These studies suggest using a target-based approach, known as Cost~~-~~-Effectiveness Analysis (CEA), as long as no better data is available (Kunreuther et al. (2014); Neubersch et al. (2014)).~~-~~

Furthermore, ~~also~~ for pragmatic reasons, one might argue that analyses should reflect ~~on~~ the consequences of climate targets ~~simply because they are there~~. Along that line, ~~Lawrence et al. [2018]~~Lawrence et al. (2018) put climate engineering proposals into the context of climate targets, however, without performing CEAs. In addition, while Arino et al. (2016), Ekholm and Korhonen (2016), and Emmerling and Tavoni (2018) evaluated SRM together with mitigation applying CEA, an inclusion of side effects of SRM was not in their focus. In particular, these studies did not define clear guardrails for~~over~~ side-effects of SRM.

~~WhileAlthough Arino et al. (2016), Ekholm and Korhonen (2016), and Emmerling and Tavoni (2018) evaluated SRM together with mitigation applying CEA, for an inclusion of side effects of SRM true risk-risk consideration was not in their focus, in particular, , one needs to define anno explicit guardrails over side-effects of SRM were defined.~~

To the best of our knowledge, here for the first time, we introduce and apply a concept for an integrated analysis of SRM and mitigation in -line with global mean temperature targets which also integrates onea side effect of SRM, in particular the '2°C temperature target'.[1] The 2°C target is the cornerstone of the Paris agreement (UNFCCC, 2015 [UNFCCC (2015): Adoption of the Paris Agreement. FCCC/CP/2015/L.9/Rev.1.]). ItThe 2°C target encapsulates society's informal risk evaluation -aversion againstof deeply uncertain global warming impacts (Neubersch et al. (2014); Schellnhuber (2010)). Driven by the expectation that in fact costs of transforming the energy system can be projectedare much more robustlyly to project than the aggregate impacts of global warming (Stern (2007)), a plethora of economic mitigation analyses has derived cost-minimal energy scenarios, which are in compliancecomply -with this target (Edenhofer et al. (2014)).

However, ifwhen SRM comes into playis employed, the global mean temperature is no longer a good proxy for regional climate impacts because SRM causesimprints patterns of regional climateprecipitation and temperature change that would differ from those induced by greenhouse gas forcing (Kravitz et al. (2013); Oschlies et al. (2017)). This particularly applies to the regional precipitation changes (Shepherd (2009); Bala et al. (2008); Robock et al. (2008)). Accordingly, and as a key innovation of this article, we suggest extending the regime of applicability of the 2°C target from mitigation--only to joint SRM-mitigation portfolios when global mean temperature and and regional precipitation are simultaneously considered. The next Ssubsection will describe in detail how we generalize the global mean temperature--target concept to take care ofconsider such regional climate effectsmismatches, induced by SRM. For our joint SRM-mitigation analysis, we utilize the integrated energy-economy-climate model MIND (Edenhofer et al. (2005)), which provides one of the simplest possible options to distinguish the renewable sector from the fossil-fuel sector under induced technological change. We then further extend the model to include a spatially- explicit resolution in terms ofterms of 'Giorgi regions' (Giorgi and Bi (2005)) and run specific policy scenarios showing the trade-offs between mitigation and SRM. We also highlight the most important factors that derive our results.

The rest of the paper is organized as follows. Section 2 provides details ofn the innovated guardrails, data, and the numerical model employed. Section 3 presents the results. Some sensitivity analyses are presented -Iin Section. 4, some sensitivity analyses are presented,. aAnd, Section. 5 concludes the paper.

2 Methods

2.1 Precipitation guardrails

WhenApplyingThe application of SRM is applied forto partially to counteracting greenhouse gas-induced global warming, this results in regional terrestrial precipitation patterns. TheseSuch regional precipitations patterns which differ from the purely greenhouse--gas-induced ones (Shepherd (2009); Bala et al. (2008); Robock et al. (2008)). Hence, when the climate system is forced by greenhouse gases and SRM simultaneously, the global mean temperature ceisesceases to bebeing a good proxy for regional precipitations. Accordingly, when one wants to preserve the target concept, one needs tomust bypass the destroyed

[1]Based on the previous version of this article (Stankoweit et al. (2015)), Roshan et al. (2019) applied a Cost--Risk Analysis and evaluated the optimal SRM in conjunction with mitigation, considering regional disparities in the precipitation risks.

link between global mean temperature and regional climate. Hence, by modelling regional climate explicitly and inventing respective regional targets are needed.

In the following, a set of regional targets is defined. in a somewhat arbitrary but distinct way such that it preserves the meaning of the global mean temperature target concept.], which It is hypothetical, however, as we claim, it is but unique. We define a corridor for admissible (Bruckner et al. (2008)) regional precipitation values, diagnosed from a global mean temperature change of at maximum 2°C and at minimum 0°C in the absence of SRM. In the following we focus on a subset of regional climate guardrails in terms of terrestrial precipitation changes that have been highlighted as a key drawback of SRM (Shepherd (2009); Bala et al. (2008); Robock et al. (2008)). Thereby, we add a necessary condition, to respect the targets only implicitly included in the orginal 2°C targetwhile keeping the original 2°C target in order to reflect those impacts which are not yet formulated in an equivalently explicit manner. Here we ask: 'For a given region, what would be its climate anomaly in a 2°C warmer world, without SRM?How much regional precipitation change, as an example of a climatic change other than temperature, would someone, who has already accepted up to 2°C of global warming, accept?' This regional climate anomaly is the maximumvery climate change which is acceptable for a deciondecision--maker who accepts a global warming of 2°C. (In the target-based literature, 'acceptable' for further consideration is called 'admissible' (Bruckner et al. (2008),; [Kriegler & Bruckner, 2004]Kriegler and Bruckner (2004) .; Petschel-Held et al., 1999Petschel-Held et al. (1999)). Hence, for further economic optimization, we If we were able to confine regional climate change to the intervals of climate variables that would be spanned by ramping the global mean temperature anomaly (as against its pre-industrial value) up from zero to 2°C. We , we could augment the 2°C target by this exact set of intervals as the more fundamental target. Note that here wWe suggest to generate such intervalsthat the intervals would being generated in the absence of without SRM because the 2°C target has emerged from a line of argument excluding SRM (Schellnhuber (2010)). This region-based, hence more fundamental, target would then be valid also for technology portfolios which include SRM. also for portfolios of SRM and mitigation portfolios. Analogous to the original global target, this target also allows for bypassingbypasses the criticized monetarization of climate impacts on which a cost benefit analysiCBAs is based.

In the following wHere, we focus on a subset of regional climate guardrails in terms of terrestrial precipitation changes becaue thesethat have been highlighted as a keycritical drawback of SRM. While regional temperature [Asseng et al., 2011](Asseng et al. (2011)) and precipitation [Portland et al., 2010](Portmann et al. (2010)) are highly relevant for agricultural productivity, the 'pattern mismatch' (i.e. the discrepancy between greenhouse gas- and SRM-induced patterns) of precipitation is of a larger order of magnitude than that of temperature [Kravitz et al., 2014](Kravitz et al. (2014)). We are not claiming that temperature and precipitation are the only relevant climate predictors for agricultural productivity or the functionality of ecosystems in general,. Still, but we acknowledge precipitation limits as sensiblea necessary boundary conditions within a target-based framework [cite Discussion reply #1?].

Figure 1 shows our suggested guardrails for two hypothetical regions r1 r_1 and r2 r_2. For this figure, as well as our whole analysis, we employ a the followingpair of assumptions: (i) Regional climate anomalies can be approximated as a superposition of a anomalies climate--induced by greenhouse gases and one by SRM, respectively (Ban-Weiss and Caldeira (2010)), (ii) both

~~any of the two each~~ regional components scale~~s~~ linearly with their~~its~~ corresponding global mean temperature component ~~[frieler et al., 2012]~~ (Frieler et al. (2012); Ricke et al. (2010)).

Equations 1 and 2 formalize our suggested guardrails for the admissible precipitation anomalies~~y~~ (ΔP_R) for all regions (R):

$$\forall_{r_1 \in R} \text{ with } C(r_1, \mathrm{CO_2}) > 0: \; -EA \leq \Delta P_{r_1} \leq \Delta P_{r_1}^{2^\circ C} + EA \tag{1}$$

$$\forall_{r_2 \in R} \text{ with } C(r_2, \mathrm{CO_2}) < 0: \; \Delta P_{r_2}^{2^\circ C} - EA \leq \Delta P_{r_2} \leq EA \tag{2}$$

where $\Delta P_R^{2^\circ C}$ denotes the regional precipitation anomaly of a 2°C warmer world without SRM ~~use~~.

~~r1~~ r_1 is characterized by a positive CO_2 (Greenhouse-gas-driven) scaling coefficient ($C(r_1, \mathrm{CO_2}) > 0$), which denotes a positive change in precipitation (P) when the global mean temperature (T) rises. ~~r2~~ r_2 is, however, characterized by a negative CO_2 scaling coefficient ($C(r_2, \mathrm{CO_2}) < 0$). The green bands in panel a) and panel b) define the regular admissible area for precipitation change ~~which is~~ compatible with the 2°C target. As noted earlier, SRM imprints patterns of regional precipitation and temperature change that would differ from those induced by greenhouse gas forcing (Kravitz et al. (2013)). Therefore, the regular admissible range~~area would totally prohibit SRM use in~~ of th~~o~~se~~e~~ regions where~~whose~~ SRM scaling coefficients have the same sign as their CO_2 scaling coefficients would prohibit any SRM use. ~~Therefore~~To avoid this~~hus~~, an extra range~~area~~ of admissibility (EA>0) is required ~~for any SRM use~~. ~~For an the extra admissible area, w~~We pragmatically suggest adding a fraction of regional standard deviation, derived from inter-annual variability, on both ends of the admissibility range~~for an extra admissible area~~. These extra ranges~~areas~~ are de~~picted~~~~monstrated~~ in blue. In this paper, we consider 5% and 10% of the standard deviation of inter-annual variability. In Sect. 4.1, we analyze the sensitivity of our results to the size of these ranges~~conduct a sensitivity analysis by changing the extra room added to the upper and lower bounds of the guardrails~~. ~~Note that~~While this extra admissible range~~area~~, as our whole analysis, is not based on formalized impacts~~.~~, ~~This~~it is ethically ~~and in that sense also~~ and formally consistent with the assumptions of ~~cost effectiveness analysis~~CEA.

