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The potential for climate engineering with stratospheric sulfate aerosol injections to reduce climate injustice

Toby Svoboda[a], Peter J. Irvine[b], Daniel Callies[c] and Masahiro Sugiyama[d]

[a]Department of Philosophy, Fairfield University College of Arts and Sciences, Fairfield, USA; [b]School of Engineering and Applied Sciences, Harvard University, Cambridge, USA; [c]Chair of International Political Theory, Goethe University Frankfurt, Frankfurt am Main, Germany; [d]Policy Alternatives Research Institute, The University of Tokyo, Tokyo, Japan

ABSTRACT

Climate engineering with stratospheric sulfate aerosol injections (SSAI) has the potential to reduce risks of injustice related to anthropogenic emissions of greenhouse gases. Relying on evidence from modeling studies, this paper makes the case that SSAI could have the potential to reduce many of the key physical risks of climate change identified by the Intergovernmental Panel on Climate Change. Such risks carry potential injustice because they are often imposed on low-emitters who do not benefit from climate change. Because SSAI has the potential to reduce those risks, it thereby has the potential to reduce the injustice associated with anthropogenic emissions. While acknowledging important caveats, including uncertainty in modeling studies and the potential for SSAI to carry its own risks of injustice, the paper argues that there is a strong case for continued research into SSAI, especially if attention is paid to how it might be used to reduce emissions-driven injustice.

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Introduction

Most justice-related research on climate engineering via stratospheric sulfate aerosol injections (SSAI) has analyzed risks of injustice associated with it (Preston 2013; Svoboda et al. 2011). Recently, some authors have argued that SSAI might instead serve the cause of justice, such as by reducing risks for the global poor (Horton and Keith 2016). For instance, Horton and Keith argue that there is a moral obligation to research SSAI because of its ability to limit climate risks. However, they stop short of offering a normative ground for the claim that a reduction of climate risk translates into a reduction of injustice. By appealing to an ecumenical moral principle, we explore SSAI's potential to reduce injustices arising from greenhouse gas emissions. We do not suggest that SSAI ought to be deployed. Instead, our aim is to improve understanding of whether (and to what extent) SSAI might be used to reduce climate-related injustice.

At the 2015 Paris Conference of the Parties to the United Nations Framework Convention on Climate Change (UNFCCC), the parties committed to limiting warming to 2.0°C (with a goal of 1.5°C) and to reach net zero emissions in the second half of the current

CONTACT Toby Svoboda tsvoboda@fairfield.edu

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century. However, the pledges voluntarily made by individual parties to the agreement sets us on course for 2.6–3.1°C of warming (Rogelj et al. 2016). Even if more ambitious cuts to emissions are made in the future, substantial climate risks are likely to remain, due to both committed warming from past emissions and the inevitability of some future emissions. Adaptation measures could reduce some risks but cannot offset all of them, as some risks are difficult to adapt to, such as sea-level rise in the case of small-island states or the destruction of coral reefs due to higher temperatures and ocean acidification.

The paper is structured as follows. In the first section, we review potential physical impacts of climate change. The second section makes the case that these impacts potentially involve injustice due to the risks they would pose for some parties. In the third section, we review the potential for SSAI to reduce some of these risks. We then argue, in the fourth section, that SSAI therefore has the potential to reduce some injustices associated with climate change. While this claim is subject to some important caveats we acknowledge in the fifth section, we conclude that further research into SSAI is warranted, particularly if it is sensitive to the question of how SSAI might be designed to reduce climatic injustice.

Potential physical impacts of climate change

Rising concentrations of atmospheric greenhouse gases (including CO_2) drive changes in the climate. Global mean temperature change–as well as other aspects of climate change–has been found to be roughly proportional to cumulative emissions of carbon dioxide (IPCC 2014a). Continued greenhouse gas (GHG) emissions will lead to more climate change, bringing about greater hazards. Reducing GHG emissions would reduce the magnitude of climate change in the future, but even were it possible to halt emissions today this would not stop the climate from changing, due to committed warming from past emissions.

