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ESSAY

Regional disparities in SRM impacts: the challenge of diverging preferences

Daniel Heyen[1] **· Thilo Wiertz**[2] **· Peter James Irvine**[3]

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Abstract Solar radiation management (SRM) has been proposed as a potential method for reducing risks from global warming. However, a widely held concern is that SRM will not reverse the climate consequences of global warming evenly, resulting in regional disparities in the combined climate response to elevated greenhouse gas (GHG) concentrations and SRM. 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. These assessments rest on the assumption that, for all regions, any deviation from a past climate state inflicts damages. We challenge this strong change-is-bad assumption by showing that diverging preferences are not only plausible, but may also have the potential to substantially alter assessments of regional disparities. We argue that current assessments yield little information on the ethical and political implications of SRM and that diverging preferences should receive more attention. Promising directions for future inquiry include bridging gaps to the general climate impact research and to research on the social implications of environmental change.

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✉ Daniel Heyen
heyen@eco.uni-heidelberg.de

Thilo Wiertz
thilo.wiertz@geographie.uni-freiburg.de

Peter James Irvine
peter.irvine@iass-potsdam.de

1 Department of Economics, Heidelberg University, Bergheimer Str. 20, 69115 Heidelberg, Germany

2 Human Geography, University of Freiburg, Werthmannstr. 4, 79098 Freiburg, Germany

3 Institute for Advanced Sustainability Studies, Berliner Str. 130, 14467 Potsdam, Germany

1 Solar radiation management and regional disparities

Human-induced global warming will pose risks to an increasing number of people and ecosystems around the world (IPCC 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 (Boucher et al. 2013).

The IPCC states that there is medium confidence that SRM by sulphate aerosol injection could produce −4 Wm^{-2} of forcing, sufficient to offset the warming from a doubling of CO_2 concentrations, but that no SRM technique can restore previous climate conditions (Boucher et al. 2013). The reason for this is the difference between the positive longwave radiative forcing pattern of GHGs and the negative shortwave radiative forcing pattern of SRM (Govindasamy and Caldeira 2000; Lunt et al. 2008; Ammann et al. 2010; Kravitz et al. 2013). The resultant changes to the energy balance, both vertically and spatially, would lead to changes in climate relative to a baseline without either forcing. This potential for regional disparities in the climate response to SRM has been seen as a major argument against such an intervention (Robock 2008; Royal Society 2009).

To assess the implications of an uneven distribution of climate effects from SRM, several studies have translated modelling outcomes into measures of regional disparities in benefits and harms (Irvine et al. 2010; Moreno-Cruz et al. 2012; Ricke et al. 2013; Ferraro et al. 2014; Kravitz et al. 2014). Two issues related to regional disparities have been examined in the literature. Firstly, several studies ask what a global optimal, i.e., global climate damage minimising intensity for SRM, would be (Ricke et al. 2012; Moreno-Cruz et al. 2012; Ferraro et al. 2014). Secondly, regional disparities in SRM impacts may produce 'winners' and 'losers', potentially undermining efforts to reach agreement amongst different actors about a particular SRM strategy (Schneider 1996; Boyd 2009; Ricke et al. 2013; Barrett 2014; Victor et al. 2009; Weitzman 2012; Preston 2012). Results from current assessments of regional climate disparities indicate that annual mean temperature and precipitation anomalies caused by increases in greenhouse gas concentrations could potentially be reduced significantly by SRM. These findings have led some authors to conclude 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; Kravitz et al. 2014).

Although climate modelling research shows that SRM could stabilize regional temperature and precipitation values, we hold that this does not yield much information on the political and ethical implications of SRM, i.e., on questions of political conflict and inequality. Research on regional disparities rests on various assumptions, e.g., about the relation between changes in the climate and the harms caused by those changes (Ban-Weiss and Caldeira 2010; Moreno-Cruz et al. 2012; Kravitz et al. 2013; 2014). In particular, and although some authors have pointed out that SRM could lead to different opinions about where to set the thermostat (MacMartin et al. 2014; Ricke et al. 2013; Robock 2008), almost all existing research on climate effects of SRM has focussed on its ability to restore past climate conditions. Existing assessments of regional disparities usually assume that a previous climate state, for example the preindustrial, is the optimal climate state for all regions. As a consequence, any deviation from this state is considered detrimental. More precisely, all the assessment studies mentioned earlier in this paragraph assume that (regional) damages are quadratic in normalized 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 climate 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 assumption*. We challenge the assumption and argue that considering diverging preferences over regional climate targets in SRM research can have substantial implications for assessments of regional disparities (section 2). Broadening the focus of assessments of regional disparities to consider impacts and preferences, therefore, can point to promising areas for further research (section 3).

