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Regional Disparities in Solar Radiation Management Impacts: Limitations to Simple Assessments and the Role of Diverging Preferences

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Abstract

Solar radiation management (SRM) has been proposed as a potential method to reduce risks from global warming. A widely held concern about SRM, however, is that its climate effects will be unevenly distributed in space. Recent research has used climate model projections to quantitatively assess how regional disparities affect the overall efficiency of global SRM and what the resulting potential for cooperation and conflict with regard to SRM may be. First results indicate that regional disparities, although present, may not be severe. We challenge this finding by reconsidering some of the simplifying assumptions made in existing assessment studies. Our main focus is the prevalent assumption in SRM research that, for all regions, any deviation from a past climate state inflicts damages. While climate change will have negative implications for most people and ecosystems around the world, it is plausible that some actors will have different preferences as regards how much climate change ought to be compensated by SRM. Using an illustrative two-region model, we show that even limited variation in actors' preferences about a target climate state can significantly change assessments of regional disparities from SRM. We also discuss other common simplifications regarding the design of damage indicators, spatial aggregation, and the neglect of uncertainties, which could have equally strong implications. We therefore suggest that current research results do not allow us to draw conclusions about the socio-political implications of regionally diverging effects of SRM. Research should pay more attention to the difficulty of assessing impacts based on climate model projections and to the general limitations of simple assessment frameworks.

Content

1. Introduction

Human-induced global warming will pose risks to an increasing number of people and ecosystems around the world (IPCC 2014). Particular concerns have been raised about the possibility of crossing thresholds, shifting key sub-systems of the earth into a qualitatively different state. Examples include the destabilisation of the Greenland ice sheet, a dieback of the Amazon rainforest, or changes in the amplitude and frequency of El Niño events (Lenton et al. 2008). In order to avoid such dangerous and irreversible climate change, the international community has formulated the goal to limit global mean temperature rise to 2°C (UNFCCC 2009). However, given the lack of progress in negotiating a binding international agreement to curb emissions of greenhouse gases, it is uncertain whether this goal can be attained. In fact, global emissions have been accelerating – CO_2 levels increased more between 2012 and 2013 than during any other year since 1984 (World Meteorological Organization 2014). The bleak outlook with regard to preventing dangerous climate change by cutting emissions has recently led to an intensified debate about the potential of various geoengineering measures to reduce some of the risks of climate change (Keith 2013; Hulme 2014; Wood et al. 2013). The IPCC defines geoengineering as "[m]ethods that aim to deliberately alter the climate system to counter climate change". This definition includes 'Solar Radiation Management' (SRM) methods, i.e. technologies that would reduce incoming solar radiation, for instance, by dispersing stratospheric aerosols or whitening marine clouds (IPCC 2013).

Recent research suggests that SRM, if technically feasible, could provide global cooling at short timescales, but cannot restore previous climate conditions due to differences in the radiative forcing patterns from greenhouse gases and SRM (Ricke et al. 2010; MacMartin et al. 2012). The effects of SRM on regional climates will thus vary, raising issues of distributional justice and increasing the potential for conflict between 'winners' and 'losers' (Victor et al. 2009; Weitzman 2012; Preston 2012). To assess the implications of an uneven distribution of climate effects, several studies have translated modelling outcomes into measures of regional disparities (Moreno-Cruz et al. 2012; Ricke et al. 2013; Ferraro et al. 2014; Kravitz et al. 2014). The results of this research indicate that although disparities are to be expected, they may not be as much of a concern as has been suggested previously (Moreno-Cruz et al. 2012; Ricke et al. 2013).

Assessments of regional disparities require simplifying assumptions, for instance, about the relation between projected climate change and its impacts, the subdivision of the world into regions, or the consideration of uncertainties. In the following, we will focus on one particular assumption that has remained largely unconsidered in SRM research so far, but may have considerable effects on discussions of regional disparities: the relation between change and damage. Most research on SRM implicitly or explicitly assumes that past climate conditions would be the optimal point for all regions. In other words, any regional deviation from past climate conditions is assumed to be detrimental, making a past climate state the target for an SRM intervention. We argue that this assumption may not hold. Even though it is pertinent to assume that continuous climate change will have negative effects for most regions and people around the world, there may be disagreement about how much climate change should be compensated, since a limited deviation from past climate conditions may be judged as advantageous by some. Using a simple model, we show that relaxing the assumption that any change in climate conditions is bad can have significant implications for assessments of regional disparities.