2.2 Regional scaling coefficients and natural variability

For the regionalization of climate change effects, we use ~~resolution, we decide on a spatial resolution in terms of~~ 'Giorgi regions' (Giorgi and Bi (2005)) (see Table 1 and Fig. 2)~~. This resolution orients itself at a resolution~~ which are, very roughly, consistent~~in line~~ with synoptic scales. This regional resolution~~It which~~ brings about a markedly different image from a global average in the sign and magnitude of effects in the climatic variables under scrutiny~~, and a~~. At the same time, it avoids a larger number of simultaneous regional targets that might be perceived as too restrictive.[2] However, we stress that the choice of the resolution is ultimately a normative decision to be taken by society.

[2]The time and resources needed for reaching a converged solution may exceedingly increase with the number of regions.

For the scaling coefficients, we diagnose annual mean regional precipitation changes from linear pattern scaling (Ricke et al. (2010)) which are derivedriven as a linear superposition (Ban-Weiss and Caldeira (2010)) of greenhouse-gas-induced and SRM-induced changes in global mean temperature. We use the outputs of nine atmosphere–-ocean general circulation models (AOGCMs).[3] The average greenhouse-gas-induced scaling coefficients includingand their sample standard deviations (c_{CO_2}[%/K] and $\sigma_{c_{CO_2}}$) and the average SRM-induced scaling coefficients includingand their sample standard deviations (c_{SRM} [%/K] and σ_{SRM}) from the nine AOGCMs are shown in Table 1. Figure A1 in the Appendix additionallyalso shows the variations of scaling coefficients for each region from nine AOGCMs. Obviously, for some regions, tThe scaling coefficients may switch the sign for some regions if a specific AOGCM is considered or not. Table 1 also shows the ratio $R_r = c_{\mathrm{SRM}}/c_{CO_2}$, which is used as an indication forto indicate co-effects of SRM and CO_2 that link temperature effects to precipitation effects. All regions are characterized bywith SRM and CO_2 coefficients that increase or decrease precipitation in opposite directions., and hHence, R_r is negative in all regions. In regions where $0 > R_r > -1$, SRM under-compensates CO_2-induced precipitation changes. However, in regions where $-1 > R_r$, SRM over-compensates CO_2-induced precipitation changes.

An important note here is that, from the average scaling coefficients, and their sample standard deviation, and the assumption of a one can read that with a normal distribution of scaling coefficients, we can determine the probabilitypositive there are chances that the signs of scaling coefficients in some regions switch [please clarify this sentence - more pieces?]. For example, c_{CO_2} and c_{SRM} in Amazonia are -1.35 and 0.18 %/K, respectively. Yet, the corresponding sample standard deviations are 2.39 and 2.43 %/K, which are large enough to likely switch the sign of scaling coefficients when scaling coefficients are randomly generated with normal distribution. Therefore, it is also likely that for some regions R_r becomes positive for some regions, which means SRM and CO_2 both either increase or decrease precipitation. In Sect. 4.2, we conduct a Monte Carlo analysis by randomly choosing the scaling coefficients from the above distributions.

We determine the standard deviation of natural variability in precipitation the following way. We use three data sets of annual precipitation, aggregated to Giorgi regions resolution, based on GPCC_WATCH (1901-2001) (Weedon et al. (2010)), PGFV2 (1901-2012) (Sheffield et al. (2006)), and GPCC_WFDEI (1979-2010) (Weedon et al. (2014)). Then, for any region r and data set s, we determine the precipitation means $\mu_{r,s}$. To also obtain the standard deviation of natural variability as distinct from global warming, for any r, s, we first subtract a polynomial fit of second order parabolic fit (i.e., $a.t + a.t^2$, with a and b being the estimated parameters) [See R1, C8] of the time evolution -from the time series for detrending. The detrended data represent a more significant variability linked with a distinct time scale of the data (Wu et al. (2007)). From the thereby detrended data wThen, we determine the inter-annual precipitation time variances ($\sigma^2_{r,s}$) from the detrended data. For each region r we average means and variances across all data sets s to obtain σ^2_r and μ_r. Finally, the standard deviation of natural variability in percent is obtained asby 100 (σ_r/μ_r). The last column in Table 1 expresses the derived regional natural variability.

[3]The AOGCMs are BNU-ESM, CanESM, CSIRO-Mk3L-1-2, HadCM3, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM, MPI-ESM-LR, and NorESM1-M.

2.3 Model

For our joint SRM-mitigation analysis, we utilize the integrated energy-economy-climate model MIND (Edenhofer et al. (2005)), which provides one of the simplest possible options to distinguish a renewable from a fossil sector and to include induced technological change. ~~Results derived from the model MIND co-shaped the mitigation chapter of the Stern Report (Stern (2007)) and turned out to deliver centered results in comparison to other models of that category.~~ Compared to more advanced models that would distinguish ~~an~~ electricity, a household, and a transport sector, it tends to underestimate mitigation costs by a factor of two (see, e.g., Edenhofer et al. (2014)). ~~However~~While its economy does not display any spatial resolution, it serves as one of the simplest possible models to project mitigation costs ~~in a realistic manner~~realistically. ~~and~~Hence, it~~to a great deal~~ can serve as a pedagogic model to mimic the ~~most important~~essential economic-climatic aspects ~~that are~~ under investigation. ~~Accordingly, its economy does not display any spatial resolution.~~ We ~~further~~ extend the model with respect to its climate diagnostics to include a spatially~~-~~ explicit resolution in terms of 'Giorgi regions' (Giorgi and Bi (2005)). This way, the SRM-side effect category ~~'~~''SRM-induced regional climate mismatch~~'~~' can be studied. In addition, we ~~further extend~~upgrade the model to include SRM as a control. We assume a reduction of the solar constant ~~as~~is a good approximation (Kalidindi et al. (2015)) of sulfur aerosol injection that is currently discussed as the most feasible SRM scheme. As the cost of SRM, we t~~ake~~ook the joint upper end of the ~~costs~~expenses reported in The Royal Society's Report on Geoengineering the Climate (Shepherd (2009) and Klepper and Rickels (2011)): 0.02% gross world product as of 2010 per W/m^2. Even with this upper end, ~~This~~ the costs of SRM are ~~is~~ at least an order of magnitude smaller ~~number~~ than the cost of mitigation (Edenhofer et al. (2014)).

Climate sensitivity is a crucial uncertain parameter, and some studies considered a log-normal probability density distribution for it (Lorenz et al. (2012); Neubersch et al. (2014); Roshan et al. (2019); Wigley and Raper (2001)). In this study, the model MIND is used in its deterministic setting with a climate sensitivity of 3°C.~~ when t~~ The time scale of the climate module has a distinct~~strict~~ relationship with the climate sensitivity suggested by Lorenz et al. (2012). MIND employs the simplest climate module (one-box climate model) (Petschel-Held et al. (1999)). Nonetheless, Khabbazan and Held (2019) showed that~~tested the validity of~~ a one-box climate model is a good~~as an~~ emulator for fourteen tested AOGCMs~~ and showed that it is a good emulator of these AOGCMs~~ (accurate to within 0.1°C for Representative Concentration Pathways, RCPs), provided the one-box climate model is tuned~~being trained according~~ to the AOGCM's equilibrium climate sensitivity and transient climate response~~sensitivity andwhen~~, and a certain time horizon (on the order of the time to peak radiative forcing) is not exceeded (see Khabbazan and Held (2019) for a detailed discussion). Therefore, according to Khabbazan and Held (2019), the results in this article can be interpreted as being influenced by a slightly larger climate response to forcing than intended. Hence, for the sake of completeness, in Sect. 4.3 we estimate the sensitivity of our results to the assumption made for ~~conduct a sensitivity analyses by altering the~~ climate sensitivity.[4]

2.4 Definition of scenarios

[4]Roshan et al. (2019) employed the MIND model developed here in its probabilistic version.

The analysis will beis based on the following scenarios (see Table 2).: a): nNo-policy case (business-as--usual scenario ('BAU') where neither SRM nor mitigation is applied; hereby, in our context of the semi-conceptual MIND model, we do not distinguish BAU from 'baseline' -- —in either case, no explicit climate policy is applied),; b) 2°C target activated and SRM is not used ('TradCEA'); bc): 2°C target is activated and SRM is not limited by regional contraints, hence complete ignorance of SRM side effects ('REF'); cd): 2°C target plus all regional (precipitation) constraints are binding, and the extra admissible rangearea (EA) is 5% of the standard deviation, $\sigma_{r,\mathrm{precip}}$ ('G0 5%'; 'G0' refers to 'Giorgi and Bi regions whereby zero regions are omitted as binding targets, in contrast to later modified applications'); de) sSimilar to c) but with 10% of the standard deviation of natural variability ('G0 10%'). Note that a specification of an admissible rangearea is irrelevant for BAU and REF, as in both scenarios, regional targets are deactivated.

3 Results [see R1, C10 - explain Figs 3-4 clearer]

Figure 3 displays the time evolution of normalized precipitation anomalies in the 26 regions in a condensed manner, in whatthe timing how many outand the number of shows normalized precipitation change for the 26 Giorgi regionals targets that are binding in a condensed manner, for the above four scenarios (BAU, REF, G0 5%, and G0 10%). for a): no-policy case (business as usual scenario ('BAU') where neither SRM nor mitigation is applied); b): 2°C target activated and unlimited admissible SRM level ('REF'); c): precipitation changes when all regional constraints are binding and the extra admissible area is 5% of the standard deviation ('G0 5%'); d) similar to c) but with 10% of standard deviation ('G0 10%'). Note that there are no extra admissible area for BAU and REF. We normalize the precipitation such that '1' is the constraint which correspondsing to the precipitation levels of a temperature anomaly of 2°C, and '0' indicates theequals the other constraint provided, which is determined by the preindustrial precipitation levels. (see Sect. 2.1 for more details on the guardrails) plus the extra admissible area due to interal variability. Note that in the calculation of the normalized precipitation for G0 5% and G0 10% the extra admissible areas are taken into account. Note that in calculating the normalized precipitation guardrails for the all scenarios, the extra admissible rangesareas are taken into account (see Sect. 2.1 for more details on the guardrails). We indicate thisese corridors as grey bands in Fig. 3. Figure 4 displays the resulting effects on the global mean temperature byfor temperature response to 'CO_2-forcing' (dotted lines), SRM-forcing (dashed lines), and the sum of both (solid lines) again for allthe four scenarios. Jointly, the two figures can be interpreted as followsA joint inspection of both figures supports an interpretation. for a): no policy ('BAU'); b): 2°C target activated and unlimited usage of SRM ('REF'); c) all Giorgi regions' precipitation guardrails being activated when the extra admissible area is 5% of the standard deviation ('G0 5%'); d) similar to c) but with 10% of the standard deviation ('G0 10%').