Climate change will cause harm where a valued system or state of affairs is negatively affected. Climate change poses many risks of such harm. Popularized in the IPCC (2012) special report on extreme events, a useful and widely adopted approach to formalize the analysis of risks in general, and the risks of climate change in particular, is the following:

$$\text{Risk} = \text{hazard} \times \text{exposure} \times \text{vulnerability}$$

To illustrate this formulation we can take the risk of mortality and morbidity that can occur during extreme heat events, such as the European heatwave of 2003. The **hazard** in this case was the persistently high temperatures that affected much of central Europe for many days and which was exacerbated by anthropogenic climate change (Stott, Stone, and Allen 2004). The **exposure** term describes who is in the affected area, and the **vulnerability** term describes the susceptibility of those affected to suffer ill-health or die as a result of exposure to this particular hazard. Exposure and vulnerability are a function of socio-economic factors, such as where people live, the quality of their homes, and under what conditions they work. In the case of the 2003 European heatwave most of those who died were poorer elderly people who didn't have air-conditioning (Robine et al. 2008).

A note on the notion of risk is in order. Risk is a holistic concept, encompassing not just physical and biological aspects but also technical, social, and political domains. To limit the focus of this paper, we focus primarily on environmental risks (e.g. the harms that arise from changes in extreme precipitation and droughts) that are framed in quantitative terms. We do not mean that other socio-political risks (e.g. technological lock-in and moral hazards) are unimportant, nor do we ignore unknown environmental risks. Our intention is to highlight the potential of SSAI to address climate injustice since many claims on this issue are in fact closely tied with environmental risks.

To make our discussion of the risks of climate change concrete we will focus on a number of well-established physical risks of climate change in this study. The IPCC identifies eight key risks of climate change relevant to the UNFCCC goal to limit dangerous anthropogenic influence in the climate system (IPCC 2014b). These risks were arrived at by considering both changes in physical climate hazards and the exposure and vulnerability of populations and ecosystems:

- Rising sea-levels and increased coastal flooding
- Extreme precipitation and inland flooding
- Systemic risks due to extreme weather events leading to breakdown of infrastructure networks and critical services
- Increased frequency and intensity of extreme heat
- Reduced agricultural productivity and food security due to warming, drought and precipitation variability
- Drought and reduced water availability
- Ocean ecosystem changes due to rising ocean temperatures, ocean acidification, and the loss of Arctic sea-ice
- Terrestrial ecosystem change due to rising land temperatures, increased frequency and intensity of extreme heat, and changes in precipitation patterns.

These risks informed judgements regarding five overarching 'reasons for concern' identified by the IPCC: risks to unique and threatened systems, extreme weather events, the distribution of impacts, global aggregate impacts, and large-scale singular events (also known as tipping points). These reasons for concern highlight different aspects of the risks that climate change poses. A recent update to this analysis suggests that the most pressing of these reasons for concern are the risks faced by unique and threatened systems (O'Neill et al. 2017). There are also regions and groups who will suffer more from climate impacts than others, leading to an uneven distribution of climate impacts. The intensity and frequency of many extreme weather events is increasing and will continue to do so. The aggregate impacts of climate change are not negative everywhere to date, but as the climate continues to warm this will change and all regions will be negatively impacted. The possibility for large-scale singular events, or tipping points, is growing with the Arctic ecosystems and many coral reef systems close to thresholds for long-term survival and with the risk of eventual, and potentially rapid (century-scale), collapses of the Greenland ice sheet and sections of the Antarctic ice-sheet rising for larger temperature changes (O'Neill et al. 2017).

Why these risks involve potential injustices

One reason climate change involves potential injustices is that it imposes grave risks on many parties who have neither benefited (much) from greenhouse gas emissions nor contributed (much) to the problem of climate change. Such parties include both currently existing persons (e.g. the low-emitting global poor) and future persons (e.g. those who will suffer from delayed impacts driven by past emissions). These risks are grave because many of those affected are likely to be highly vulnerable to the hazards to which they are exposed. For example, sea-level rise exposes many persons in low-emitting, low-income areas to the hazard of more frequent coastal flooding. Because of their economic conditions, such parties are extremely vulnerable to the hazard in question, lacking the resources to adapt to the increased occurrence of flooding. For those living in high-income areas, exposure to the same hazard is less problematic, as they are less vulnerable than their low-income counterparts. With their greater resources, high-income parties can afford to invest in infrastructure that might largely avert the harmful effects of coastal flooding. Intuitively, it is unjust for some parties to impose grave risks on parties that have neither significantly contributed to nor benefited from the risk-imposing activity. This does not mean that *all* such risk-imposition is necessarily unjust. For instance, suppose someone opens a business that fairly and legally competes with someone else's business. The first party has imposed a risk (e.g. of reduced profits) on the second party, the latter of whom neither contributes to nor benefits from the opening of the new business. Nonetheless, the first party does not commit an injustice merely by competing with the other party. The climate risks we discuss in this paper are not comparable to the risk of reduced profit, however. This is partly because we focus on grave risks, which (for example) threaten to prevent many parties from satisfying their basic needs. We think the aforementioned principle–i.e. that it is unjust for some parties to impose grave risks on parties that are neither significant contributors to nor beneficiaries of the risk-imposing activities–is a plausible one in the case of climate change. We think there is good reason to accept it as a general rule, although there may be particular cases (e.g. like that of the new business) in which there are reasons to think the principle admits of exception.