In the following section 2, we review existing assessments of regional disparities due to SRM and question the prevalent assumption that in any region any deviation from a past climate state causes damages. We call this assumption the (strong) change-is-bad paradigm. In section 3, we use a standard assessment framework to illustrate that relaxing this assumption may substantially alter conclusions about SRM's ability to reach climate targets and bring about agreement among different actors. Section 4 critically discusses other simplifications usually made in assessments of SRM and points to the limited informative value of simple assessment frameworks. We conclude in section 5.

2. Reconsidering the change-is-bad paradigm in SRM research

SRM cannot restore past climate conditions. Even if SRM were able to offset the entire human-induced radiative forcing that results from increased CO_2 levels, it would not be possible to turn back climate indicators such as precipitation or temperature in all regions at the same time. The reason is a divergence of the (longwave radiation) warming pattern of CO_2 and the (shortwave radiation) cooling pattern of SRM (Govindasamy and Caldeira 2000; Lunt et al. 2008; Ammann et al. 2010; Kravitz et al. 2013). This divergence in radiative forcing patterns would lead to spatial differences in the climate effects of SRM, and the potential for regional disparities in SRM impacts has been a major argument against SRM (Robock 2008; Royal Society 2009). Two issues related to regional disparities have been examined in the literature. Firstly, against the background of different effects in different parts of the world, one can ask what a global optimal intensity for SRM would be, i.e. an intensity that would minimise overall global damages from climate change (Ricke et al. 2012; Moreno-Cruz et al. 2012; Ferraro et al. 2014). Secondly, regional disparities in SRM impacts may produce 'winners' and 'losers' and would thus impact the potential to reach agreement amongst different actors about a particular SRM strategy (Schneider 1996; Boyd 2009; Barrett 2014).