In BAU, for most regions, regional precipitation would surpass this corridor, indicating the need for an active policy if a 2°C framing is of interest (see Fig. 3 (a)). Analogously, the 2°C target is transgressed in figure 4.

In BAU, the 2°C target is transgressed (Fig. 4 (a)) and also the precipitation leaves the admissible corridors for most regions (Fig. 3(a)).to reach aif atargetframing is of interestFfWe now inspect the REF scenario. As a first policy scenario we simply add SRM to the option folder without activating the regional precipitation guardrails while keeping the global 2°C target (REF scenario). As expected, SRM almost completely crowds out mitigation. As shown in Fig. 4 (b), withUnder unrestricted SRM usage in REF, the CO_2-contribution would mimic BAU, andbut SRM would totally compensate for anavoid overshooting ofthe 2°C target (Fig. 4 (b)). This also means that, dDue to its relatively low costs, SRM almost completely crowds out mitigation. On the regional level, the pattern mismatch expresses itself. However, f For about half of the regions, however, precipitation transgresses the 2°C-compatible precipitation corridor (see Fig. 3 (b)) to a large degree 'large' compared to the scales spanned by 2°C warmer world. This demonstrates thathow ThisHence, it demonstrates that athe definition of regional targets and subsequent G0 scenarios was a necessaryallows act in order to preserve the value system encoded in the 2°C target when includingafter the advent of SRM.

Now we activate tThe precipitation corridors for any of theof all regions are activated in (the G0 scenarios). By construction, for anyll of the regions, the precipitation trajectories stay confined to the grey band (see Fig. 3 (c) and (d)). Comparing G0 5% with G0 10%, one notices that the upper and lower bounds in G0 5% isare touched 15 years earlier, which is due to the smallerlimmer admissible rangearea in G0 5% compared toas against G0 10%. Compared to REF, with regional precipitation constraints being activated in G0 5% and G0 10%, SRM usage is restricted to about 1/6 and 1/3 respectively in the G0 5% and G0 10% scenarios [where does this claim come from? What are the data?]. Hereby temperature anomaly peaks at 2°C and then declines, for example to 1.5°C in G0 10%, which means SRM partly overcompensates the CO_2-effects (see Fig. 4 (c) and (d)). SRM usage is highly restricted in the G0 5% and G0 10% scenarios compared to REF. As a result of this, the temperature anomaly peaks at 2°C and then declines, for example, to 1.5°C in G0 10%, which means SRM partly overcompensates the CO_2-effects (see Fig. 4 (c) and (d)) on global temperature.

This overcompensation can be explained from the panels c) and d) in Fig. 3 in which the following four phases along the time axes can be identified. (i) No guardrail is active, and- the paths mimic a BAU development (compared to panel a)). (ii) The 2°C guardrail is active, and SRM is utilized (as in the case depicted in Fig. 4 (b)), and for most regions, the normalized precipitation anomaly declines for most regions. (iii) For one region, either the upper ('1') or lower ('0') normalized precipitation guardrail is reachedtouched and activated. In the course ofOver time, for several regions the normalized precipitation approachesevolves towards the guardrails (either '0' or '1') for several regions, -and simultaneously the global mean temperature decreases simultaneously. (iv) For a different region, tThe lower ('0') normalized precipitation guardrail is reachedtouched in a different region, and the system becomes quasi-stationary.

The first binding region reaching its upper normalized precipitation guardrails, and thereby starting phase 3, -is 'AMZ' (Amazonia, see Fig. 2). Here itAMZ is characterized by a negative c_{CO_2} and positive, but comparatively small c_{SRM} with a comparatively small modulus., which makes AMZ's absolute value of R (c_{SRM}/c_{CO_2}=-0.14) one of the lowest among the regions-. Precipitation in AMZ is continuing to increase in phase 2 as the increase due to further CO_2 emissions is merely compensated by SRM. Note that there are two regions whose R is lower than AMZ; CNA (R_{CNA}=-0.11) and NAU (R_{NAU}=-0.07). Nevertheless, the comparably lower standard deviation of natural variability (and hence, the extra admissible range, EA) in AMZ (4.42) than in CNA (8.93) and NAU (17.83) results in AMZ reaching its boundary of regional normalized precipitation faster than others.[5] ~~Although the CO_2- and the SRM-effects on precipitation levels in 'AMZ' work in opposite directions, the regional SRM-effect cannot significantly compensate for the CO_2-effect that in phase 2 activates to compensate for any overshooting of 2°C. Therefore 'AMZ' appears a likely candidate to touch the upper bound and start phase 3~~. ~~However, o~~Once ~~precipitation~~ in ~~'~~AMZ~~'~~ ~~reaches~~ the upper boundary of regional normalized precipitation levels ~~(~~is reached (start of phase 3), any CO_2-induced change in AMZ's precipitation needs to be compensated for by an SRM-induced contribution. ~~As~~Due to AMZ's ~~scaling coefficient has a small modulus~~small absolute *R*, more SRM forcing needs to be applied per unit of CO_2-induced radiative forcing than in phase 2~~,~~ to stop AMZ's normalized precipitation trajectory from growing any further. Therefore, in phase 3, SRM overcompensates CO_2 in terms of ~~their~~its effects on the global mean temperature. Finally, one of the regions with larger~~, yet negative~~absolute scaling coefficient ratio~~s~~ (in this case, 'SQF' (South Equatorial Africa)) ~~would~~ hits the lower ~~bound~~boundary of regional normalized precipitation, ~~triggering~~starting phase 4, where no further CO_2 emissions are admissible because because any attempt to compensate their temperature effect would result in a transgression of the precipitation corridor of at least one region.[6] ~~-~~Therefore, the 'G0' scenario is characterized by the interplay of~~ two regions'~~ scaling coefficients and precipitation standard deviations~~-~~ of two specific regions~~of two regions~~. Please note, however, that for different regional *R*s, there could be less than four phases, and the interplay could be between the global 2°C target itself and precipitation in one region. This would, e.g., be the case if the absolute *Rs* of all regions are negative, as in our case, but all absolute values are larger than 1. If at least one of the regions has a positive *R,* an implementation of SRM could lead to a transgression of the region's precipitation guardrail even before the 2°C temperature limit is reached.

What are the economic effects of allowing for G0 (i.e., restricted SRM) instead of mitigation only? Figure 5 displays mitigation costs for a step-wise omission of regional precipitation guardrails. ~~with~~ It is not a straightforward task to express policy-induced time-aggregated relative economic changes such as 'mitigation costs' in a consistent manner. We choose the option to utilize ~~Regional~~ 'Balanced Growth Equivalent (BGE) values'~~-~~ (Anthoff and Tol (2009)). Policy-induced relative BGE changes represent relative changes of the initial and any future consumption of a stylized consumption path ~~being~~ that are~~is~~ welfare-equivalent to the real consumption changes. ~~attributed to a region are the losses in comparisoncompared to the BAU scenario, if the analysis is henceforth not constrained by the precipitation guardrails of the respective regions. The acronyms of regions are defined in Fig. 6.~~ The leftmost bars display the economic losses (disregarding impacts) induced by a 2°C policy without SRM usage (TradCEA).~~ is displayed by the leftmost bar (hereafter we call it 'TradCEA'), t~~T~~hen~~ he economic losses

[5]The absolute R_r can also be perceived as the change in SRM-induced precipitation relative to CO_2-induced precipitation change for the same effect on global mean temperature. Because the extra admissible range is only activated when SRM comes into play, it can be adjusted according to the R_r to measure the effective slimness of the regions' EA. For this measurement, we can define an effective admissible range (EAR_r=R_r.$\sigma_{r,\mathrm{precip}}$). Therefore, AMZ would have the lowest EAR, and hence, it is the region that will most likely touch its precipitation guardrail when SRM is applied. One note is important to be mentioned: As there are chances that the deployment of SRM starts earlier than the temperature guardrail is touched, EAR_r only indicates the likely candidates to touch their upper boundary of normalized precipitation faster than others.

[6]Depending on the signs of $c_{\mathrm{CO_2}}$ and EAR_r, a larger absolute value of EAR_r can also be perceived as how quickly region r departs from its upper boundary of normalized precipitation. This is equivalent to say how quickly region r may approach its lower boundary of normalized precipitation. Therefore, according to EAR_{SQF}, SQF is likely to touch its lower boundary quicker than others if SRM is applied. However, as SRM deployment starts when the regions are relatively nearer to their upper boundary than their lower boundary, R_r might be a better index than EAR_r to signal which region may be quicker in reaching its lower boundary of normalized precipitation.

for the G0 scenarios are shown byin the following barsfor SRM included when all regional precipitation guardrails are active (G0), and, continued bywith the scenarios when the guardrails of binding regions are disregarded one by one. Hereby 'BGE' losses (y-axis of Fig. 5) can be approximately interpreted as consumption losses, or, in other words, the loss in Global World Production (GWP) (for details see Anthoff and Tol (2009) and Lorenz et al. (2012)). The results indicateFrom the graphresults, we read that 2/5 and 3/5 of the mitigation costs could be saved respectively in G0 5% and G0 10%. For someone who interprets mitigation costs as largehigh, this could be an argument for employing SRM. For someone who perceives the scale of 1% of consumption GWP loss as smalllow, the mitigation cost of mitigation would not providebe a reason to become interested in SRM.