Rather than adopting some particular–and controversial–theory of justice, we take an ecumenical approach in this paper. Virtually any plausible theory of justice will identify the aforementioned case as unjust, although they will provide different accounts regarding why this is so. We rely on the following principle, adapted from one defended by Darrell Moellendorf: If a person is especially at risk of very bad things happening due to the actions and omission of others, that person has a prima facie claim to have the risk reduced (Moellendorf 2015). We might call this a 'mid-level' principle. Although it is general enough to apply in many different cases, it is compatible with a broad range of 'high-level' principles of justice, including those (for example) of desert-based, luck-egalitarian, and utilitarian varieties. Desert-based principles often highlight the importance of agents' contributions to social cooperation when judging the justice of certain outcomes. Luck-egalitarian views stress the importance of individuals receiving benefits and burdens in accordance with their own free choices, condemning benefits and burdens that arise outside of those choices (e.g. due to luck or the actions of others). Utilitarian conceptions of justice allocate benefits and burdens in a way that maximizes net utility across the population.

It is the case that climate change puts many parties 'especially at risk of very bad things happening,' including the various hazards noted in the previous section. This, of course, is attributable to the actions (e.g. high emissions) of others, which expose various parties to these hazards. Many of those who are at risk due to climate change bear little or no responsibility (causal or moral) for the grave risks in question, given that their emissions are low and are of the subsistence (rather than luxury) variety (Shue 1993). Because of this, we think the mid-level principle is not only plausible in its own right but also an appropriate fit for the issue at hand. If we take this principle seriously, then those at grave risk due to climate change have a prima facie claim on high emitters to reduce that risk. The obvious–and, by virtually all accounts, best–way to do this is through mitigation of anthropogenic emissions, perhaps coupled with assistance on adapting to the climate change to which we are (or soon will be) committed. We do not dispute this view. Below, however, we investigate whether there is also a justice-based case to be made for utilizing SSAI, presumably in addition to mitigation and adaptation measures. Our goal is not to advocate SSAI, but rather to understand whether its use has the potential to limit climatic injustice.

We want to highlight that considering the potential for SSAI to reduce climate-related injustice may change one's overall moral assessment of this technology.[1] For instance, SSAI – and geoengineering as a category more generally – has been subject to a number of moral concerns (Gardiner 2011).[2] One of these moral concerns, for example, is the thought that manipulating the planet is just something humans should not be engaged in. One could question whether intentionally manipulating the planetary environment in order to, for instance, simply bring about more enjoyable beach weather throughout the year is morally permissible. Modifying the planet for such a relatively trivial end may be morally impermissible, perhaps because it exemplifies a kind disrespect for nature. But when one considers the extent of the injustices that are engendered by climate change, the moral calculus regarding SSAI may change. It may be the case that, despite risking a kind of disrespect for nature, the potential for SSAI to reduce climate-related injustice tips the moral scales. In order to know whether the moral scales are, in fact, tipped one way or the other, one needs an all-things-considered judgement. But it is not our aim to make such an all-things-considered judgement in this paper, but rather to understand a specific way in which SSAI may reduce climate injustice. This understanding would be integral to developing an all-things-considered judgement in the future.

Review of SSAI's capacity to reduce some physical risks of climate change

SSAI is a proposed technology to reflect incoming solar radiation in order to cool the planet and, it is hoped, to reduce some of the risks of climate change. SSAI would do this through the continual release of aerosol particles in the upper atmosphere, where they would have a lifetime of over a year. Several different aerosol particles have been suggested, but the most-studied proposal is to release sulfur-bearing substances to produce a sulfate aerosol layer, which has a natural analogue in the sulfate aerosol layers formed after large volcanic eruptions. Depending on how much cooling was desired, somewhere between a few megatons and a few tens of megatons of material would need to be injected each year (Niemeier and Timmreck 2015). Feasibility studies into this proposal have consistently found that releasing the needed aerosols in the stratosphere could be achieved at a cost of billions of dollars per megaton per year through the use of new-design high-flying jets (McClellan, Keith, and Apt 2012; Moriyama et al. 2016). In the rest of this article, we assume that SSAI could indeed achieve substantial cooling, and we evaluate the potential consequences of such a cooling.