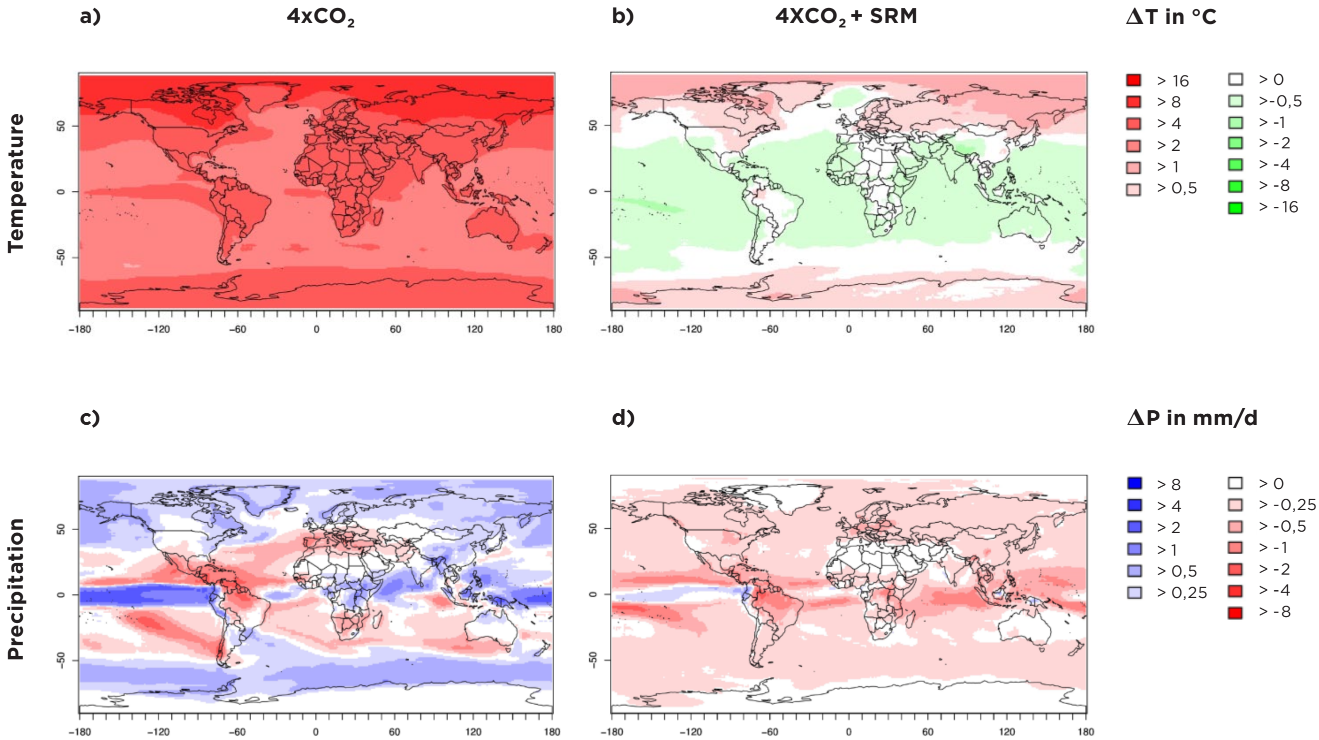

Figure 1: GeoMIP modelling results (Kravitz et al. 2011, 2013) for temperature (top panels) and precipitation (bottom panels) responses to $4xCO_2$(left panels) and additional SRM (right panels).

A look at climate modelling results can provide a first qualitative overview of the potential for regional disparities in SRM impacts. The plots in figure 1 are based on simulations of the Geoengineering Model Intercomparison Project (GeoMIP) (Kravitz et al. 2011, 2013). They show typical temperature (top panels) and precipitation (bottom panels) anomalies in the case of quadrupled CO_2 (left panels) and additional SRM (right panels). While these results indicate that temperature and precipitation anomalies (over land) could potentially be significantly reduced, this compensation is imperfect, in particular for precipitation. In order to evaluate SRM's ability to attenuate regional disparities more systematically, different frameworks have been proposed for the quantitative assessment of regional disparities (Ban-Weiss and Caldeira 2010; Moreno-Cruz et al. 2012; Kravitz et al. 2013, 2014). The results suggest that the compensation of climate impacts with SRM is imperfect, but reasonably good, and that temporally and spatially heterogeneous deployment schemes may further reduce regional disparities (MacMartin et al. 2012).

These assessment frameworks make simplifying assumptions, for instance, about the relation between environmental changes and impacts, the regions to be considered, and the relevance of uncertainties (see section 4). An important common assumption in existing assessments of regional disparities due to SRM is the assumption that a previous climate state, for example preindustrial, is the optimal climate configuration. As a consequence, every deviation from this configuration is counted as damage. More precisely, all the assessment studies mentioned above assume that (regional) damages are quadratic in temperature and precipitation deviations from past values. In this view, an optimal SRM implementation would minimise the sum of squared deviations from a past climate state. While some studies have used alternative ways of measuring damage, they still follow the assumption that any change from a baseline configuration is detrimental (Ricke et al. 2012; Ferraro et al. 2014).[1] We dub this dominant assumption in the SRM literature the (strong) *change-is-bad paradigm*.

Climatic changes are threatening an increasing number of people and ecosystems worldwide and there is no reason to question the fact that limiting climate change by significantly reducing global emissions of greenhouse gases is necessary and pertinent (IPCC 2014). The main reasons why changes in climate conditions are detrimental stem from the fact that existing ecosystems and socio-economic systems are well adapted to existing conditions and that change, especially rapid change, can cause serious disruptions to those systems. However, this does not mean that the strong change-is-bad paradigm used in the SRM literature will hold in all circumstances: even though climate change is expected to have severe negative impacts *overall*, this does not mean that *any* change in *any* region will cause damages and be perceived as detrimental by all actors in the same way. Examples that some climate change may be perceived as beneficial under certain circumstances can be seen in the case of countries that gain access to resources in the Arctic (Emmerson and Lahn 2012), actors that benefit from free shipping routes (Stephenson et al. 2011), those set to gain from more favourable agricultural conditions in some high-latitude regions (Porter et al. 2014), or regions that could profit from comparative advantages in food production (Calzadilla et al. 2013).

In the broader climate change discourse we find a weaker version of the change-is-bad paradigm. This weak change-is-bad paradigm holds that global climate change will be damaging overall and should therefore be limited, but it does not preclude that some actors benefit (or expect to benefit) from a confined deviation from a baseline climate state. In the light of limited international progress on mitigation, there may already be actors that hope to benefit from some degree of global warming, for example by gaining comparative advantages from better adaptation to changing conditions. If at some point in the future the question is asked how much climate change should be compensated by SRM, it is therefore reasonable to assume that the (so far 'silent') beneficiaries of climate change will oppose an immediate reduction in global mean temperatures, while people who are already suffering from that change may want to limit or reverse temperatures more strongly.