,If saving 2/5 to 3/5 of mitigation costs were of interest, however, instead of utilizing SRM, one could also imagine relaxing the 2°C target instead. What would be the equivalent additional global warming? From Fig. 4, we read: about 0.1°C and 0.3°C respectively in G0 5% and G0 10%. IfSuppose one interprets the 2°C target as an (academically informed) political target that does not represent a singular global threshold (Neubersch et al. (2014)),. In that case, society might want to discuss whether a modest transgression of the target to the extents of, for examples, 0.1°C and 0.3°C, could be seen as acceptable in view ofgiven the risk of potential further side-effects of SRM such as stratospheric ozone depletion (Tilmes et al. (2008)). In that sense, the extrapolation of SRM impacts to the regional precipitation corridors has proven almost prohibitive for SRM.In order to come to an assessment of the above trade-off, aA to assess the above trade-off,the

However, the picture can gradually change if the society is willing to successively disregard the step-wise (economically) most binding corridor boundary, and, hence, toto 'sacrifice' the region that causes the strongest limitation ofthat would to induce the largestmost significant economic welfare gain, the picture can gradually change. Progressively, a more economic gainimprovement could be gainedharvested (see Fig. 5, further right bars). when From one bar to the next, tthe region's guardrail of that very region is omitted that would deliver the largest economic welfare gain from one bar to the next is omitted. We choose the region to be omitted by asking which omission would cause the largest welfare gain. Figure 6 indicates the economic gain per region when the precipitation is allowed to leave the respective regional corridor. Similar fFor both G0 5% and G0 10%, the order of the first four regions whose guardrail should be omitted to gain the most areis AMZ, SQF, CAM, and WAF. However, while for G0 10% these four regions are followed by CNA, MED, and CAS for G0 10%, in G0 5%, CAS, CNA, and SAH follow. Note that the precipitation changes in other regions are already within the guardrails in the REF scenario, and . hHence, there is no need for omission ofto omit their guardrails to gain morebenefit welfare (see Fig. 3).

Notably, evenAlthough it is not so significant for the analysis regarding the welfare gains, tThe order of regions may depends on the decision about the extra room for guardrails, as shown in panels a) and b). The reason behind this observation is that with a tighter guardrail, while SRM is used less and at the same time mitigation must be employed more, the interplay of different scaling coefficients would likely cause different ordering. In additionNevertheless, if such an extra admissibility rangeroom is tighter, then the economic gain from its omission is higher. The same rule applies to the G0 scenarios, too. For example, the BGE loss in G0 5% is almost 60% higher than the BGE loss in G0 10%,. Also, and the BGE loss when the extra room is 5% of natural variability andfrom omittinged AMZ when the extra rangeoom is 5% of the natural variability is omitted is nearly double the cost for the same scenario when the extra room is 10% of the natural variability.

4 Sensitivity analysis

The results in the previous section were derived based on~~ some~~ specific assumptions. Here we pick up some of the most ~~important~~critical assumptions and investigate~~ the likely~~ alternative scenarios.

4.1 Extra room as a fraction of natural variability

Figure 7 depicts the BGE loss (%) for the G0 scenario when ~~the~~ an addition of some fraction of the standard deviation of natural variability ~~the share of natural variability~~ as the extra room varies from 0.05 (5%) to 0.5 (50%). ~~Note that t~~The first two bars on the left, 0.05 and 0.1, are the same as the G0 scenarios in Fig. 5 (a) and (b), respectively. As can be expected~~Expectedly~~, with larger admissibility ranges~~the higher extra rooms~~, the BGE loss decreases. ~~such that w~~When the extra range~~room~~ is 50% of the standard deviation of natural variability (the rightmost bar), the BGE loss is negligible (about -0.01% of BAU). However, such a decrease in BGE loss is not linear with respect to the increase in the extra range~~oom~~, but it is convex. ~~That is, f~~For example, while the ~~decrease~~reduction in BGE loss is about 0.25% when the extra range~~oom~~ changes from 0.05 to 0.1, the ~~decrease~~reduction in the BGE loss will ~~amount only~~decline to nearly 0.15% when the extra range~~oom~~ changes from 0.1 to 0.15. Note that, according to the argument presented in Sect. 3, there is a chance that the order ~~or~~of regions changes.

4.2 Scaling coefficients

As discussed earlier, the SRM and CO_2 scaling coefficients determine the order of regions as well as when ~~to hit~~ the guardrails in the G0 scenario are reached. However, the scaling coefficients depend on the ~~may vary based on from which~~ AOGCM from which~~data~~ they are derived~~ from~~. The results in Sect. 3 were derived from the average value of scaling coefficients from nine AOGCMs. These data can also be ~~also~~ used to derive specific standard deviations for each scaling coefficient. Figure 8 shows the box plots for a Monte Carlo study on 1000 random, simultaneous variations in scaling coefficients and measures the BGE loss in the G0 scenario. In addition, the extra room in guardrails can increase in each scenario from 10% of the standard deviation of natural variability to 100% of ~~natural variability~~it. In each G0 scenario, the sign of ~~some~~ scaling coefficients ~~as well as~~and the binding regions in the four phases can be different.[7]

According to the Monte Carlo study, it is more likely that the random variation of the scaling coefficient results in a higher BGE loss in G0 scenarios. For example, while~~ in the deterministic results for an extra room for guardrail equal to 10% of natural variability~~ the BGE loss is about 0.45% in the deterministic results for an extra admissibility range~~room for guardrail~~ equal to 10% of natural variability, the median of BGE loss in the Monte Carlo study can reach ~~to~~ about 0.85%. In addition, with the higher extra ranges~~ooms~~, the median of the BGE loss decreases. ~~However~~Nonetheless, similar to its deterministic case, ~~a~~the ~~decrease~~reduction in the median of the BGE loss is convex. Therefore, although for an extra admissibility range~~room for guardrail~~ equal to 50% of natural variability~~,~~ the BGE loss is negligible in the deterministic case, ~~in the Monte Carlo study~~ the BGE loss is about 0.4% in the Monte Carlo study. In other words, if the precipitation guardrails are considered, the likelihood ~~that~~of SRM ~~being used~~use may still be low if no region's guardrail is about to be omitted. Note that the decision about SRM

[7] Here we do not go further into the discussion about the order of regions.

~~being~~use ~~used~~ may involve many more factors than just an economic study. However, our results at least call for attempts to better estimate the sensitivities of regional precipitation changes to SRM and global tem~~e~~perature increase.

4.3 Climate sensitivity

Figure 9 shows the BGE loss in ~~Traditional CEA (~~TradCEA~~, where the temperature target is active without SRM use) and the~~, G0 5%, and G0 10% scenarios with the climate sensitivity varying between 1.5°C to 5°C. As expected, with ~~a~~ higher climate sensitivit~~y~~ies, BGE losses for the~~ G0 5%, G0 10%, and TradCEA~~se scenarios increase rapidly. The 2°C target is not attainable without ~~the use of~~ SRM when the climate sensitivity is equal and higher than 3.75°C for our model. Yet, by using SRM, the 2°C target is reachable with higher climate sensitivities. Nonetheless, the feasibility space depends on the extra room in the guardrails. If the extra room is 10% of the natural variability, the 2°C target is still reachable when the climate sensitivity is below 5°C (not reachable at 5°C). However, if the extra room is only ~~-~~5% of the natural variability, the 2°C target is only reachable when the climate sensitivity is below 4.25°C (not reachable at 4.25°C).

5 Conclusion

We ~~have~~ performed a CEA (cost~~-~~-effectiveness analysis) study where SRM (solar radiation management) and mitigation are simultaneously allowed ~~for~~ as climate policy options. We investigated~~, asking for~~ the minimal-cost~~ minimal~~ mix of these options under certain environmental constraints (i.e., targets). ~~act as substitutes in idealized policy scenarios of immediate action.~~ As the key innovation, we defined a scheme to include one prominent side-effect category of SRM, ~~'~~regional climate pattern mismatches~~'~~, in the integrated assessment, ~~in a manner~~ ethically consistent with the global mean temperature target. (By 'pattern mismatch' we refer to discrepancies in greenhouse gas- and SRM-induced spatial climate anomalies for the same global mean temperature change.) For this, we defined a metric to extend the functionality of global mean temperature targets into a regime of SRM deployment. This extension is necessary as SRM destroys the relation of global mean temperature and regional climate~~, as otherwise~~ known from greenhouse gas forcing. Hence, global mean temperature alone ~~ceises being~~ceases to be a good proxy for the status of the climate system. Accordingly, we augment the global mean temperature target by ~~set of~~ equivalent regional temperature targets under pure greenhouse gas forcing. Thereby, the analysis does not rely on the global mean temperature target alone, ~~but~~and it ~~-~~can directly employ the equivalent regional targets when SRM is ~~added to the option folder~~considered. We suggest somewhat arbitrary~~hypothetical,~~ but ethically consistent regional targets by asking what climate those regions would have experienced in a 2°C warmer world without any~~before the advent of~~ SRM. Accordingly, for economic optimization, we would allow only for those scenarios which, for any region, would stay in the ~~very~~same interval as generated by global mean temperature anomalies~~values~~ between 0 and 2°C. From all possible SRM-induced climate mismatches, we chose precipitation as a particularly significant one.

Without accounting for SRM side effects~~risk-risk accounting~~, ~~SRM~~it would crowd out mitigation due to its comparatively low costs~~, thereby lowering the costs of~~ for achieving the 2°C target~~ to a negligible value~~ (compared to the original mitigation costs). However, ~~already due to the limitation ofif~~ when only one single regional climate variable (in our case 'precipitation') is required to stay withinis confined to regional bounds compatible with the global 2°C target, the still allowed cooling contribution -by SRM needs to beis reduced to a value lower than of global warming 2/5 and 3/5 of mitigation costs could be saved respectively within an accuracy of 5% and 10% of the standard deviation of natural variability. Furthermore, the additional amount of carbon dioxide that could be released to the atmosphere corresponds to only about 0.541°C (to nearly 10.80.3°C) of further global warming for depending on the allowed overshoot (5% (10%) of the standard deviation of annual mean regional precipitation).natural variability in terms of tolerance in regional overshoot. Society might debate whether should take the risks of SRM for that ratherrelatively small amount of allowed additional carbon emissions, the risks of SRM should be taken. However,Tthe related mitigation savings are, however, 2/5 orand 3/5 of mitigation costs , which could be saved, due to the steepness of the mitigation cost curve. AHowever, a significantly largermore significant role for SRM would be possible in caseif the guardrails of a few regions were relaxed. The ordering of regions presented in this article might provide a way to support the then necessary trade-off between the the relaxations ofto what extent relaxingto relax -global versus regional targets. Nonetheless, the order of regions whose omission brings about the most economic welfare gain depends on the magnitude of CO_2- and SRM-induced effects on precipitation as well as the normative decision on the extra rooms on the upper and lower bounds of the precipitation guardrails.