The details of an SSAI deployment would shape its effect on the climate. It would be possible to inject the sulfate or sulfate precursors at different altitudes in the stratosphere and at different latitudes, thus controlling the distribution of the resultant aerosol cloud to some extent (Niemeier, Schmidt, and Timmreck 2011). Due to the strong zonal winds in the stratosphere, any release of sulfate would see the material quickly spread across all longitudes. The Brewer-Dobson circulation which lifts tropical stratospheric air and transports it poleward would make a Tropical release of sulfates into a global aerosol layer. These strong patterns of circulation limit the degree to which SSAI could be fine-tuned. The SSAI aerosol layer could be modified to be thicker in one hemisphere or the other, and thicker at high or low latitudes; it would not be possible to create an aerosol layer limited to one particular nation (Irvine et al. 2016). Furthermore any regional deployment, for example one limited to high Northern latitudes, would still have far-reaching effects on global circulation (Robock, Oman, and Stenchikov 2008). In the rest of this paper we focus on the case of a deployment of SSAI to produce a global, relatively homogeneous aerosol layer and do not consider the effects of SSAI fine-tuned to pursue specific goals.

SSAI would have a cooling effect, as it would reduce the radiative imbalance of the planet, and hence the buildup of thermal energy induced by elevated GHG concentrations. However, SSAI would not simply reverse all the effects of elevated GHG concentrations. Climate model simulations of SSAI are consistent in showing that, if deployed to offset global-mean temperature change from GHGs, it could restore regional temperature fairly well, resulting in a small over-cooling of tropical regions and a small under-cooling of high-latitude regions (Niemeier et al. 2013). However, if global mean-temperature was restored by SSAI, it could produce a substantial net reduction in the intensity of the hydrological cycle, as well as a reduction in both global-mean precipitation and evaporation. Studies show a consistent reduction in precipitation in the tropics and at high latitudes, and reductions in evaporation worldwide, with the greatest effect in sub-tropical regions (Kravitz et al. 2013; Tilmes et al. 2013). The regional implications for water availability will depend on the balance of changes in precipitation and evaporation (Dagon and Schrag 2016; Kravitz et al. 2013). As the IPCC reports, SSAI 'could substantially offset a global temperature rise and partially offset some other impacts of global warming' (IPCC 2014a, ch. 7). This being the case, a climate with high greenhouse gas concentrations and SSAI would be closer to that of a scenario of low greenhouse gas concentrations than to a scenario of high greenhouse gas concentrations and no SSAI. For more details on the climate consequences of SSAI geoengineering, an overview of the state-of-the-art on the earth system science of this proposal has been made by Irvine et al. (2017).

There are few studies that directly evaluate the effect SSAI would have on valued systems, such as human health and agriculture, and so a comprehensive evaluation of the risks and benefits of SSAI is not possible at this stage (Irvine et al. 2017). However, Keith and Irvine argue that it is possible to make an initial assessment of the risks and benefits of SSAI by evaluating its effects on the physical hazards (changes in temperature, sea-level rise, etc.) behind the key risks of climate change identified by the IPCC and discussed in the previous section (Keith and Irvine 2016). Keith and Irvine draw on this approach to argue that it is reasonable to hypothesize that SSAI, deployed to ramp up gradually, halving the increase in global temperatures from the date of deployment, could reduce aggregate climate risks across all countries. As SSAI is roughly 1.5 to 2 times as effective as GHG forcing at changing the intensity of the hydrological cycle per degree C, this scenario would lead to little change in the global mean precipitation rate. They argue that many of the key climate risks identified by the IPCC are primarily driven by temperature change and so SSAI geoengineering would be highly effective at reducing these risks. Because nations face a mix of different risks, were one risk to be increased by SSAI, this could still result in an aggregate reduction in risk if this were offset by decreases in the other risks. Below we follow the same approach to evaluating the potential risks and benefits of SSAI by briefly reviewing its simulated effects on the key risks of climate change, but we do not attempt to evaluate claims about the regional distribution of these risks and benefits. Nonetheless, we do argue that, on the whole, such a reduction of the physical hazards of climate change is likely to benefit vulnerable parties the most, just as they feel the risks of climate change most strongly.

