Trade-offs of 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 main innovation, we present a scheme by which the applicability regime of temperature targets is extended from mitigation-only to SRM-mitigation analyses. Hereby we explicitly account for a risk-risk

5 comparison of SRM and global warming, while minimizing economic costs for complying with the 2°C temperature target. To do so, we suggest precipitation guardrails that are compatible with the 2°C target. Our analysis shows that the value system enshrined in the 2°C target would be almost prohibitive for SRM, while still about half to nearly two-third of mitigation costs could be saved, depending on the choice of extra room for precipitation. 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-

10 offs compared to a mitigation-only future. In addition, in our analysis for climate sensitivities higher than 4°C, SRM will be an unavoidable policy tool to comply with the temperature targets.

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

15 anthropogenically 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 research needs to be complemented by integrated analyses to reflect that the society might take decisions on SRM in view of alternative policy options such as adaption or mitigation. In a non-welfare-optimal setting, Smith and Rasch (2013) studied the role of SRM in

20 conjunction with mitigation for a limited set of pre-defined 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) 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 assumed relatively low compared

5   to mitigation, any meaningful assessment must include a risk-risk trade-off between impacts from SRM against impacts from global warming as the dominant effect. The earlier studies presented trade-off results for stylized impact assumptions within the standard economic paradigm of cost benefit analysis. This is as much as possible in-line with standard economic axioms. But, at the same time, some studies suggest that it is challenging to directly recommend climate policy through only cost benefit analysis, due to the presence of deep uncertainty about impact functions (Ekholm (2018); Kolstad et al. (2014); Kunreuther

10 et al. (2014)). They would suggest 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)).

Although Arino et al. (2016), Ekholm and Korhonen (2016), and Emmerling and Tavoni (2018) evaluated SRM together with mitigation applying CEA, for a true risk-risk consideration, one needs to define an explicit guardrail over side-effects of SRM.

15 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 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.]). The 2°C target encapsulates society's informal risk evaluation of deeply uncertain global warming impacts (Neubersch et al. (2014); Schellnhuber (2010)). Driven by the expectation that in fact costs of transforming the energy system are much more robustly to project than the aggregate impacts

20 of global warming (Stern (2007)), a plethora of economic mitigation analyses has derived cost-minimal energy scenarios which are in compliance with this target (Edenhofer et al. (2014)).

However, when SRM comes into play, global mean temperature is no longer a good proxy for regional climate impacts because SRM imprints patterns of regional precipitation and temperature change that would differ from those induced by greenhouse gas forcing (Kravitz et al. (2013); Oschlies et al. (2017)). Accordingly, and as a key innovation of this article, we

25 suggest extending the regime of applicability of the 2°C target from mitigation only to joint SRM-mitigation portfolios when temperature and precipitation are simultaneously considered. 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 of 'Giorgi regions' (Giorgi and Bi (2005)) and run specific policy scenarios

30 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 details on the innovated guardrails, data, and the numerical model employed. Section 3 presents the results. In Sect. 4, some sensitivity analyses are presented. And, Sect. 5 concludes the paper.

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[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.

2 Methods

2.1 Precipitation guardrails

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

5   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, while keeping the 2°C target in order to reflect those impacts which are not yet formulated in an equivalently explicit manner. Here we ask: '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?' If we were able to confine regional climate change to the intervals of

10   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 could augment the 2°C target by this exact set of intervals as the more fundamental target. Note that here we suggest that the intervals would be generated in the absence of 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 portfolios of SRM and mitigation. Analogous to the original global target, this target also allows for bypassing the

15   criticized monetarization of climate impacts on which a cost benefit analysis is based.

    Figure 1 shows our suggested guardrails for two hypothetical regions r_1 and r_2. r_1 is characterized by a positive CO_2 (Greenhouse-gas-driven) scaling coefficient ($C(r_1, co_2) > 0$) which denotes a positive change in precipitation (P) when the global mean temperature (T) rises. r_2 is, however, characterized by a negative CO_2 scaling coefficient ($C(r_2, co_2) < 0$). The green bands in panel a) and panel b) define the regular admissible area for precipitation change which is compatible with the

20   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 area would totally prohibit SRM use in the regions whose SRM scaling coefficients have the same sign as their CO_2 scaling coefficients. Therefore, an extra area of admissibility is required for any SRM use. For the extra admissible area, we pragmatically suggest adding a fraction of regional standard deviation, derived from inter-annual variability, on both ends. These areas are demonstrated in blue.

25   In this paper, we consider 5% and 10% of inter-annual variability. In Sect. 4.1, we conduct a sensitivity analysis by changing the extra room added to the upper and lower bounds of the guardrails.

2.2 Regional scaling coefficients and natural variability

For the regional resolution, we decide on a spatial resolution in terms of 'Giorgi regions' (Giorgi and Bi (2005)) (see Table 1 and Fig. 2) which brings about a markedly different image from a global average in the sign and magnitude of effects in the

30   climatic variables under scrutiny, and 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.

For the scaling coefficients, we diagnose annual mean regional precipitation changes from linear pattern scaling (Ricke et al. (2010)) which are driven as a linear superposition (Ban-Weiss and Caldeira (2010)) of greenhouse-gas-induced and

5 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 and their sample standard deviation (c_{CO_2} [%/K] and $\sigma_{c_{CO_2}}$) and the average SRM-induced scaling coefficients and their sample standard deviation (c_{SRM} [%/K] and σ_{SRM}) from the nine AOGCMs are shown in Table 1. Figure A1 in the Appendix also shows the variations of scaling coefficients for each region from nine AOGCMs. Obviously, for some regions, the scaling coefficients may switch the sign if a specific AOGCM

10 is considered. Table 1 also shows the ratio $R_r = c_{SRM}/c_{CO_2}$ which is used as an indication for co-effects of SRM and CO_2 that link temperature effects to precipitation effects. All regions are characterized with SRM and CO_2 coefficients that increase or decrease precipitation in opposite directions, and hence 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.