Given that the strong change-is-bad assumption may not hold in all situations, we need to ask how relaxing this paradigm would affect assessments of regional disparities due to SRM. We expect implications in two dimensions: the first dimension is a 'global social planner' assessment of SRM's potential to counteract climate change damages and increase overall welfare. The second dimension is that regional disparities in (perceived) gains and losses due to SRM will affect the likelihood of cooperation and conflict. The next section uses a simple model to illustrate how assessments of regional disparities change if the change-is-bad assumption is relaxed, assuming that regional actors want to stay within the confines of avoiding globally dangerous climate change, but, within these confines, have different preferences with regard to an optimal climate state.

[1] *Cautious insinuations of alternative targets in Ban-Weiss and Caldeira (2010), Ricke et al. (2010, 2012) and Kravitz et al. (2014) are confined to the discussion section and do not influence the main analysis.*

3. Diverging preferences in a simple two-region model

In this section we apply a commonly used model for the assessment of regional disparities. We consider two hypothetical regions and compare outcomes for two different cases: in case one, we adopt the strong change-is-bad paradigm and assume that a baseline climate state (e.g. preindustrial) is the most desirable climate state for both regions. In case two, we relax the strong change-is-bad paradigm. We assume that one region benefits from a limited degree of climate change and would thus prefer not to revert climate change by means of SRM as strongly as the other region. We consider the implications for global welfare optimisation and the potential for agreement and conflict.

3.1 Case 1: optimal SRM under the strong change-is-bad paradigm

We consider two regions and focus on temperature as the relevant climate indicator. Our example is illustrative and does not represent existing regions: our goal is to consider the sensitivity of prevalent assessment models to changing assumptions, not to assess real regional disparities. One may conceive of a region in our example as a state, a group of states, or any other spatial entity chosen as a unit for the assessment. Table 1 reflects typical baseline temperatures and changes in the case of a doubling in CO_2 levels with and without SRM for two temperate regions of the world, with Region A situated in lower latitudes than Region B. The temperature increase due to global warming is more pronounced in the high latitude Region B than it is in Region A, a prevalent finding in the literature (Serreze and Francis 2006). In our example we assume that SRM could restore baseline temperatures in Region A, but only at the expense of a residual temperature increase in Region B.

	Baseline	$2xCO_2$	$2xCO_2$+SRM
Region A	15.0°C	17.5°C	15.0°C
Region B	8.0°C	11.0°C	8.5°C

Table 1: Stylised example of (mean) temperatures in two regions in a baseline scenario, under climate change, and with additional SRM.

Figure 2a is a graphical representation of our example. The x-axis and y-axis give temperature deviations relative to the baseline in Region A and Region B respectively so that the origin represents the baseline temperature configuration (15°C, 8°C). Global warming due to an increase in CO_2 levels is represented by the vector T_{2xCO_2}. In the literature it is often assumed that the climate response to an SRM intervention increases linearly with the intensity of SRM deployment (Ricke et al. 2012). As a consequence, all points along the line defined by T_{SRM}, that is all homogeneous cooling patterns, represent theoretically feasible combinations of temperature values with SRM deployment. That the origin is not part of the feasible points implies that SRM is an imperfect tool for restoring the baseline climate state: irrespective of the amount of SRM, there always remains a residual vector T_{RES}.