Sea-level rise

The two-main contributions to future sea-level rise, the thermal expansion of ocean waters and the melting of land-ice, are primarily determined by changes in temperature, and simulations confirm that SSAI could greatly reduce sea-level rise (Irvine et al. 2009; Moore, Jevrejeva, and Grinsted 2010).

Extreme heat

Extreme heat is straightforwardly related to changes in temperature, and SSAI is found effectively to offset the projected increase in the frequency and intensity of extreme heat events (Aswathy et al. 2015; Curry et al. 2014).

Precipitation intensity

The intensity of precipitation, or the tendency for rain to fall in intense bursts (a key driver for flood risk), has been observed to increase at a rate equal to or greater than that predicted by the Clausius–Clapeyron relation (~7%°C^{-1}), which relates the moisture content of air to its temperature (Berg, Moseley, and Haerter 2013). Simulations confirm that SSAI could generally offset this intensification of precipitation, though this effect would not be even given the heterogeneous change in mean precipitation (Curry et al. 2014).

Given the central role of temperature change in the above-listed risks, it is clear from the first-order theoretical considerations noted above that SSAI could greatly reduce this key risk of climate change across most of the world (Keith and Irvine 2016). It is therefore unsurprising that climate model simulations also show that SSAI would reduce this risk. However, the other climate risks identified by the IPCC depend on a number of factors beyond temperature and so the effect of SSAI geoengineering on these risks is less clear cut, the outcomes more heterogeneous and mixed, and the confidence in model projections of these risks is lower.

Storms

Projections of the change in the frequency and intensity of storms under climate change are highly uncertain and no study has directly addressed the effect that SSAI would have on them. However, the Clausius–Clapeyron relation noted above indicates that a cooler atmosphere would contain less moisture, which provides energy for storms when it condenses. This is supported by limited modeling evidence, which suggests that associated precipitation and storm surge risks would be reduced in most places (Curry et al. 2014).

Crop yield

Studies of agricultural yield find that SSAI could help avert some of the global yield losses projected for climate change (e.g. from high temperature extremes), although regions which would benefit from climate change (e.g. marginal cold regions and dry regions projected to see an increase in precipitation) would lose out if SSAI geoengineering were deployed (Pongratz et al. 2012; Xia et al. 2014; Yang et al. 2016).

Drought and water availability

SSAI reduces the intensity of the hydrological cycle, reversing some aspects of the hydrological response to climate change, but also leading to reduced precipitation in some regions (Tilmes et al. 2013). However, studies show there would also be a reduction in evaporative demand from the atmosphere due to the lower temperatures, which leads to increased soil moisture and river runoff in many regions that show a decline in precipitation (Dagon and Schrag 2016; Glienke, Irvine, and Lawrence 2015). The overall effect of SSAI on water availability and drought is unclear at this stage, but it seems likely to be mixed, offsetting the increase in this risk in some regions and exacerbating it in others.

Terrestrial ecosystems

Temperature change is expected to play the leading role in driving terrestrial ecosystem change in scenarios of global warming (Warren et al. 2013), although regional hydrological changes and the direct physiological effect of CO_2 on plants (which SSAI will not address) will also be important. Few studies into the effects of SSAI on terrestrial ecosystems have been made, and these have focused only on the large-scale vegetation response (Glienke, Irvine, and Lawrence 2015; Ito 2017; Xia et al. 2014). However, because SSAI would reduce the magnitude of climate change overall, it seems reasonable to expect reduced impacts, although there may be some regional exceptions.

Oceanic ecosystems

Ocean ecosystems are less affected by hydrological change but more affected by the direct effects of CO_2, which is causing ocean acidification. The only studies of the effect of SSAI on ocean ecosystems have pertained to coral reefs, and these have found both that temperature change is by far the dominant factor affecting corals and that SSAI could greatly reduce the risks faced by coral reefs (Couce et al. 2013; Kwiatkowski et al. 2015).

In addition to its climate effects, SSAI has a number of non-climatic side-effects, which may pose novel risks to humans and natural ecosystems.

Stratospheric ozone depletion and ultraviolet radiation

SSAI would change the chemistry of the stratosphere and affect the stratospheric ozone layer, which absorbs harmful ultraviolet radiation. Simulations suggest that SSAI could result in a small reduction in global stratospheric ozone concentrations, with a net increase in surface UV at the poles and no change in the mid-latitudes due to the scattering of UV light by the aerosols (Pitari et al. 2014). However, the outcome would depend on how much SSAI is done and when, with less impact expected in the future as ozone-destroying chlorofluorocarbon concentrations continue to decline.