15 An important note here is that, from the average scaling coefficients and their sample standard deviation, one can read that with a normal distribution of scaling coefficients, there are chances that the signs of scaling coefficients in some regions switch. Therefore, it is also likely that for some regions R_r becomes positive 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.

20 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 subtract a parabolic fit of the time evolution from the time series. From the thereby detrended

25 data we determine the inter-annual precipitation time variances ($\sigma_{r,s}^2$). For each region r we average means and variances across all data sets s to obtain σ_r^2 and μ_r. Finally the standard deviation of natural variability in percent is obtained by $100\,(\sigma_r/\mu_r)$. The last column in Table 1 expresses the derived regional natural variability.

2.3 Model

For our joint SRM-mitigation analysis we utilize the integrated energy-economy-climate model MIND (Edenhofer et al.

30 (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

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

[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.

(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, it serves as one of the simplest possible models to project mitigation costs in a realistic manner and to a great deal can serve as a pedagogic model to mimic the most important

5 economic-climatic aspects that are under investigation. We further extend the model to include a spatially-explicit resolution in terms of 'Giorgi regions' (Giorgi and Bi (2005)). In addition, we upgrade the model to include SRM as a control. We assume a reduction of the solar constant as a good approximation (Kalidindi et al. (2015)) of sulfur aerosol injection that is currently discussed as the most feasible SRM scheme. As cost of SRM we took the joint upper end of the costs reported in The Royal Society's Report on Geoengineering the Climate (Shepherd (2009) and Klepper and Rickels (2011)): 0.02% gross world prod-

10 uct as of 2010 per W/m^2. This 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 (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 the time scale of the climate module has a strict rela-

15 tionship 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) tested the validity of a one-box climate model as an emulator for fourteen 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 being trained according to the AOGCM's equilibrium and trasient climate sensitivity and a certain time horizon (on the order of the time to peak radiative

20 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 conduct a sensitivity analyses by altering the climate sensitivity.[4]

3   Results

Figure 3 shows normalized precipitation change for the 26 Giorgi regions for a): no-policy case (business as usual scenario

25 ('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 precipitation such that '1' is the constraint which corresponds to the precipitation levels of a temperature anomaly of 2°C and '0' equals the other constraint, which is determined by the preindustrial precipitation levels

30 (see Sect. 2.1 for more details on the guardrails). Note that in the calculation of the normalized precipitation for G0 5% and G0 10% the extra admissible areas are taken into account. We indicate this corridor as grey band in Fig. 3. Figure 4 displays the resulting effects on global mean temperature for temperature response to 'CO$_2$-forcing' (dotted lines), SRM-forcing (dashed

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

lines), and the sum of both (solid lines) 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)).

5 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), with unrestricted SRM usage, the CO_2-contribution would mimic BAU, and SRM would totally compensate for an
overshoot of 2°C. However, for about half of the regions, precipitation transgresses the 2°C-compatible precipitation corridor
(see Fig. 3 (b)).

10 Now we activate the precipitation corridor for any of the regions (G0 scenarios). By construction, for any 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% is touched 15 years earlier, which is due to the slimmer admissible area in G0 5% as
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. Hereby temperature anomaly peaks at 2°C
15 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)).

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, the paths mimic a BAU development (compare 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, normalized
20 precipitation declines. (iii) For one region, either the upper ('1') or lower ('0') normalized precipitation guardrail is touched
and activated. In the course of time, for several regions normalized precipitation evolves towards the guardrails (either '0' or
'1') and simultaneously global mean temperature decreases. (iv) For a different region, the normalized precipitation guardrail
is touched and the system becomes quasi-stationary.

The first binding region is 'AMZ' (Amazonia, see Fig. 2). Here it is characterized by a negative c_{CO_2} and positive c_{SRM}
25 with comparatively small modulus. 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,
once precipitation in 'AMZ' reaches the upper boundary of regional normalized precipitation levels (phase 3), any CO_2-induced
change in AMZ's precipitation needs to be compensated for by an SRM-induced contribution. As AMZ's scaling coefficient
30 has a small modulus, 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 effects on global mean temperature. Finally, one of the regions with larger, yet negative scaling coefficient ratios
(in this case 'SQF' (South Equatorial Africa)) would hit the lower bound, triggering phase 4. Therefore, the 'G0' scenario is
characterized by the interplay of scaling coefficients and precipitation standard deviations of two regions.

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 Balanced Growth Equivalent (BGE) values attributed to a region are the loss in comparison to the BAU scenario, if the analysis is henceforth not constrained by the precipitation guardrails of the respective region. The acronyms of regions are defined in Fig. 6. The economic losses (disregarding

5   impacts) induced by a 2°C policy without SRM usage is displayed by the leftmost bar (hereafter we call it 'TradCEA'), then for SRM included when all regional precipitation guardrails are active (G0), and continued with 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)). From the graph we read that 2/5 and 3/5 of mitigation costs could be saved respectively in G0 5% and

10   G0 10%. For someone who interprets mitigation costs as large, this could be an argument for employing SRM. For someone who perceives the scale of 1% GWP loss as small, the cost of mitigation would not provide 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

15   respectively in G0 5% and G0 10%. If one interprets the 2°C target as an (academically informed) political target that does not represent a singular global threshold (Neubersch et al. (2014)), society might want to discuss whether a modest transgression of the target to extents of, for examples, 0.1°C and 0.3°C, could be seen as acceptable in view of 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 regional precipitation corridors has proven almost prohibitive for SRM.