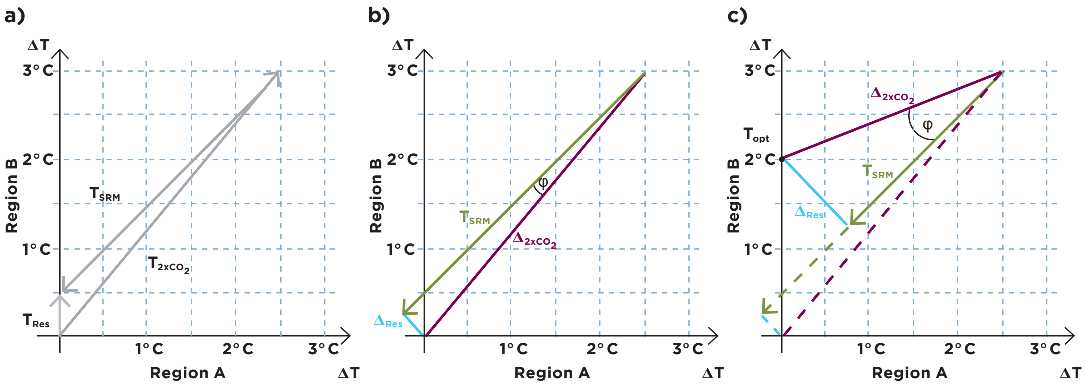

Figure 2 a–c: Graphical representation of the two-region example. The origin represents the baseline temperature configuration. Panel 2a shows the temperature changes in the case of a doubling of CO_2 with and without a specific SRM intervention designed to restore temperatures in Region A. Panel 2b shows the SRM level that minimises global damages if the rationale is to restore the baseline climate. Panel 2c demonstrates that SRM is less capable of establishing an alternative climate target T_{opt}.

Assuming that damages increase more than linearly with climate change, the SRM scenario depicted in Figure 2a is not optimal for minimising overall global damages, i.e. the sum of regional damages. More specifically, if damages are assumed to be a quadratic function in the deviation (Ban-Weiss and Caldeira 2010; Moreno-Cruz et al. 2012; Kravitz et al. 2014), the optimal SRM intensity is the one for which the length of Δ_{Res} is minimised (because the sum of damages equals the length of Δ_{Res} squared). This is the residual climate response model outlined in Moreno-Cruz et al. (2012).

Figure 2b applies the residual climate response model to our example and depicts the optimal SRM scenario (green line) that minimises the residual deviation (blue line) that occurs when the green and blue line become orthogonal. The angle φ provides an indicator for the regional disparities: a low angle means that SRM can reduce residual climate deviations for all regions relatively well if the optimal intensity is chosen, with perfect compensation being possible in the best case $\varphi = 0°$. By contrast, large angles imply that considerable regional deviations from the baseline would remain, causing disagreement between the regions over the desirable intensity of SRM. Regional disparities are maximal under $\varphi = 90°$ when a reduction of temperature damages using SRM is not possible.[2] The optimisation depicted in Figure 2b follows the change-is-bad paradigm: we assume that damages increase with the deviation from a past climate state (the origin) and that this holds for every region. Optimal SRM would minimise the length of Δ_{Res} and thus the overall deviation from the origin.

The results shown in Figure 2b and in the first row in Table 2 show that the compensation of warming using SRM is imperfect, but relatively good. With quadratic damages, the small angle of 5° translates into residual damages of 0.8 per cent. In other words, SRM can compensate in this example for more than 99 per cent of the temperature damages expected

[2] The angle measure does not depend on the specific formulation of convex damages and is also meaningful in more than two dimensions. A shortcoming is that it is not robust against aggregation and disaggregation of regions. See also section 4.

from a doubling of CO_2. This mirrors common findings in the literature (Moreno-Cruz et al. 2012; Ban-Weiss and Caldeira 2010): SRM may not fully restore the past pattern of regional climate indicators, but the remaining regional climate changes are relatively small, in particular for temperature.

3.2 Case 2: optimal SRM under diverging preferences

As discussed in section 2, the change-is-bad paradigm in its strong form may not hold insofar as some regions (or actors) may expect to benefit from a confined change in climate conditions. To illustrate the implications of relaxing the assumption, let us assume that Region B benefits from a limited amount of global warming, for instance, due to agricultural advantages. As an example, we assume that Region B would prefer to limit warming to 2°C, while Region A would prefer to return to its past climate state baseline temperature. With that, the new climate target becomes T_{opt} = (15°C, 10°C).

Note that the contrast between both targets is not extreme. In our example, both regions still consider the temperature increases due to a doubling in CO_2 levels to be detrimental and are generally willing to undertake SRM in order to avoid greater climate change. The alternative target T_{opt} may still be compatible with avoiding dangerous climate change globally and is in line with suggestions in the literature about different potential applications of SRM to either restore past temperatures or shave off a temperature peak. Nevertheless, as the following discussion shows, this alternative target substantially alters the assessment of regional disparities. We first consider the issue of optimising global welfare and then turn to the potential for controversy between regions about the desirable level of SRM.