2 Diverging preferences and the implications for assessments of regional disparities

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). However, this does not justify the change-is-bad assumption in its strong form: 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). Arnell et al. (2013) calculate benefits of global warming that would be lost under different mitigation scenarios.

Accordingly, the broader climate change discourse is characterized by a weaker version of the change-is-bad assumption. This weak change-is-bad assumption 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 moderate change in climate conditions. 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. Or, shifting the temporal point of reference, some may prefer present climate conditions over some past climate state. Consequently, if at some point in the future the question arises how much climate change should be compensated by SRM, it is reasonable to assume that beneficiaries of a limited change in climate conditions will prefer a moderate reduction in global mean temperatures, while others who are already suffering from the effects of climate change may want a greater reduction in temperatures.

Consider a simple illustrative example with two regions A and B. The baseline annual mean temperature of region A is 15 °C, and future warming is projected to increase temperatures by 2.5 °C. Region B is cooler, with a baseline temperature of 8 °C and is expected to warm by 3 °C. If SRM would reduce absolute temperatures in both regions equally then it would not be possible to restore the temperature of both regions to the baseline state, i.e., our example would reproduce the disparity in climate response seen in the studies of SRM described above. We assume that damages arising from changes in temperature are quadratic in deviations from the baseline, i.e., we are

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

adopting the same damage function as in the abovementioned studies. We can now assess how well SRM performs in our idealized case by looking at two indicators: the difference between preferred and achieved temperatures in each region respectively, and the overall residual damage that results from these deviations. Choosing a *socially optimal* level of SRM, i.e., a level that minimizes overall damages across both regions (Moreno-Cruz et al. 2012), yields residual damages of less than 1 %. In region A, this results in a temperature of 14.75 °C, −0.25 °C from its optimum. In region B, temperature is then 8.25 °C, 0.25 °C above its optimum. This level of SRM reflects a mid-way between the preferences of region A and B. Alternatively, we can consider a *Pareto optimal* level of SRM where any further increase in the intensity of SRM would be opposed by one of the regions. Residual damages then increase to 2 %; region A achieves its preferred temperature, while region B lies 0.5 °C above its preferred state. At this point, further cooling would be detrimental to region A.[2] In this example, residual damages and regional disparities are low, and for both social optimal and Pareto optimal policies both regions are close to their preferred climate state.

Now consider a case of diverging preferences by assuming that the cooler region B benefits from a limited amount of global warming, for instance due to increased agricultural productivity. We assume region B would prefer an absolute temperature of 10 °C, i.e., a warming by 2 °C, while region A prefers to return to its baseline temperature as in the previous case. As before the social optimal state will be found at the mid-point between the two regions preferred levels of cooling and the Pareto optimal state at the point where one region will lose from further cooling. Note that the contrast between the change-is-bad and the diverging preferences example is not extreme. In the latter case, 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. Despite the confined modification, the alternative target of region B considerably alters the assessment of regional disparities. Employing the social optimization criteria using this new target for region B would increase residual damages from 1 % to 15 %, and damages under Pareto optimization would increase from 2 % to 31 %. The results from the example are summarized in table 1.

These changes bear significant implications for considerations of regional disparities. Because the Pareto optimal scheme eliminates all damages in Region B (the region which prefers the least cooling) this region must accept greater damages if it is to compromise with region A, which would prefer a greater cooling.

Comparing these two illustrative cases suggests that relaxing the prevalent strong change-is-bad assumption may have substantial implications for assessments of regional disparities of a deployment of SRM. In particular, conclusions drawn from existing research on regional disparities, which adopt this strong change-is-bad assumption, certainly need to be treated with caution. Having demonstrated that diverging preferences are both plausible and consequential for the assessments of regional disparities of SRM, we conclude this essay by outlining possible and fruitful directions for future research.