20   However, if the society is willing to successively disregard the step-wise (economically) most binding corridor boundary, and hence to 'sacrifice' the region that would induce the largest economic welfare gain, the picture can gradually change. Progressively, more economic gain could be harvested (see Fig. 5, further right bars). From one bar to the next, the guardrail of that very region is omitted that would deliver the largest economic welfare gain. Figure 6 indicates the economic gain per region when precipitation is allowed to leave the respective corridor. Similar for both G0 5% and G0 10%, the order of the first

25   four regions whose guardrail should be omitted to gain the most are AMZ, SQF, CAM, and WAF. However, while for G0 10% these four regions are followed by CNA, MED, and CAS, in G0 5% CAS, CNA, and SAH follow. Note that the precipitation change in other regions are already within the guardrails in the REF scenario, and hence, there is no need for omission of their guardrail to gain more welfare (see Fig. 3). Notably, even not so significant for the analysis regarding the welfare gains, the order of regions depends on the decision about the extra room for guardrails, as shown in panel a) and b). The reason behind

30   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 addition, if such extra room 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%, and the BGE loss when the extra room is 5% of natural variability and AMZ is omitted is nearly double the cost for the same scenario when the extra room is 10% of natural

35   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 assumptions and investigate the likely alternative scenarios.

4.1 Extra room as a fraction of natural variability

5 Figure 7 depicts the BGE loss (%) for G0 scenario when the the share of natural variability as the extra room varies from 0.05 (5%) to 0.5 (50%). Note that 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. Expectedly, with the higher extra rooms, the BGE loss decreases such that when extra room is 50% of the 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 room, but it is convex. That is, for example, while the decrease in BGE loss
10 is about 0.25% when the extra room changes from 0.05 to 0.1, the decrease in the BGE loss will amount only to nearly 0.15% when the extra room 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 regions change.

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
15 in the G0 scenario. However, the scaling coefficient may vary based on which AOGCM data they are derived from. The results in Sect. 3 were derived from the average value of scaling coefficients from nine AOGCM. These data can 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 natural variability to 100% of natural variability. In each G0 scenario, the
20 sign of some scaling coefficients as well as the binding regions in the four phases can be different.[5]

According to the Monte Carlo study, it is more likely that the random variation of 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%, the median of BGE loss in the Monte Carlo study can reach to about 0.85%. In addition, with the higher extra rooms, the median of the BGE loss decrease. However, similar to its deterministic case, a
25 decrease in median of the BGE loss is convex. Therefore, although for an extra 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 other words, if the precipitation guardrails are considered, the likelihood that SRM being used may still be low if no region's guardrail is about to be omitted. Note that the decision about SRM being 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
30 and global tmeperature increase.

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

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 sensitivity, BGE loss for the G0 5%, G0 10%, and TradCEA scenarios increase rapidly. The 2°C target is not attainable without

5   the use of SRM when the climate sensitivity is equal and higher than 3.75°C. 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 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 study where SRM and mitigation act as substitutes in idealized policy scenarios of immediate action. Without risk-risk accounting, SRM would crowd out mitigation due to comparatively low costs, thereby lowering the costs of achieving the 2°C target to a negligible value (compared to the original mitigation costs). However, if only one single regional climate variable (in our case 'precipitation') is confined to regional bounds compatible with 2°C of global warming

15   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 0.1°C to nearly 0.3°C of further global warming. Society might debate whether for that rather small amount of allowed additional carbon emissions, the risks of SRM should be taken. However, a significantly larger role for SRM would be possible in case the guardrails of a few regions were relaxed. The ordering of regions presented in this article might provide

20   a way to support the then necessary trade-off to what extent relaxing 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 see SRM and mitigation as complements if a global climate policy were put in action only within decades. The

25   results showed that in our model the 2°C target is not attainable without the use of SRM when the climate sensitivity is equal and higher than 3.75°C. Then we would necessarily need some sort of climate engineering in order to comply with the 2°C target. If the potential for carbon dioxide removal was exhausted, some amount of SRM would become indispensable if the 2°C target still should be complied to. Nonetheless, the feasibility space depends on the extra room in the guardrails. The tighter the extra rooms on the upper and lower bounds of the precipitation guardrails, the earlier the use of SRM become useless to

30   comply with the targets.

We need to point to a series of caveats of the analysis. The assumptions made in the construction 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 a decision

about SRM use. Yet, by employing a Monte Carlo study, we showed that it is more likely that the random variation of scaling coefficients results in larger economic losses when all temperature and precipitation targets are active. Furthermore, annual mean precipitation is only one possible driver of regional impacts in addition to temperature or evaporation, or intra-annual changes. Finally, our model does not include carbon dioxide removal options yet. Hence above-mentioned economic gains

5   through SRM must be interpreted as upper limits of costs savings.

Here we demonstrate that someone who pushes for SRM in view of the 2°C target should carefully consider the consequences this target would have when extended to SRM. Already a single climate variable (such as precipitation) when explicated regionally almost completely bans SRM from a joint SRM-mitigation portfolio.

DATA

10   The output of nine AOGCMs were supplied by the scientists from GCESS, Beijing Normal University (John Moore's Group).

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. opti-

15   mized 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. calculates 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 M.M.K wrote most of this report.

20   **Competing interests**

The authors declare that they have no conflicts of interest.

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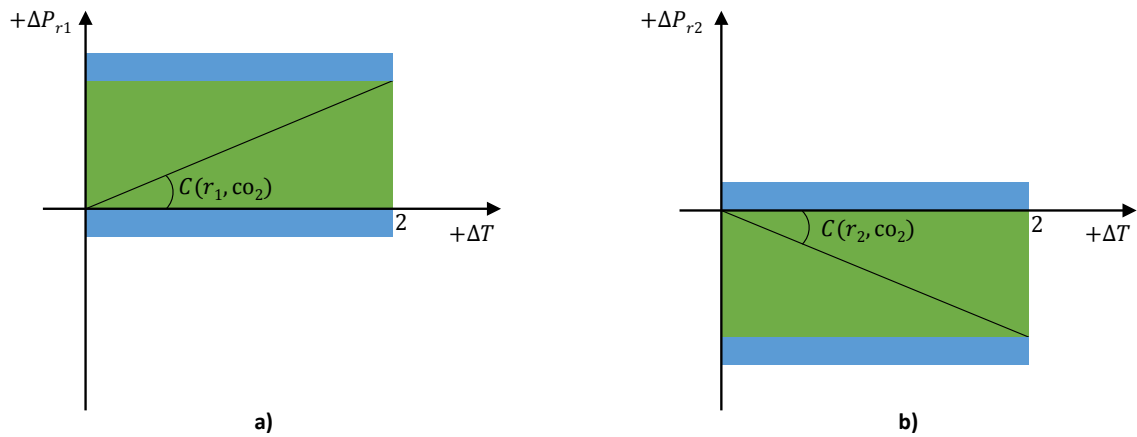