We also would see SRM and mitigation as complements if only a global climate policy were put in actionimplemented only within decades. The results showed that in our model, the 2°C target is not attainable without the use of SRM when the climate sensitivity is equal orand higher than 3.75°C. From the perspective of mitigation politicspolicy perspective, this is equivalent into saying, that abatement climate policy is delayed so much thatuntil, even for more centered values of climate sensitivity such as 3°C, the emission budget becomes exhausted. Then we would necessarily need some sort of climate engineering in order to comply with the 2°C target [Lawrence et al., 2018](Lawrence et al. (2018)). If the potential for carbon dioxide removal waswere exhausted, some amount of SRM would become indispensable ifwhen the 2°C target still should be reachedcomplied towith. Nonetheless, the feasibility space of SRM depends on the exact definition ofextra room in the guardrails. The tighter they are extra rooms on the upper and lower bounds of the precipitation guardrails, the earlier the use of SRM becomes useless to comply with the targets.

We need to point to a series of caveats of the analysis. The assumptions made in the constructionong of regional scaling patterns for precipitation may be oversimplifying the complex hydrological effects of greenhouse gases and SRM. Hence, we need to emphasize that regional precipitation guardrails can only be interpreted as necessary, not as sufficient conditions for decisions about the use of SRMa decision about SRM use decisions. Yet, by employing aour Monte Carlo study, we showsed that it is more likely that the random variation of scaling coefficients would likely results in larger economic losses when all temperature and precipitation targets are activebinding. Furthermore, annual mean precipitation is only one possible driver of regional climate impacts in addition to temperature, or evaporation, or intra-annual changes. Finally, our model does not include carbon dioxide removal options yet. Hence, the -above-mentioned economic gains through SRM must be interpreted as upper limits of costs savings.

Here, we demonstrate that someone who pushes for SRM in view ofto reach -the 2°C target should carefully consider theis target's- consequences this target would have when in part achieved by extended to SRM. Already aA singleregionally explicated ~~-~~climate variable (such as precipitation) ~~-when explicated regionally~~ reduces the usage of ~~almost completely bans~~ SRM to 1/3 ~~from a joint SRM-mitigation portfolio~~ even if one allows for a transgression of regional targets ~~only in terms of~~by 10% of the standard deviation of natural variability. Inclusion of further side effects of SRM would result in additional reduction factors.

DATA

The output~~s~~ of nine AOGCMs was~~ere~~ supplied by the scientists from GCESS, Beijing Normal University (John Moore's Group). Three data sets of annual Giorgi regions precipitation were supplied by M. Büchner and K. Frieler from the Potsdam Institute of Climate Impact Research (PIK). All climate model outputs used in this paper are available online on The Earth System Grid Federation (ESGF) webpages.

~~Three data sets of annual Giorgi regions precipitation are supplied by M. Büchner and K. Frieler from the Potsdam Institute of Climate Impact Research (PIK).~~

Authors' contributions

M.M.K. and M.S. performed the numerical analyses, wrote most of the code, and integrated SRM into MIND, M.M.K. optimized the GAMS code, wrote the code for ordering regions, designed and conducted the sensitivity analysis, and prepared most of the visualization, M.S. and E.R derived spatially resolved SRM-coefficients, E.R. calculate~~s~~d natural variability of precipitation, H.S. provided the system-analytic link between SRM experiments and integrated assessment, H.H. and E.R. explained the non-monotonic temperature response of Fig. 4, H.H. triggered this work and supplied the concept of extending temperature targets to SRM climate risks, H.H. and H.S. developed the 4 phases model, M.M.K., H.S., and H.H. developed the explanation of the regions' selection mechanism, H.H. and M.M.K. wrote most of this report.

Competing interests

The authors declare that they have no conflicts of interest.

Acknowledgments

E.R. has been supported by the DFG grant HE 555812-1 within the DFG priority program~~me~~ 'Climate engineering – Risks, Challenges, Opportunities? (SPP1689). H.S. acknowledges support under the DFG grant SCHM 2158/4-1. We are thankful to scientists from GCESS, Beijing Normal University (John Moore's Group), for supplying the output nine of AOGCMs. Also, we are thankful to M. Büchner and K. Frieler from the Potsdam Institute of Climate Impact Research (PIK) for supplying data sets of annual Giorgi regions precipitation.

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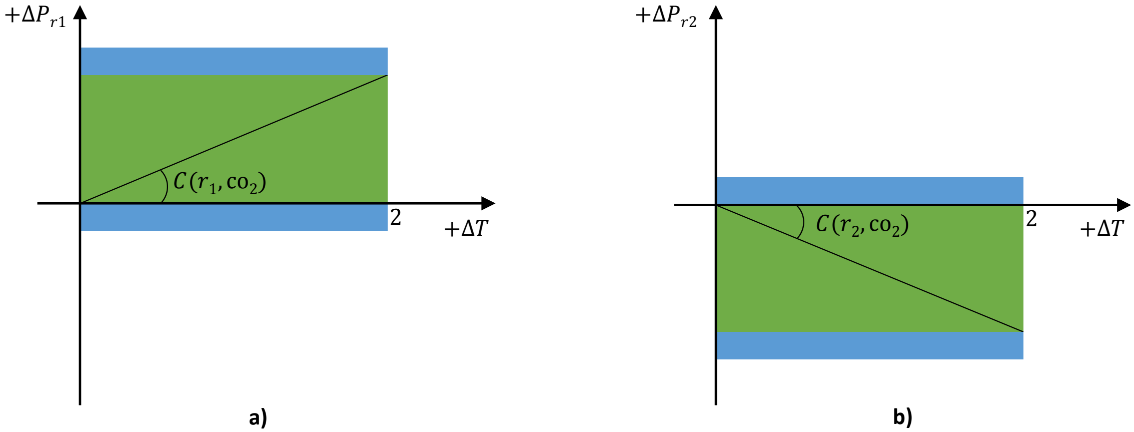


Figure 1. Schematic of precipitation guardrails for two hypothetical regions ~~r_1~~ $r1$ and ~~r_2~~ $r2$. ~~r_1~~ $r1$ is characterized by a positive CO_2 (Greenhouse-gas-driven) scaling coefficient ($C(r1, CO_2) > 0$), and ~~r_2~~ $r2$ is characterized by a negative CO_2 scaling coefficient ($C(r2, CO_2) < 0$). The graphs show regional precipitation vs. global mean temperature, the latter in °C. The green bands in panel a) and panel b) define the regular admissible area for precipitation change. The~~-~~ extra admissible areas (EA), as a fraction of regional standard deviation of natural variability, are demonstrated in blue.

Giorgi region		$c_{\mathrm{CO_2}}$[%/K]	$\sigma_{c_{\mathrm{CO_2}}}$[%/K]	c_{SRM}[%/K]	$\sigma_{c_{\mathrm{SRM}}}$[%/K]	$R_r = c_{\mathrm{SRM}}/c_{\mathrm{CO_2}}$	$\sigma_{r,\mathrm{precip}}$[%]
ALA	Alaska	5.51	1.12	-6.38	1.09	-1.16	4.84
AMZ	Amazonia	-1.35	2.39	0.18	2.43	-0.14	4.42
CAM	Central America	-4.11	1.87	2.54	1.32	-0.62	7.19
CNA	Central North-America	-0.37	3.27	0.04	3.18	-0.11	8.75
CAS	Central Asia	1.02	2.02	-2.31	1.52	-2.25	8.93
CSA	Central South-America	1.01	0.84	-1.84	1.01	-1.83	8.66
EAF	East Africa	4.78	2.86	-5.71	3.17	-1.20	6.45
EAS	East Asia	1.81	1.34	-2.36	1.26	-1.30	5.65
ENA	East North-America	1.10	1.10	-1.75	1.13	-1.59	5.85
EQF	Equatorial Africa	4.52	3.49	-6.15	4.07	-1.36	11.36
GRL	Greenland	4.66	1.08	-5.37	1.00	-1.15	5.50
MED	Mediterranean	-4.01	1.34	3.54	1.18	-0.88	7.28
NAS	North Asia	5.26	1.14	-6.06	1.10	-1.15	3.71
NAU	North Australia	-0.31	3.47	0.02	3.37	-0.07	17.83
NEE	North-East Europe	3.08	1.27	-4.68	1.44	-1.52	6.57
NEU	Northern Europe	2.19	0.77	-3.47	1.01	-1.59	6.14
SAF	South Africa	-1.78	1.20	1.74	1.12	-0.98	15.79
SAH	Sahara	2.99	10.07	-2.15	10.71	-0.72	21.80
SAS	South Asia	1.66	1.28	-2.43	1.25	-1.46	5.47
SAU	South Australia	-2.16	1.44	1.76	1.72	-0.81	15.19
SEA	South-East Asia	1.74	1.60	-2.46	1.55	-1.41	8.43
SQF	South Equatorial Africa	0.04	1.63	-0.91	1.78	-22.28	5.74
SSA	South South-America	0.93	0.75	-1.63	0.77	-1.74	7.84
TIB	Tibetan Plateau	4.13	1.56	-5.17	1.86	-1.25	14.62
WAF	West Africa	0.11	1.39	-0.57	1.17	-4.99	6.29
WNA	West North-America	1.93	2.96	-2.41	2.77	-1.25	11.64

Table 1. Scaling characteristics of Giorgi regions.