		Social Planner		Pareto Optimality	
Climate Target	φ	Amount SRM	Residual Damage	Amount SRM	Residual Damage
Baseline	5°	1.00	0.8 %	0.91	1.6 %
Alternative Target	23°	0.64	15.5 %	0.36	31.0 %

Table 2: Regional disparities of SRM in the case of two different climate targets, a baseline climate state and an alternative target where region B prefers a 2°C warming. The indicators are the angle between temperature damages and the SRM vector, the amount of SRM deployed as a fraction of the socially optimal amount under the baseline climate target, and the relative residual damages $||\Delta_{Res}||^2/||\Delta_{2xCO_2}||^2$, i.e. the residual damages with optimal SRM in percentages of the damages without the SRM option. The amount of SRM and residual damages depend on whether the objective is to minimise total global damages (Social Planner) or restrict SRM deployment to Pareto improvement.

Figure 2c shows the optimisation under the new climate target T_{opt}. The relevant deviations Δ_{CO_2} and Δ_{Res} that determine temperature damages are now measured relative to T_{opt}, not relative to the baseline climate configuration in the origin (Figure 2b). As a result, the angle φ, the measure for regional disparities, increases from 5° to 23°. Accordingly, the residual damages that accrue under damage-minimising SRM relative to the temperature damages without SRM increase by a factor of almost 20 from 0.8 to 15.5 per cent (Table 2), and the (global optimal) amount of SRM has reduced significantly: under the new target, the optimal SRM amount is only 64 per cent of the amount that was optimal under the baseline target.

Although residual damages and optimal levels of SRM change considerably, SRM could still yield a global welfare benefit in the above example. However, reaching agreement may become considerably more difficult. The potential for controversy over SRM can be considered by looking at its potential for *Pareto improvement*, i.e. a deployment scheme that would leave no region worse off compared to a situation without SRM. A *Pareto optimal* SRM scheme is the level of SRM at which it is not possible to make *all* regions better off by intensifying deployment. In other words, the Pareto optimal SRM level is found when more SRM would make at least one region worse off. The reason for considering the Pareto criterion is that minimising aggregate global damages implicitly assumes that compensation between regions is possible. With a well-designed compensation scheme, damage-minimising SRM would maximise welfare and thus represent the most desirable state for all regions. However, given the different kinds of risks people face with regard to environmental change, compensation is inherently limited. In the absence of a supranational entity that could guarantee compensation, the global damage-minimising SRM level in turn loses some of its appeal: even an SRM scheme that is generally beneficial may bring significant harm to some regions. Several papers have thus analysed Pareto optimal levels of SRM (Moreno-Cruz et al. 2012; Kravitz et al. 2014). This is not only insightful from a normative perspective; it also helps in understanding whether and where potentially conflicting views about SRM may emerge.

Our two-region model demonstrates that Pareto optimal schemes depend heavily on the assumed climate target. In case one, under the strong change-is-bad paradigm, the Pareto optimal SRM deployment is a reduction in temperatures by 2.5°C; further cooling would make Region A worse off (Figure 2b). To increase the amount of SRM beyond this level can reduce the overall sum of damages, but it is not uncontroversial. The divergence between global optimal and Pareto optimal is still rather small. Pareto optimisation reduces the level of SRM under global optimisation by only 9 percent and can still compensate for a large share of climate impacts since residual damages remain small (1.6 per cent compared to 0.8 per cent).This is very different for case two with the alternative target T_{opt}. Here, the Pareto optimal scheme is limited cooling by 1.0°C. The Pareto restriction cuts the amount of SRM under global optimisation by half (0.36 vs. 0.64). Furthermore, the residual damages under Pareto optimal SRM rise to 31.0 per cent of the temperature damages (15.5 per cent without the Pareto restriction). Moreover, because the Pareto optimal scheme eliminates all damages in Region B, this region has a major incentive to favour this particular deployment profile. Region A, by contrast, would prefer a much more intense application of SRM. The alternative climate target thus considerably increases the potential for diverging interests with regard to SRM, a concern that is relevant to debates about conflicts due to unilateral SRM deployment or the formation of coalitions (Victor et al. 2009; Weitzman 2012; Ricke et al. 2013).

The simple two-region model presented in this section illustrates that relaxing the strong change-is-bad paradigm has substantial implications for assessments of regional disparities from SRM and the potential for conflicting interests about a desirable implementation scheme. The sensitivity of the assessment framework to diverging preferences suggests that conclusions drawn from existing assessments of regional disparities need to be treated with caution. While Moreno-Cruz et al. (2012) stress that regional inequalities due to SRM “may not be as severe as it is often assumed”, our example shows that this diagnosis may change considerably if the potential for diverging climate targets is taken into account. Beyond the change-is-bad paradigm, a series of other simplifications have been made in assessments of regional disparities due to SRM that may have a similarly strong effect on results. The next section briefly discusses some of these assumptions.