Figure 1. Schematic of precipitation guardrails for two hypothetical regions r₁ and r₂. r_1 is characterized by a positive CO_2 (Greenhouse-gas-driven) scaling coefficient ($C(r_1, co_2) > 0$), and r_2 is characterized by a negative CO_2 scaling coefficient ($C(r_2, co_2) < 0$). The green bands in panel a) and panel b) define the regular admissible area for precipitation change. The extra admissible areas are demonstrated in blue.

	Giorgi region	c_{CO_2} [%/K]	$\sigma_{c_{CO_2}}$ [%/K]	c_{SRM} [%/K]	$\sigma_{c_{SRM}}$ [%/K]	$R_r = c_{SRM}/c_{CO2}$	σ_{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.

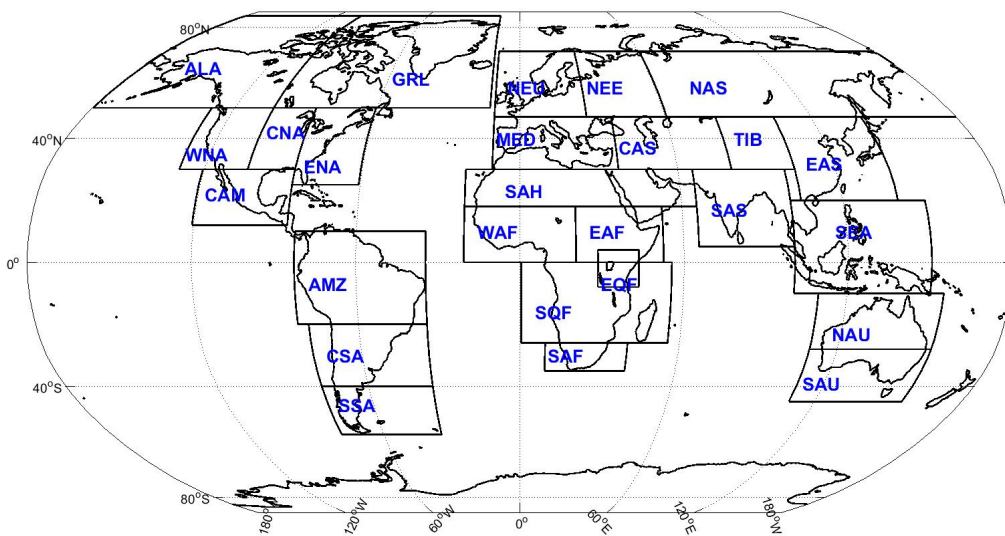



Figure 2. Spatial resolution of our analysis. 'Giorgi regions' Giorgi and Bi (2005).