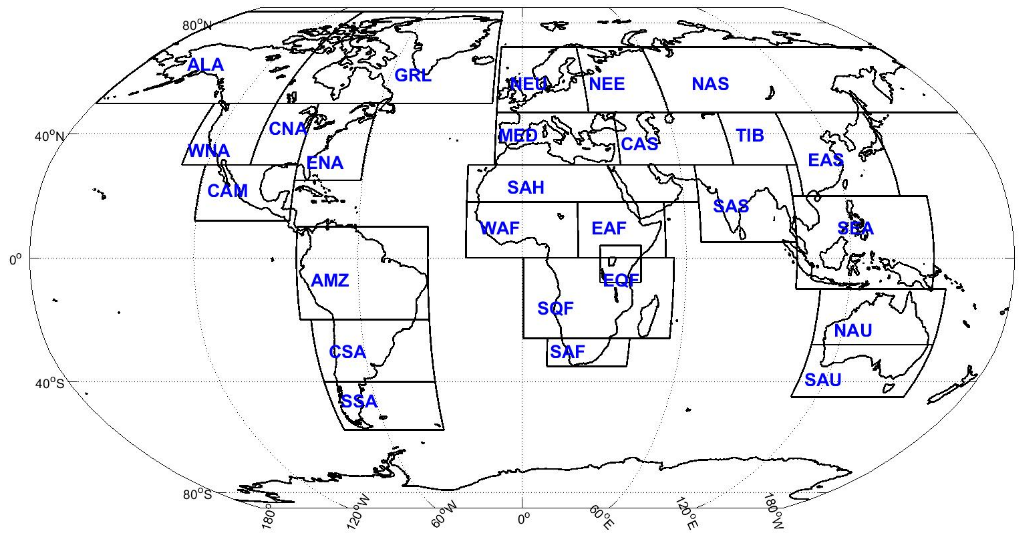


Figure 2. Spatial resolution of our analysis. 'Giorgi regions' Giorgi and Bi (2005).

Scenario	SRM	Mitigation	2°C Target	Precipitation Guardrails	$AE = 0.05.\sigma_{r,\text{precip}}$	$AE = 0.10.\sigma_{r,\text{precip}}$
BAU					✓	
TradCEA		✓	✓		✓	
REF	✓	✓	✓		✓	
G0 5%	✓	✓	✓	✓	✓	
G0 10%	✓	✓	✓	✓		✓

Table 2. Scenarios and their characteristics.

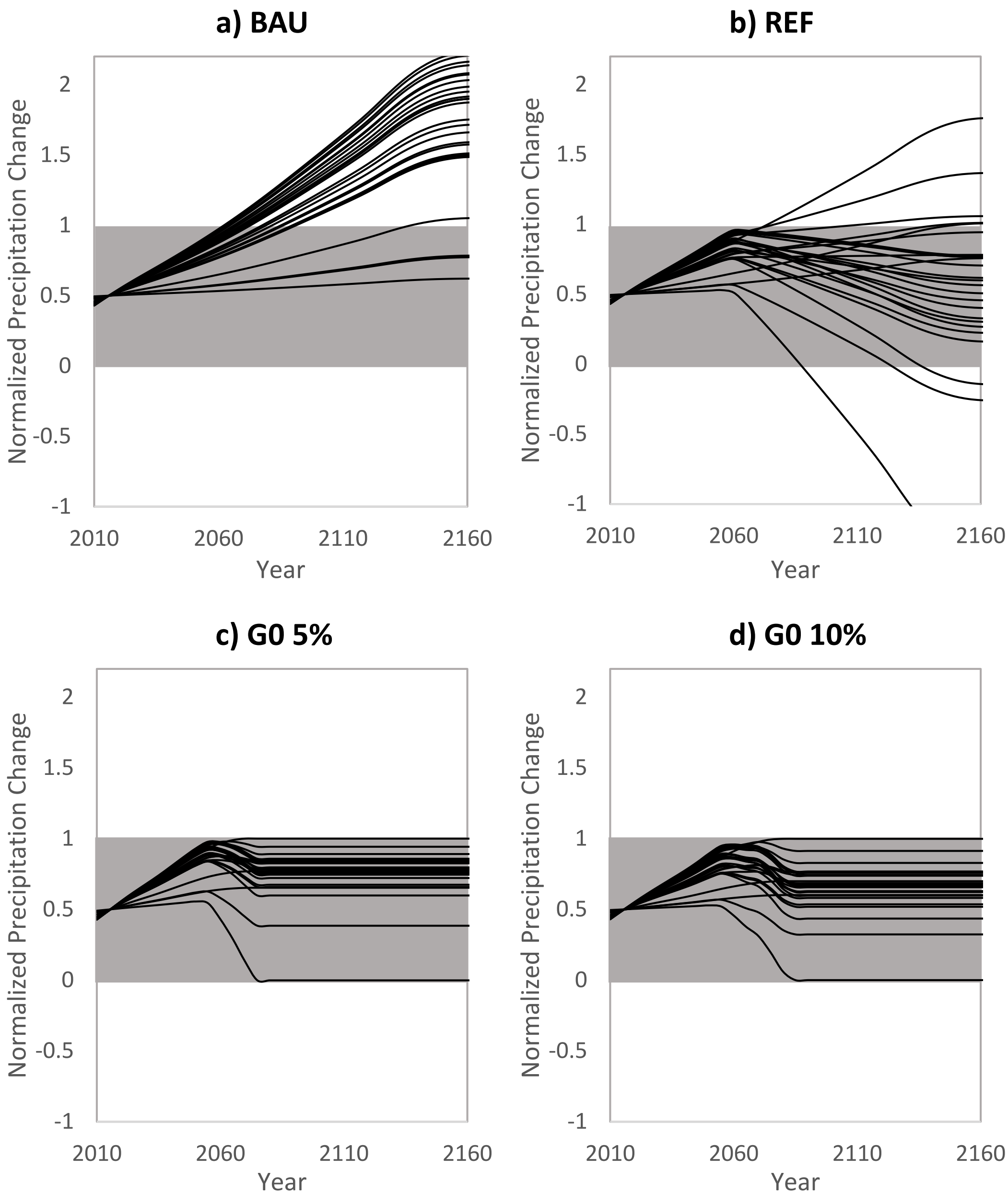


Figure 3. Normalized precipitation change. ~~For the 26 Giorgi regions and different policy scenarios, precipitation change is normalized such that ‘1’ is the constraint which corresponds to the precipitation levels of a temperature anomaly of 2°C (induced by CO_2 plus a fraction of standard deviation), and ‘0’ equals the constraint which is determined by the preindustrial precipitation levels (minus a fraction of standard deviation).~~ a): No policy (‘BAU’); b): 2°C target activated and unlimited usage of SRM (‘REF’); c) all Giorgi regions’ precipitation guardrails being activated when the extra admissible area is 5% of the standard deviation (‘G0 5%’); d) similar to c) but with 10% of the standard deviation (‘G0 10%’). For the 26 Giorgi regions and different policy scenarios, precipitation change is normalized such that ‘1’ is the constraint which corresponds to the precipitation levels of a temperature anomaly of 2°C, and ‘0’ equals the constraint which is determined by the preindustrial precipitation levels. Note that in calculating the normalized precipitation guardrails for G0 5% and G0 10% scenarios, the extra admissible areas are taken into account (see Sect. 2.1 for more details on the guardrails). These corridors are indicated as grey bands.