3 Perspectives for future research on regional disparities

In the previous section we argued that relaxing the change-is-bad assumption has considerable implications for assessments of regional disparities in climatic changes caused by SRM. In this

[2] A detailed description of the illustrative model and the assessment framework can be found in the supplementary materials to this article.

Table 1 Disparities in regional climate responses of SRM in the case of the two different climate targets, a baseline climate state and an alternative target where region B prefers a 2 °C warming

Climate target	Social planner		Pareto optimality	
	Cooling	Residual damage	Cooling	Residual damages
Baseline	2.75 °C	0.8 %	2.5 °C	1.6 %
Alternative target	1.75 °C	15.5 %	1.0 °C	31.0 %

The indicators are the cooling by SRM deployment and the relative residual damages $||\Delta_{Res}||^2 \ / \ ||\Delta_{2xCO2}||^2$

section, we identify lines of inquiry that in our view could contribute substantially to our understanding of regional disparities in SRM impacts and their ethical and political implications.

Climate damage metrics, such as those employed in integrated assessment models and the studies described above, are simplifications that ought to reflect our understanding of the underlying risks of changes in the climate. However, whilst such simplifications can be useful, it is important to recognize that changes in climate, whether due to Greenhouse gases or SRM, will affect a myriad of systems that we value, and the response of these systems to climate change can be very complex. This is why there are projects like the Agricultural Model Intercomparison Project (AgMIP), that assess the projected responses of a wide variety of crop cultivars to scenarios of climate change to better inform adaptation and other climate policies (Rosenzweig et al. 2013). These process-based models directly simulate the response of systems we care about to climate conditions and thus avoid making assumptions about what the optimal climate condition would be. The damage functions employed in the literature to date have been developed by drawing on the results of studies into the impacts of Greenhouse gas warming. However, little is currently known about the impacts that a deployment of SRM would have on agricultural productivity and many other impacts sectors (IPCC 2013).

A better understanding of the disparities in benefits and risks of SRM requires primary research into the effects of SRM on various impacts sectors and the development of damage functions that synthesize these findings without oversimplifying. The Geoengineering Model Intercomparison Project (Kravitz et al. 2011) has produced a dataset of climate output that could be employed by groups such as AgMIP to provide best estimates of the effects of SRM on agriculture and the other sectors affected by climate change (Rosenzweig et al. 2013). In terms of improving damage functions, the study of Aaheim et al. (2015) represents a step in the right direction as it employs sector-specific damage functions to assess the effects of SRM which should allow a more nuanced view. However, critical to future developments will be the cross-checking of damage function performance against more fundamental process-based understandings of climate risk.

While climate impact research promises a significant contribution to understanding the physical effects of SRM, a comprehensive analysis of regional disparities of SRM needs to place more emphasis also on social and political matters. One aspect is the definition of regions, a crucial step for any analysis of distributional justice and the potential for conflict. Existing studies on SRM have delineated regions based on the grid size of the model simulation or based on shared environmental characteristics (Giorgi and Francisco 2000). These regions lack immediate social or political relevance, and other levels of aggregations, such as states, would lead to more meaningful insights. On the other hand it is likely that such a politically based level of aggregation will lead to less robust climate model predictions, a trade-off that deserves further attention.

Another, more fundamental challenge, revolves around the connection of physical impacts and social implications of climatic changes. The IPCC makes clear that impacts are only partially determined by physical environmental changes. Other 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). Many of these aspects are likely to feature in political disputes about the distribution of risks and benefits from SRM, but few of them are amenable to model-based projections and assessments. The trap to avoid is sticking to a "climate reductionism" in which, as Mike Hulme attests, "[s]imulations of future climate from climate models are inappropriately elevated as universal predictors of future social performance and human destiny" (Hulme 2011). Making research on regional disparities a place of more intense interdisciplinary engagement would be a useful step in this respect. Such an engagement should not just look for improved quantitative prediction, but extend the intellectual landscape to consider research from the environmental social sciences and humanities (Castree et al. 2014). Questions that deserve further attention are, for example, how preferences about environmental futures are formulated by different people in different places, how conditions of substantial uncertainty influence decision-making, and how model-based projections inform these processes. Such an exchange is likely to provoke critical discussions about simple assessments of complex social phenomena. However, it also promises to substantially improve our understanding of important issues surrounding regional and social disparities of SRM and their political implications.

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