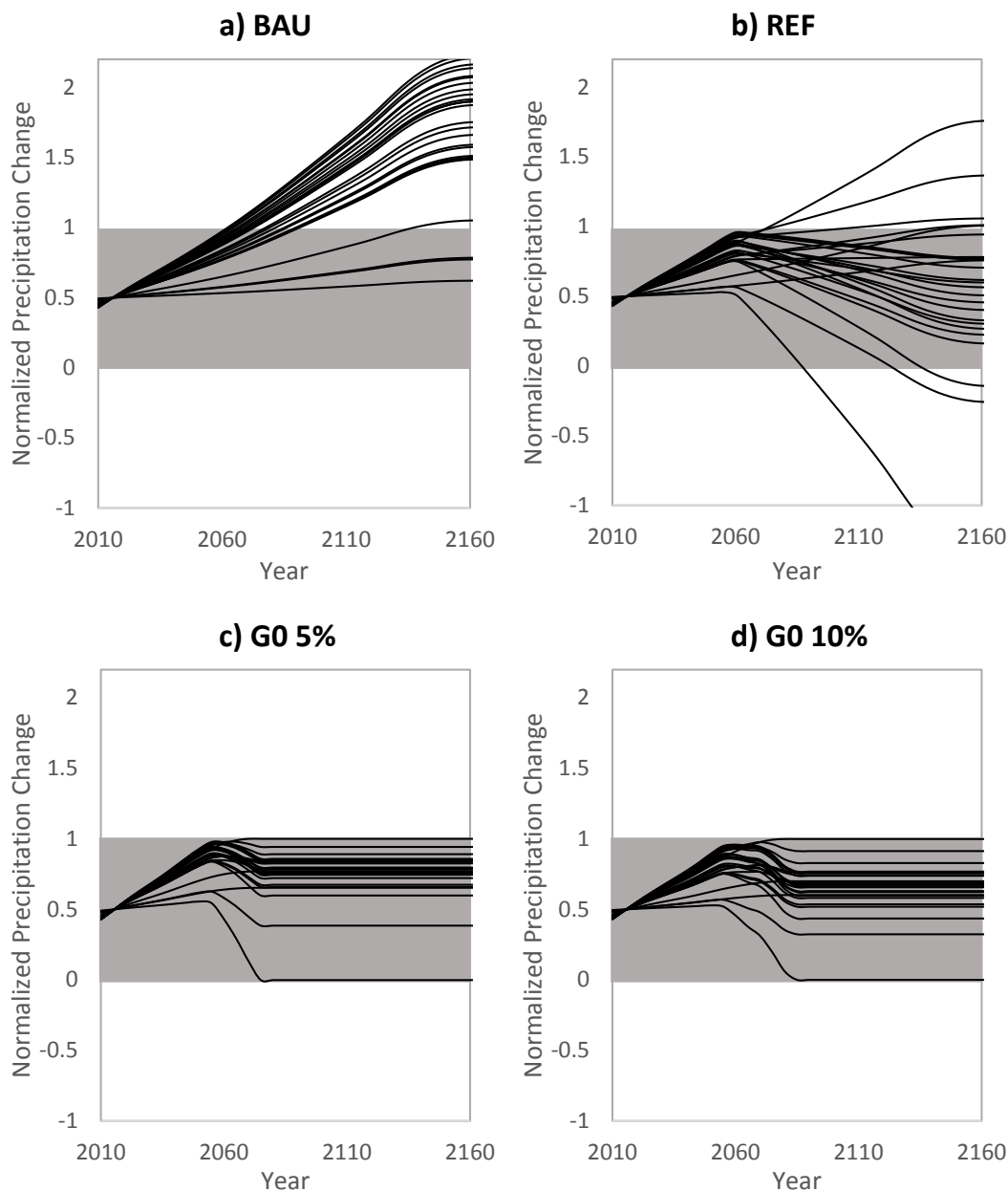



Figure 3. Normalized precipitation change. For the 26 Giorgi regions and different policy scenarios, precipitation change is normalized such that '1' is the constraint which corresponds to the precipitation levels of a temperature anomaly of 2°C (induced by CO_2 plus a fraction of standard deviation), 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%')

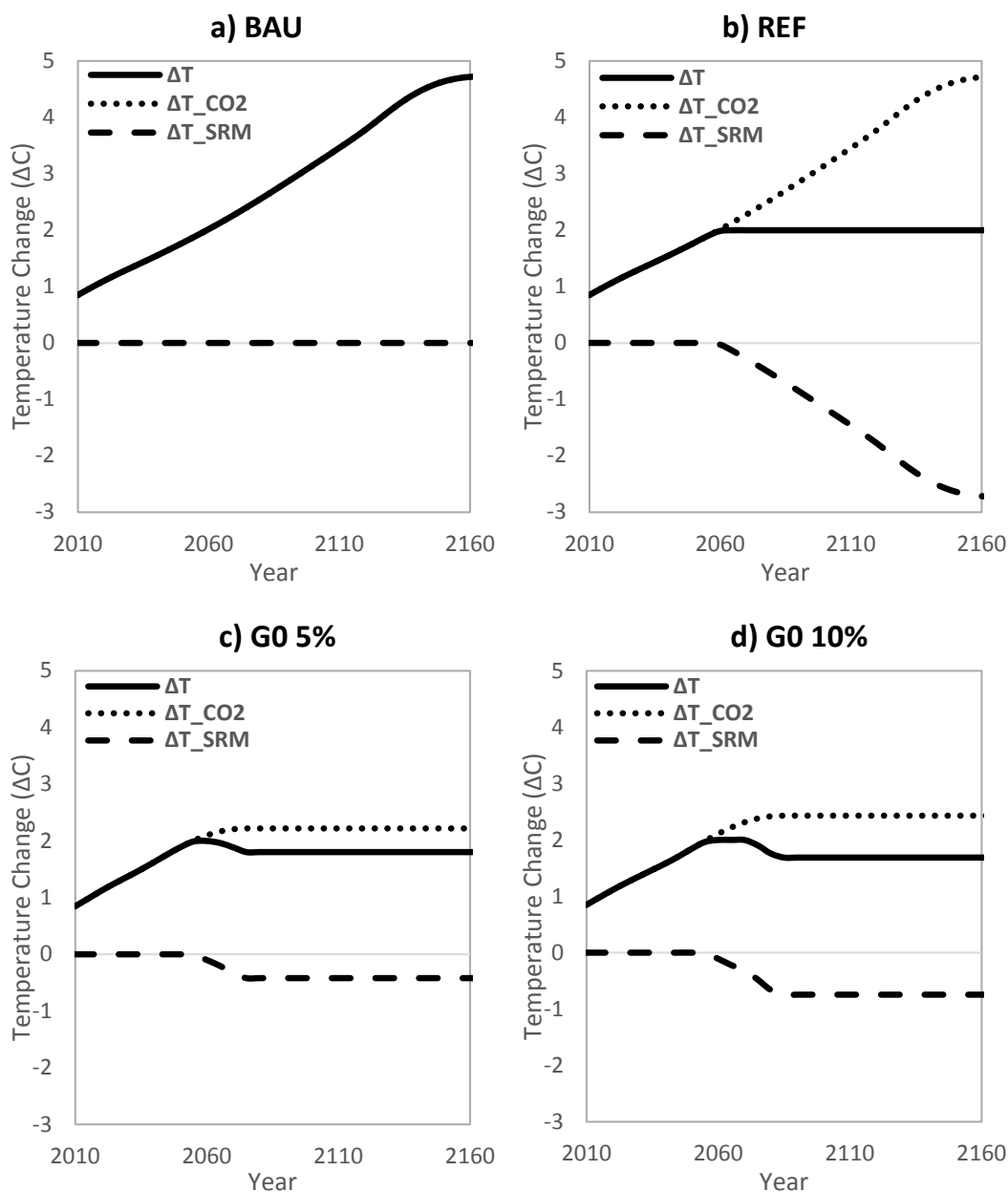



Figure 4. Global mean temperature response to SRM and carbon dioxide forcing. Dotted lines are the resulting effects on global mean temperature for temperature response to CO_2-forcing; The dashed lines are the resulting effects on global mean temperature for temperature response to SRM-forcing; the 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%')