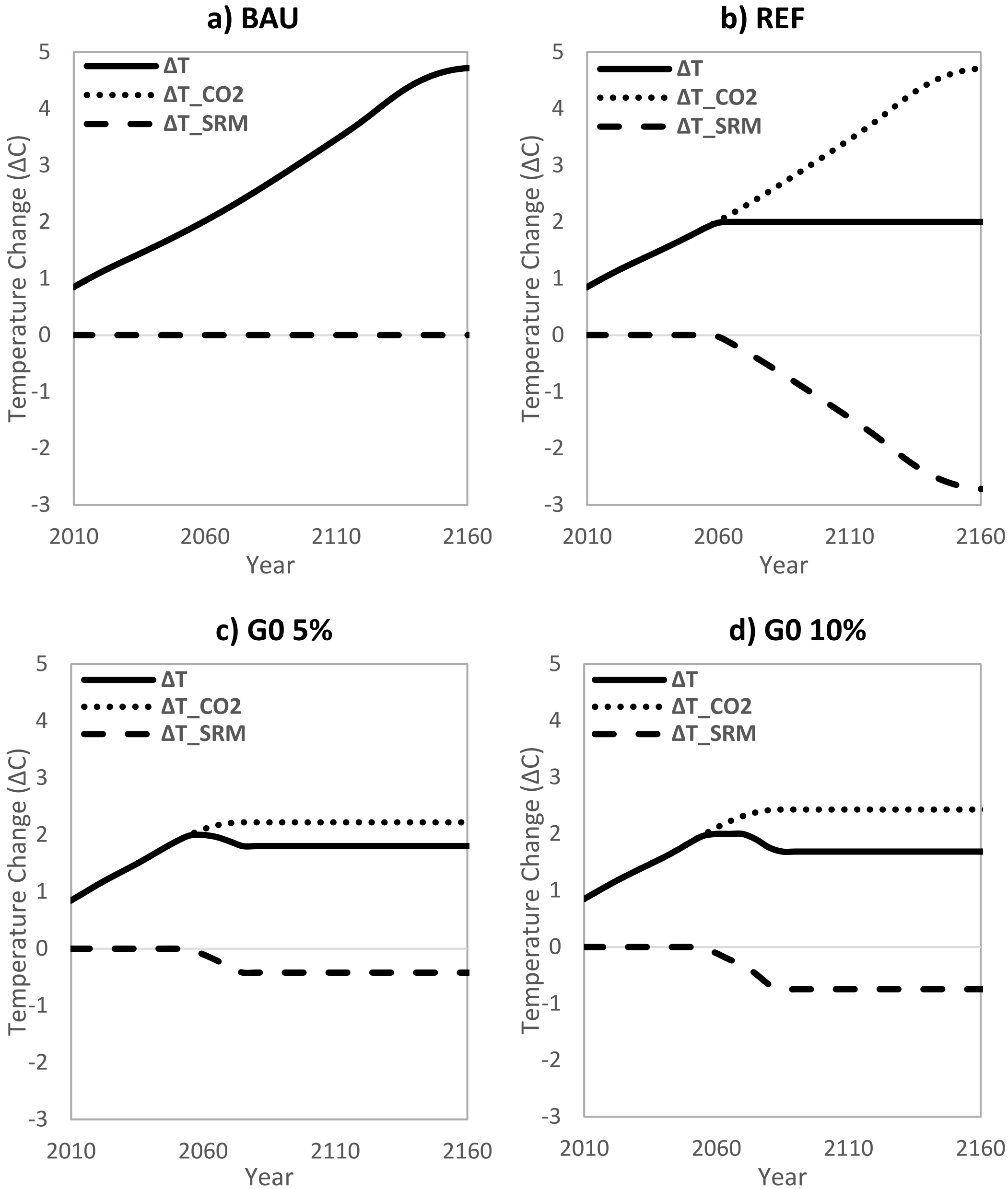


Figure 4. Global mean temperature response to SRM and carbon dioxide forcing. Dotted lines are the resulting effects on global mean temperature for temperature response to CO_2-forcing; The dashed lines are the resulting effects on global mean temperature for temperature response to SRM-forcing; the solid lines are the sum of both dotted ~~lines~~ and dashed lines. a): No policy ('BAU'); b): 2°C target activated and unlimited usage of SRM ('REF'); c) all Giorgi regions' precipitation guardrails being activated when the extra admissible area is 5% of the standard deviation ('G0 5%'); d) similar to c) but with 10% of the standard deviation ('G0 10%').

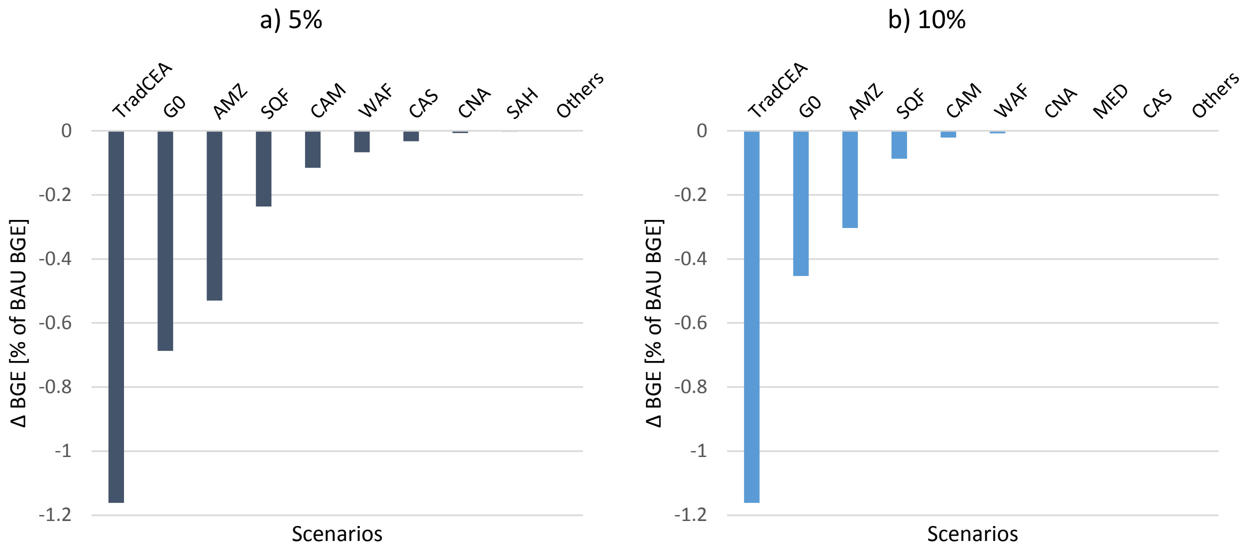
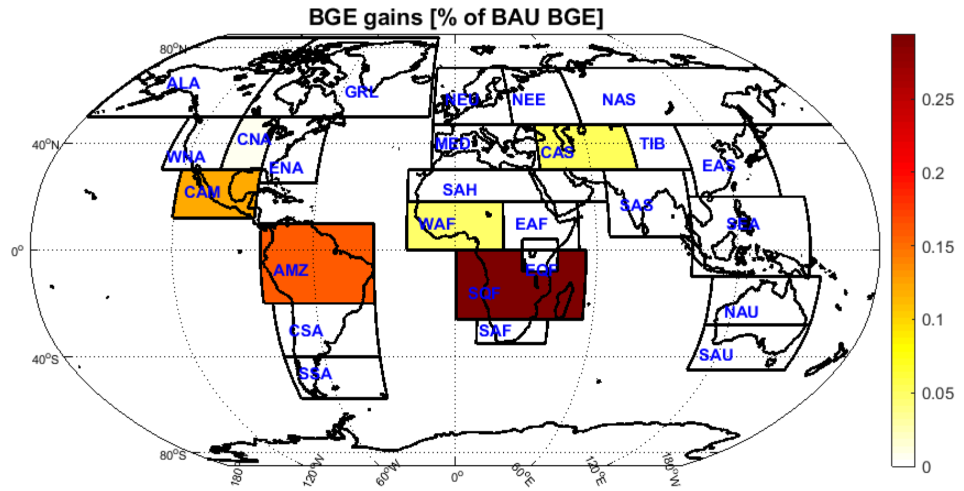
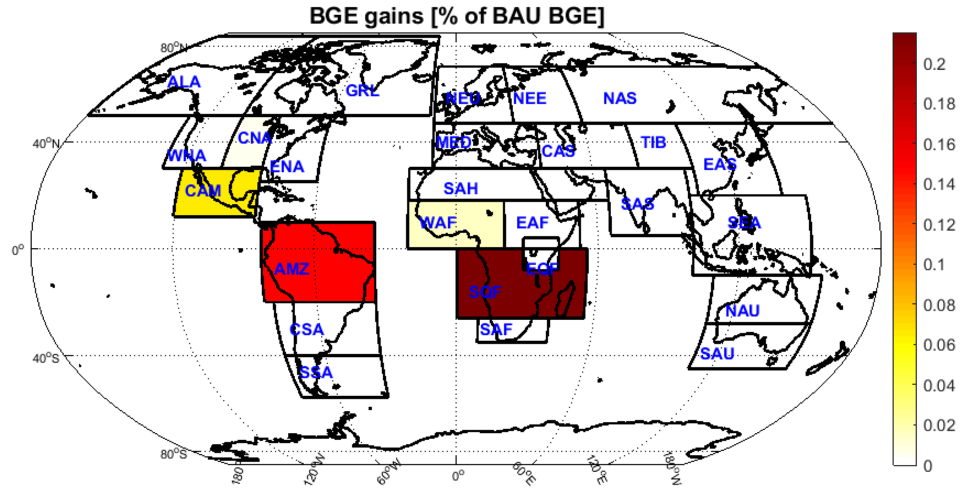


Figure 5. Mitigation costs for a step-wise omission of regional precipitation guardrails. 'TradCEA' is a 2°C policy without SRM usage; 'G0' is a 2°C policy when SRM is included, and all regional precipitation guardrails are active; 5% and 10% denote the fraction of the standard deviation of natural variability as the extra admissible area. BGE values attributed to a region are the loss in comparison to a no policy (BAU – business as usual) scenario, if the analysis is henceforth not constrained by the precipitation guardrails of the respective region. The acronyms of regions are defined in Table 1.



(a) G0 5%



(b) G0 10%

Figure 6. Economic gains from omission on regional guardrails. Darker colors indicate more economic gain per region when the precipitation leaves the respective regional corridor. 5% and 10% denote the fraction of the standard deviation of natural variability as the extra admissible area.

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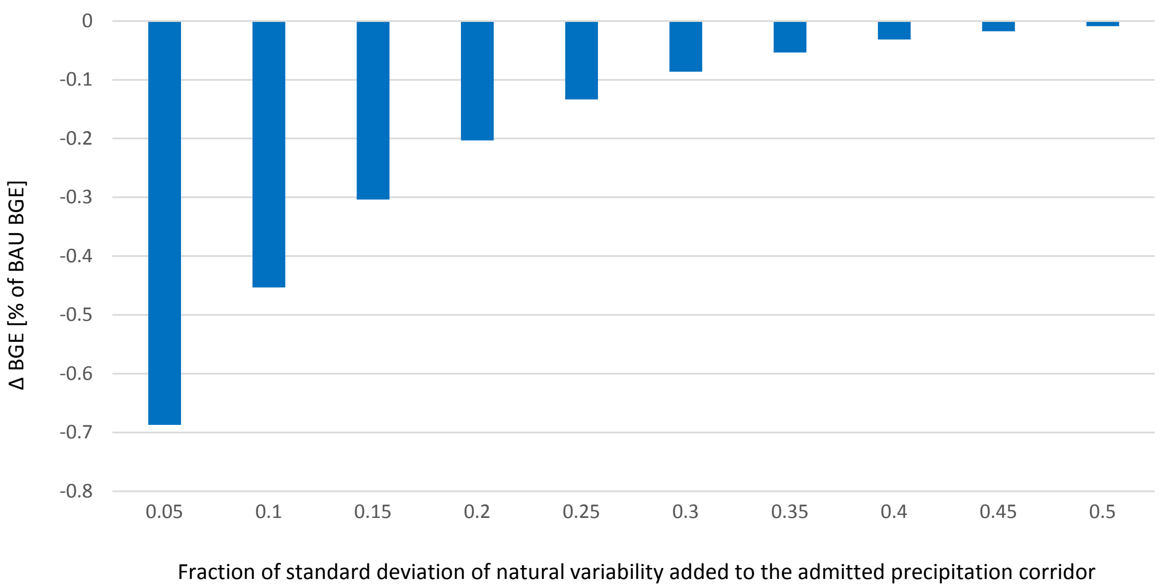

Figure 7. Sensitivity analysis on the fraction of standard deviation of natural variability added to the admitted precipitation corridor. The extra admissible is increased from 5% of the standard deviation of natural variability to 50% of the standard deviation of natural variability. The leftmost two bars (0.05 and 0.1) correspond to the G0 5% and G0 10% in Figure 5.-