4. Beyond diverging interests: limitations of simple assessment frameworks

The previous section illustrated how relaxing the change-is-bad assumption has a considerable influence on discussions of regional disparities in SRM impacts and on conclusions about 'optimal' levels of SRM. We used a highly stylised scenario to demonstrate the sensitivity of simple assessments to diverging preferences regarding a target climate state. Simple assessments usually rely on a series of further simplifications – as does our illustrative example above – that may have an equally strong (or even stronger) impact on results. In this section, we briefly reflect on some of these assumptions and point to their relevance in assessments of regional disparities. We focus on three issues: the choice of indicators used to measure impacts, spatial aggregation, and the importance of accounting for uncertainties.

4.1 Assessing damages

Discussions about regional impacts of SRM require climate model projections as input. In the current literature, a narrow range of indicators has been used to measure regional impacts. Usually, assessments are based on projections of annual average temperature and precipitation values, yet a few studies have weighted projected physical changes with socio-economic indices, such as regional economic output or population densities (Moreno-Cruz et al. 2012; Irvine et al. 2010; MacMartin et al. 2012). These indicators are then used to calculate the degree to which SRM compensates for (regional) climate changes and to identify globally optimal levels of SRM.

It is questionable whether the use of such simple indicators allows for meaningful conclusions to be drawn about impacts, because in different regions different kinds of changes matter: the Summary for Policymakers of the IPCC Working Group II identifies 10 different climate-related drivers, ranging from a warming trend, extreme precipitation, snow cover and damaging cyclones to ocean acidification and carbon dioxide fertilisation (IPCC 2014, 21–25). The report goes on to relate particular risks on different continents to one or more of these drivers, which implies that relevant physical indicators for an assessment of SRM impacts are likely to vary between and even within regions. And since different climate variables are projected to react differently to SRM interventions, assessments of regional disparities will also vary depending on the variables considered.

The IPCC also makes clear that impacts are only partially determined by physical environmental changes. The more important influencing factors identified by the report are, for example, "wealth and its distribution across society, demographics, migration, access to technology and information, employment patterns, the quality of adaptive responses, societal values, governance structures, and institutions to resolve conflicts" (IPCC 2014, 11). These factors are of course not adequately reflected by weighting projected physical changes with simple socio-economic indices, nor can they be projected into the future with a similar degree of confidence as some climate variables. As a consequence, the social determinants of impacts from climatic changes are much more difficult to account for in an assessment framework – and have by and large been neglected in the current discussion on regional SRM disparities.

4.2 Spatial aggregation

Another challenge is the consideration of adequate spatial units. To assess the political implications of regional SRM disparities, regions would have to reflect meaningful social categories. In our example we used two regions in a purely illustrative fashion, and different interpretations of this example are possible: one could think of a partial assessment of disparities between two states, for example, or interpret our regions as aggregated groups of spatially defined actors with similar preferences and expectations with regard to climatic changes.

For the results of any assessment, however, the design of regions is critical, since spatial aggregation effectively masks disparities at sub-regional levels. The existing literature has mostly used regions in an illustrative manner. Motivated by climate modelling restrictions, it has tended to assess regional disparities on spatial levels such as pixel values (Ban-Weiss and Caldeira 2010) or 'Giorgi regions' (Giorgi and Francisco 2000; Kravitz et al. 2014; Ricke et al. 2010), entities that do not match with any socially meaningful categories. One might consider states as a more plausible and meaningful spatial subdivision. However, disaggregating to state level (or below) makes it even more difficult to identify an indicator that would account equally well for climate impacts across an increasing number of regions with different ecological and social characteristics. Furthermore, disaggregation may not be compatible with the availability of reliable scientific projections. And because of limitations with regard to the spatial resolution of climate models, some states, such as most small island nations, are not even represented in some simulations.

The effect of aggregation and disaggregation is particularly strong on considerations of Pareto-optimisation. Since environmental changes due to climate change and vulnerabilities vary not only between, but also within regions (e.g. between continents, states, rural areas, cities, neighbourhoods, etc.), disaggregating to a level where only one region expects detrimental effects from SRM would reduce the Pareto optimal level of SRM instantaneously to zero. Conversely, aggregating over larger regional entities averages out small scale spatial differences (Irvine et al. 2010) and would thus produce more positive assessments of SRM's distributional effects. The choice of regions is therefore central to conclusions about social and political concerns regarding SRM and is itself likely to become controversial.