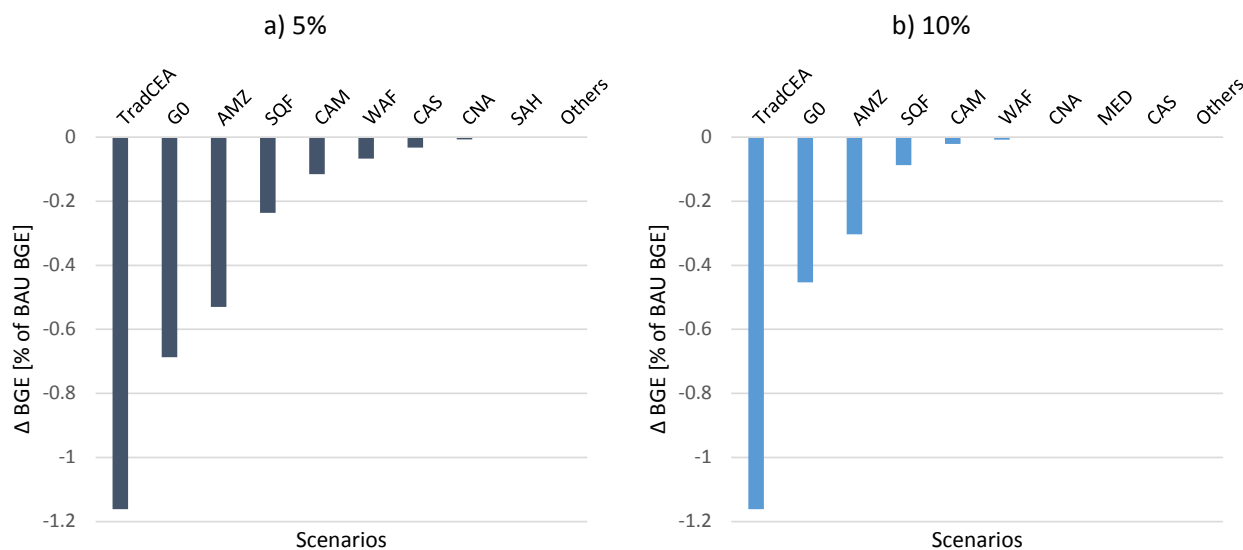



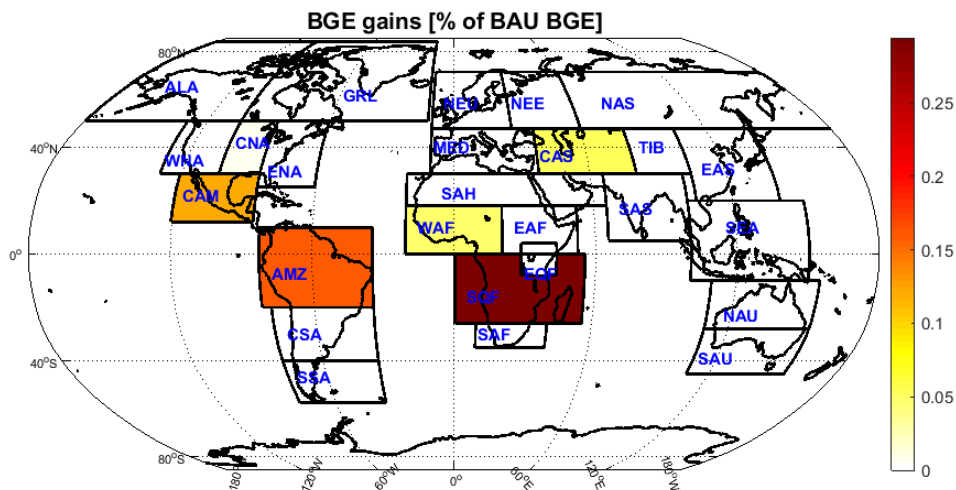
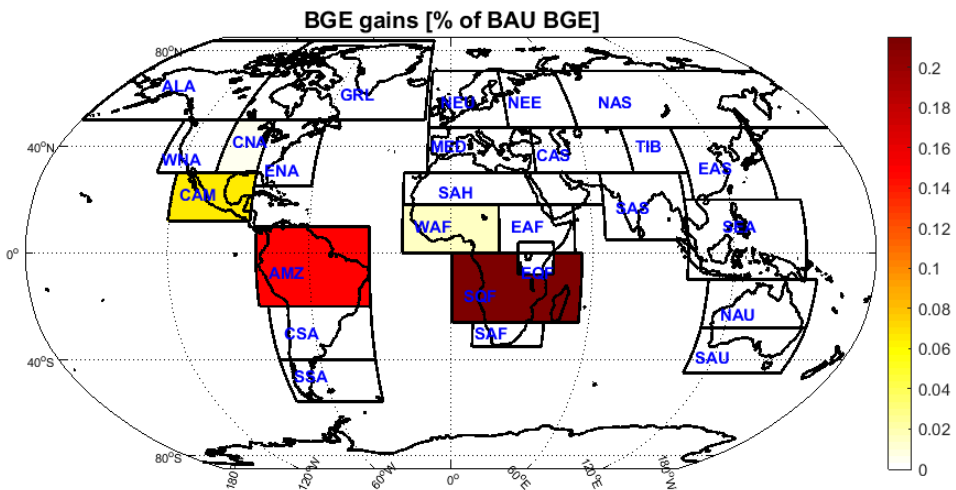
Figure 5. Mitigation costs for a step-wise omission of regional precipitation guardrails. 'TradCEA' is a 2°C policy without SRM usage; 'G0' is a 2°C policy when SRM is included and all regional precipitation guardrails are active; BGE values attributed to a region are the loss in comparison to a no policy (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.