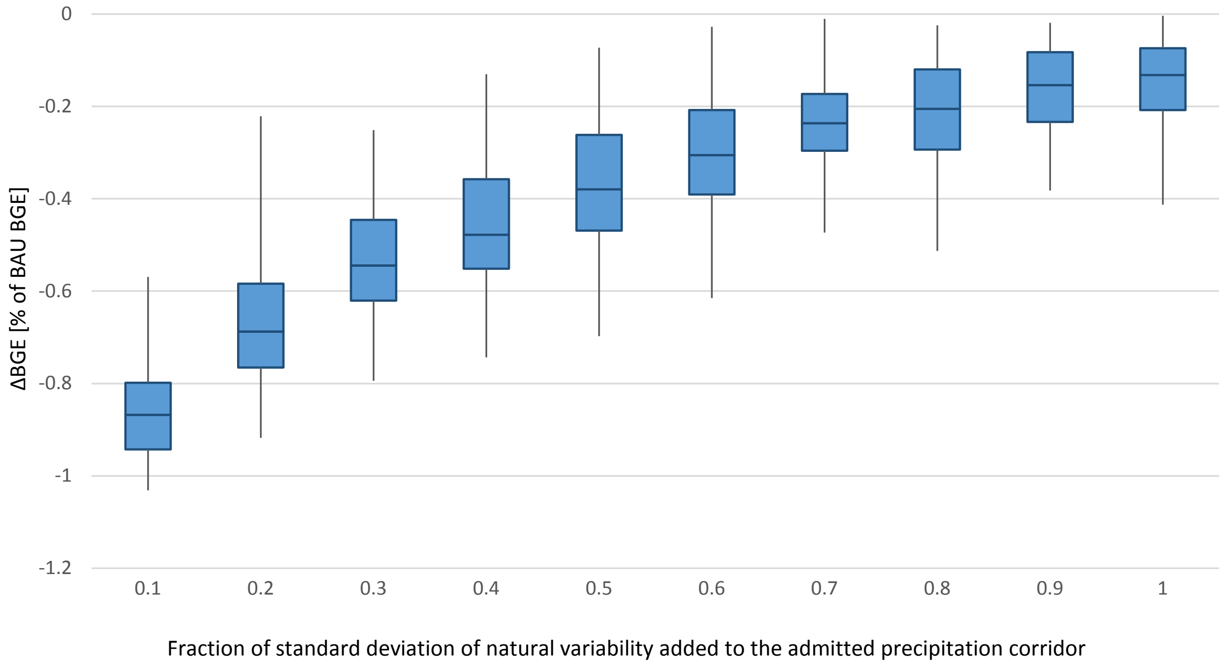

Figure 8. Monte Carlo study of SRM and CO_2 scaling coefficients. The box and whisker plots show ~~T~~the minimum, first quartile, median, third quartile, and maximum BGE losses.~~ are shown in the box and whisker plots.~~ The boxes are drawn from the first quartiles to the third quartiles. The horizontal lines go through the boxes at the medians. The whiskers go from each quartile to the minimums or maximums.

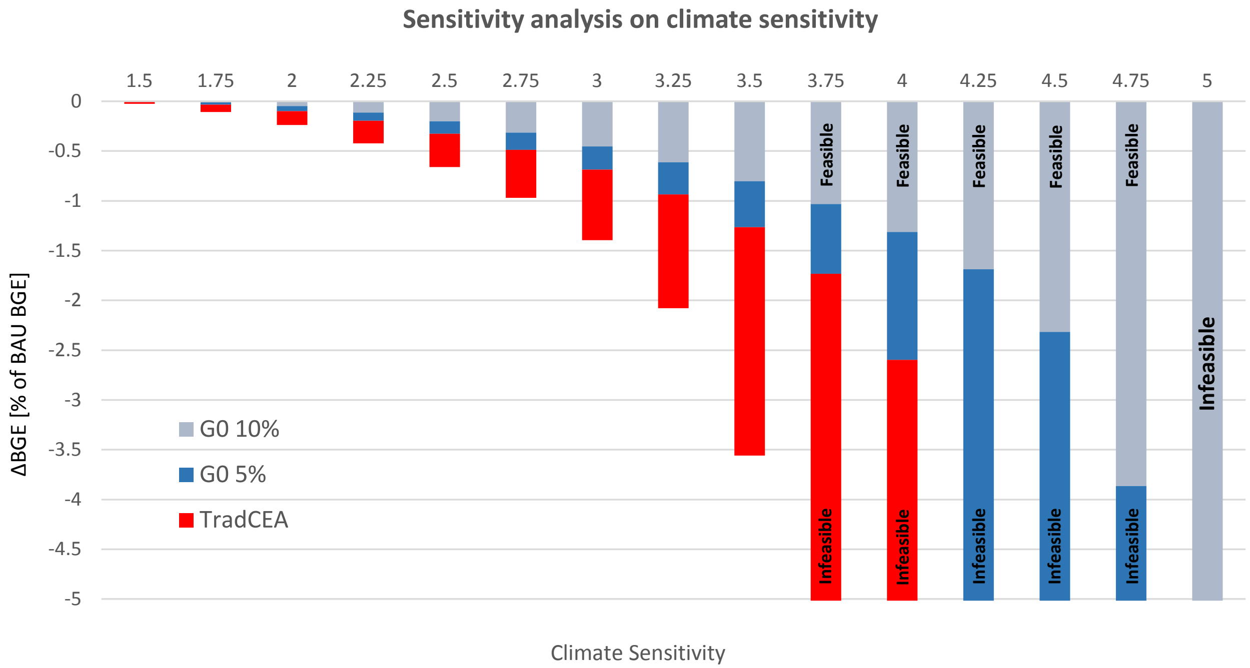

Figure 9. Sensitivity analysis on climate sensitivity. The grey bars show the BGE losses for the G0 10% scenarios. The blue bars show the BGE losses for the G0 5% scenarios. The red bars show the BGE losses for the TradCEA scenarios. For all scenarios, the climate sensitivity ranges from 1.5°C to 5°C.

Appendix

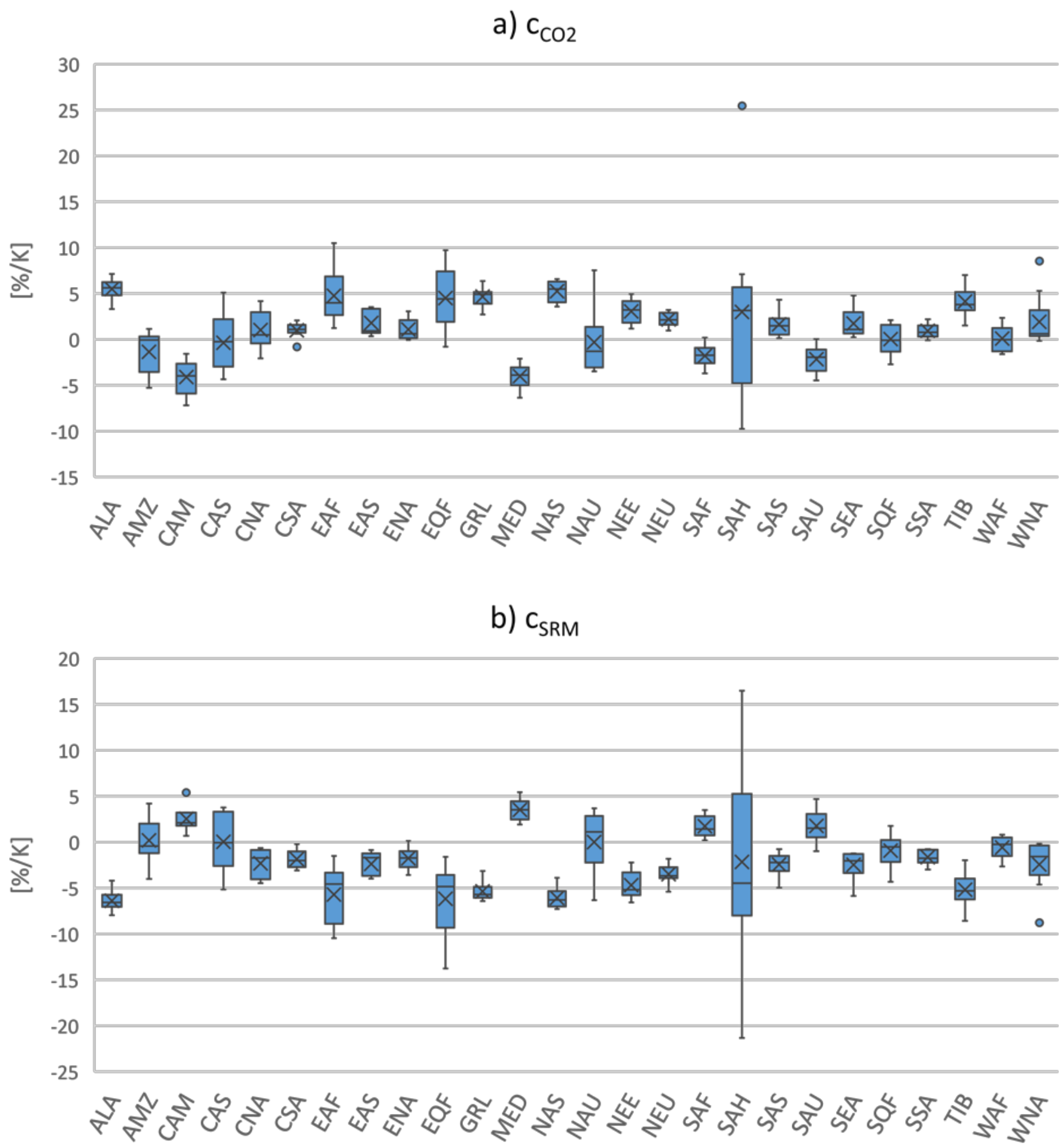

Figure A1. Variation of scaling coefficients for regions from nine AOGCMs. The boxes are drawn from the first quartiles to the third quartiles. The horizontal lines go through the boxes at the medians. The crosses show the averages. The whiskers go from each quartile to the minimums or maximums. The dots represent the outliers.