4.3 Considering uncertainties

The challenge of deriving meaningful indicators for damages on spatial scales of nation states or even below hints at another simplification in existing assessments of regional disparities: the neglect of uncertainty. While the results of regional disparity assessments yield a precise measure (e.g. the angle in our case), the uncertainty of such measures can be enormous. Uncertainty in projections of climate change, particularly for variables other than mean temperatures, increases considerably for smaller spatial units (Hawkins and Sutton 2009; Knutti and Sedlacek 2013). In some cases this can mean that even the direction of change in a particular region and for a particular variable is unclear. Uncertainty is further exacerbated when considering damages that depend not only on physical variables, but even more so on socio-economic and political constellations. This has implications for the metrics considered in an assessment, e.g. the potential of SRM to reduce damages or the degree of inequality. But it also has implications for assumptions about climate targets and actors' preferences.

The implicit assumption in many studies, as well as in our example above, is that actors define their preferences based on perfect knowledge of the impacts of both CO_2- and SRM-induced changes. Actual political discussions, however, will take place in a situation of significant uncertainty. Hence, to be able to draw conclusions about the likelihood of conflict and cooperation, the relevant question would become 'what actors expect' and how they formulate their preferences in a situation of scientific uncertainty. How consideration of uncertainty would affect the strategic dimension of regional disparities remains an open question. Yet given that uncertainty is a crucial concern for decision-making in the context of climate change (Weitzman 2009; Polasky et al. 2011), it will need to become a key consideration in SRM assessment frameworks if meaningful conclusions are to be derived.

5. Conclusions

Most model-based assessments of SRM have found that regional disparities are modest. Yet such assessments rely on a series of simplifying assumptions with regard to the selection of climate indicators, the relation between climate change and damage and the choice of regions, and they typically do not consider uncertainties. Furthermore, most studies on SRM impacts follow a strong change-is-bad paradigm, positing that a past climate state is the most desirable climate configuration in every region. This latter assumption has been the focus of our analysis and, using an illustrative model, we have demonstrated that allowing for modest divergence in actors' preferences can have considerable implications for the assessment of SRM's capacity to avoid climate damages and the likelihood of conflict and cooperation.

Simple assessment frameworks are attractive because they create a direct link between the knowledge generated in climate modelling studies and socio-political issues in relation to SRM. In this way, they meet decision-makers' demand for systematic and simple findings on which to base their decisions – and they fulfil the aspirations of researchers who would like to make their work accessible and politically relevant. However, this quest for simplicity can lead to an analysis where readily available and quantifiable data dominates the discussion at the expense of the social and political dimensions of climate risks that are less amenable to prediction and calculation (Hulme 2011). As a consequence, while much effort is put into including state of the art simulations of atmospheric processes into assessment models, consideration of social concerns remains superficial.

Natural scientific frameworks clearly dominate existing assessments of regional disparities. Indicators that are based on average annual temperature and precipitation values and grid-cell or Giorgi regions as units of analysis clearly derive from climate modelling, but have no immediate meaning in socio-political considerations. The same is true for the strong change-is-bad paradigm: as climate modelling studies usually compare changes against a (past climate) control run, using this as the basis for assessments of SRM seems like an opportune starting point. However, modelling baselines designed to improve our understanding of climate system behaviour should not be confused with a meaningful reference point for preferences regarding desirable climate conditions. Given that assumptions made in existing simple assessment frameworks about the relation between climate change and social implications largely lack both theoretical and empirical justification, conclusions derived from such frameworks should be treated with a good deal of scepticism.

With this paper we want to encourage researchers to examine the link between model projections and socio-political considerations more thoroughly. Existing research on climate change and climate impacts as well as on vulnerability and politics can help to revise existing assessment frameworks, for example, by increasing our understanding of impacts and damages. Furthermore, there may be benefits to linking quantitative assessment frameworks with deliberative approaches and qualitative research in order to better understand how people do (or do not) make sense of quantitative projections. This could happen, for example, by considering model projections on regional change in the context of considering broader socio-political scenarios. And it should involve a general discussion about the purpose and usefulness of simple assessment frameworks. Given their limitations, such frameworks will certainly not put an end to discussions about regional disparities, but as they will continue to inform discussions about SRM, a thorough understanding of their premises is needed.

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