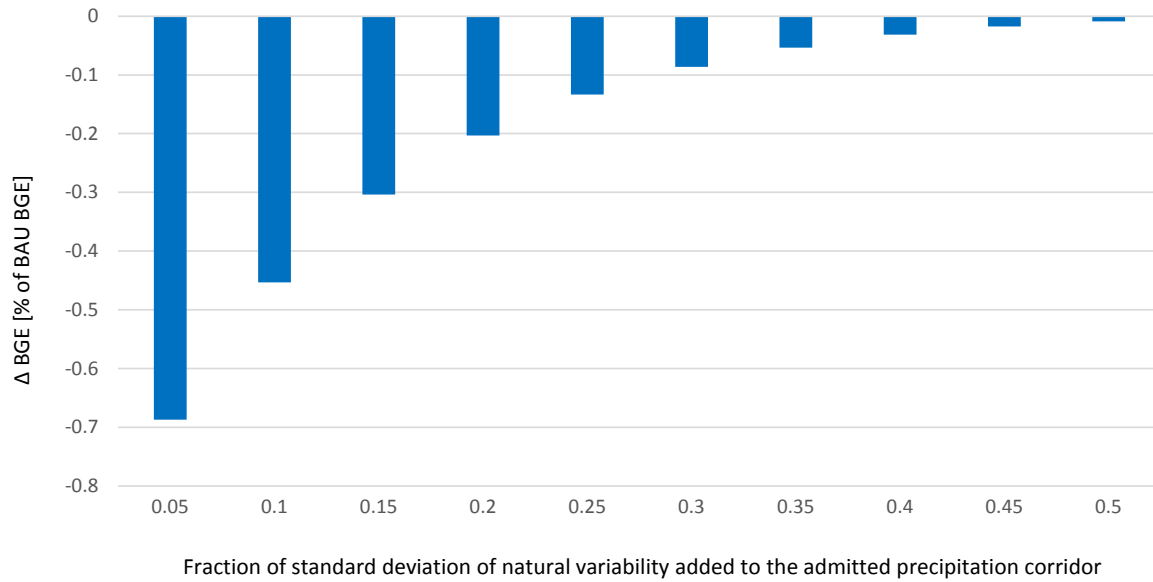



Figure 7. Sensitivity analysis on fraction of standard deviation of natural variability added to the admitted precipitation corridor.

Fraction of standard deviation of natural variability added to the admitted precipitation corridor

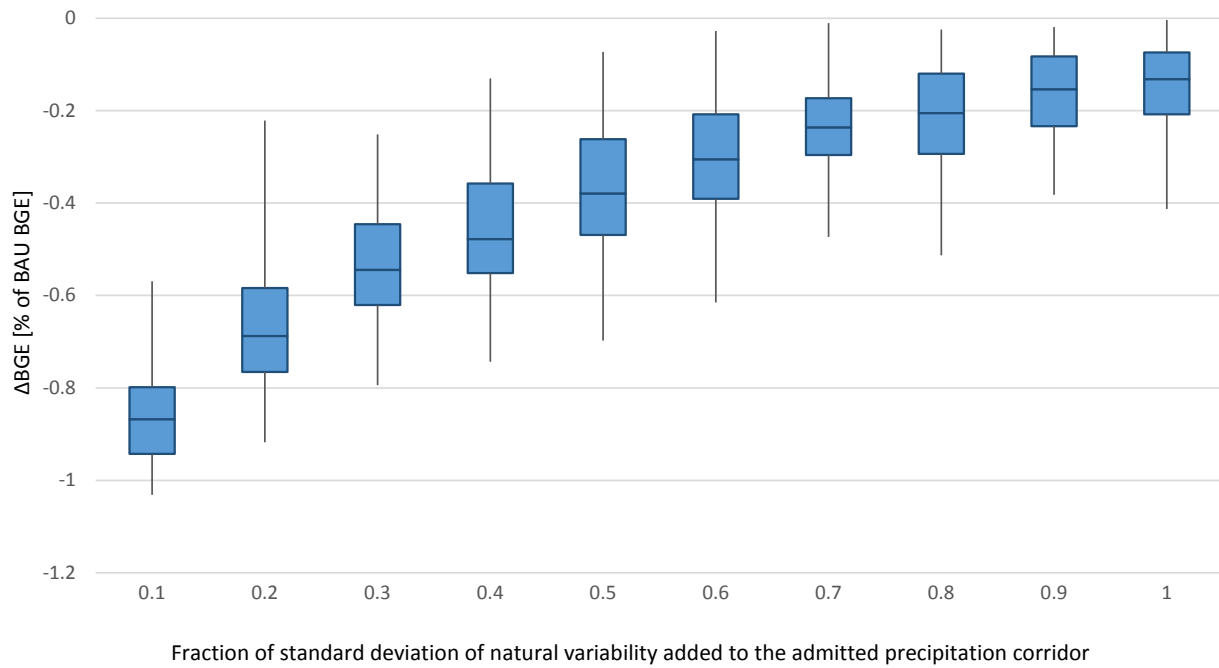



Figure 8. Monte Carlo study of SRM and CO₂ scaling coefficients. The minimum, first quartile, median, third quartile, and maximum are shown in the box and whisker plots. The boxes are drawn from the first quartiles to the third quartiles. The horizontal lines go through the boxes at the medians. The whiskers go from each quartile to the minimums or maximums.

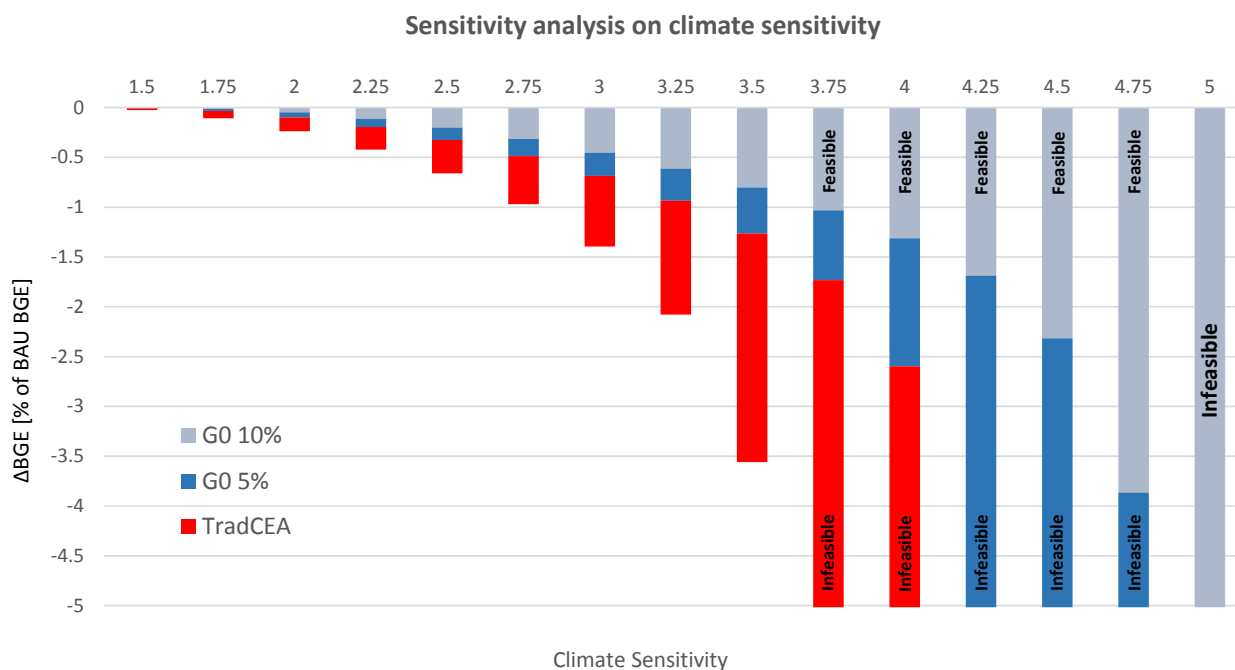



Figure 9. Sensitivity analysis on climate sensitivity. The grey bars show the BGE losses for the G0 10% scenarios. The blue bars show the BGE losses for the G0 5% scenarios. The red bars show the BGE losses for the TradCEA scenarios.

Appendix

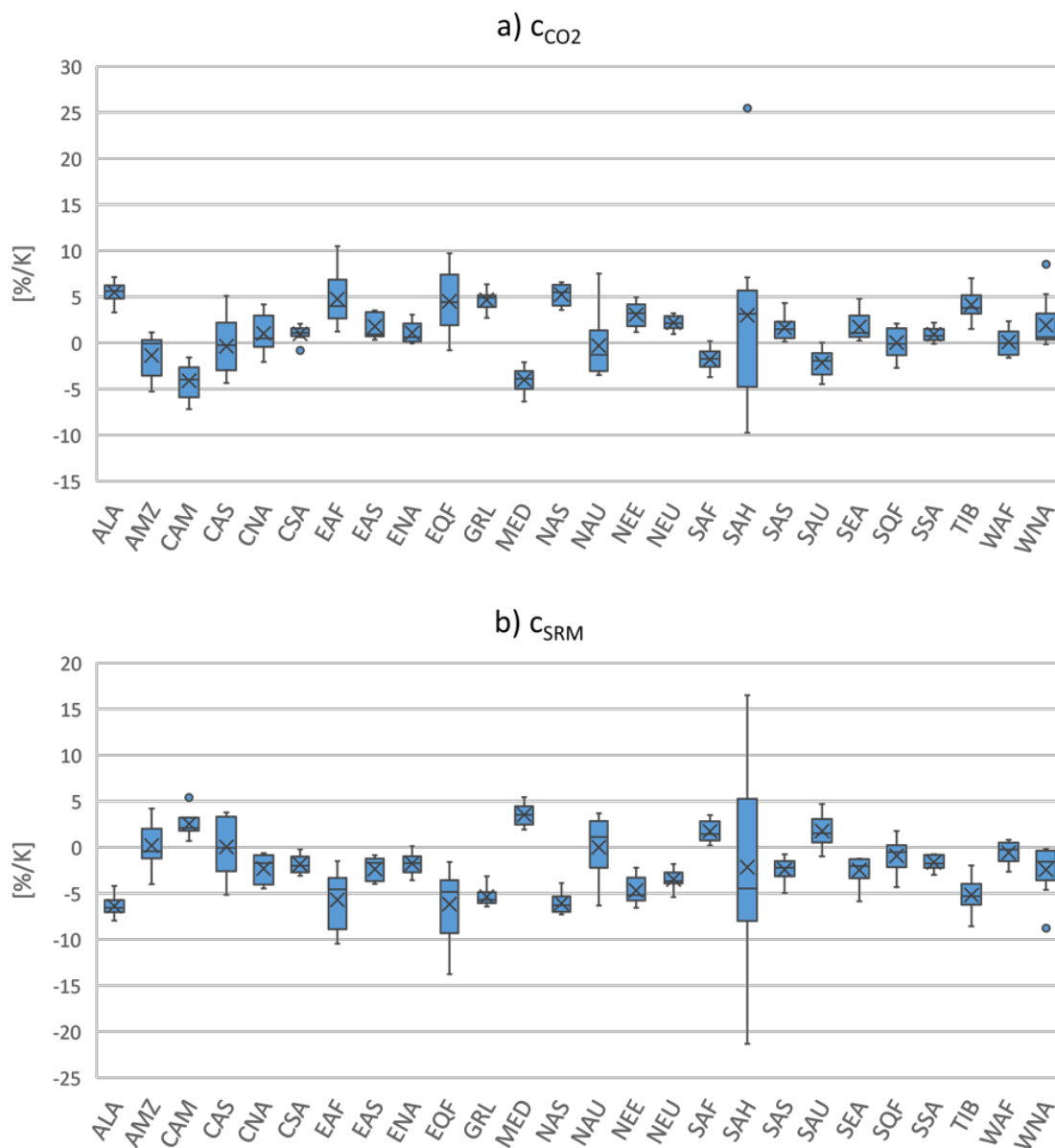



Figure A1. Variation of scaling coefficients for regions from nine AOGCMs. The boxes are drawn from the first quartiles to the third quartiles. The horizontal lines go through the boxes at the medians. The crosses show the averages. The whiskers go from each quartile to the minimums or maximums. The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