Diffuse light

SSAI would not simply reduce the amount of incoming solar radiation, but would also scatter it, converting some direct beam light into diffuse light. This would reduce the ability of concentrating solar power plants to generate power, and it is projected to increase plant productivity and affect competition between plant species (McCormack et al. 2016; Mercado et al. 2009; Murphy 2009).

Deposition of aerosols

The aerosols used for SSAI would be deposited on the planet's surface after some time, where they could cause harm. However, the rate of injection for SSAI geoengineering would be smaller than current rates of emissions of sulfate aerosols as a byproduct of fossil fuel use, and most of the injected aerosols would be widely dispersed (Kravitz et al. 2009) and caught up in rain droplets before they reach the surface, reducing their health impact (Eastham 2015).

These non-climatic side-effects would pose risks, but at the global level the magnitude of these risks seems likely to be much smaller than the risks posed by climate change. Some regions would likely see greater impacts from these side-effects than others. For example, high-latitude regions are likely to see a greater reduction in ozone concentrations than elsewhere.

Termination shock

Although not a purely environmental risk, a sudden shutdown of SSAI would unmask the radiative forcing of greenhouse gases, leading to a sharp rise in globally averaged temperature and precipitation within a short period of time (Jones et al. 2013). Since environmental risks are a function of not just the magnitude of temperature change but also its rate, this novel risk could pose an enormous challenge to ecosystems and socio-economic systems, depending on the magnitude of radiative forcing masked by SSAI (Goes, Tuana, and Keller 2011). The risk of termination shock is a serious concern regarding SSAI. This being the case, before deployment were ever to be pursued, there should be legitimate governance of the technology. A legitimate governance institution should make reducing the risk of termination shock one of its primary goals. It seems possible to build resiliency into the administration of aerosol injections (e.g. through decentralization of delivery systems), which could reduce the risk of termination shock (Parker and Irvine 2018).

In sum, existing studies suggest SSAI could offset many, though not all, of the climate effects of elevated greenhouse gas concentrations while introducing a number of side-effects. Reviewing the key risks posed by climate change, it seems that SSAI has the potential to reduce some risks substantially, to have little effect on others, and to exacerbate a limited number of risks in some regions. Overall, with the caveat that substantial uncertainty remains, this suggests that SSAI could reduce aggregate climate risks, although it would produce a different distribution of climate risks and introduce some novel risks (Keith and Irvine 2016).

Prospects for SSAI to reduce climate injustices

Because of SSAI's potential to reduce many of the aforementioned risks of climate change, there is a strong *prima facie* case that SSAI could be used in ways that, on the whole, substantially reduce emissions-driven injustices. As we have seen, the potential impacts of climate change in a high-greenhouse-gas world threaten injustice in harming low-emitters and those who receive little or no benefit from past and ongoing emissions. Once again, we understand risk to be a function of hazard, exposure, and vulnerability. Recall our 'mid-level' principle of justice adapted from Moellendorf: 'If a person is especially at risk of very bad things happening due to the actions and omission of others, that person has a prima facie claim to have the risk reduced.' Relying on evidence from existing studies, SSAI could greatly reduce risks to some parties arising from the emissions of others. For example, as we have seen, SSAI has the potential to reduce the hazards of sea-level rise, the occurrence of extreme heat events, and instances of intense precipitation. Many of those exposed to these hazards are particularly vulnerable, because they currently lack the resources to adapt. Many such parties have prima facie claims to have these risks reduced, because the risks have been imposed on them by others (e.g. high emitters). If it is true that, holding all else (e.g. mitigation and adaptation) equal, SSAI would reduce such unjust risks for such parties, then, all else being equal, SSAI would reduce the injustice of climate change.

At the same time, as we have seen, SSAI has the potential to introduce risks of its own, some of which (intuitively) carry injustice. For instance, due to SSAI-driven stratospheric ozone depletion, some parties would be at increased risk of developing skin cancer. If they are not themselves agents or supporters of SSAI, then our mid-level principle of justice appears to be activated, for such parties would be vulnerable to harm due to the action of others, namely deployment of SSAI. These parties would have a *prima facie* claim to have the risk in question reduced. Relatedly, it is normally unjust to impose risks of harm on innocent parties (e.g. low-emitting, non-beneficiaries of SSAI). If SSAI succeeds in reducing risks of injustice for some while imposing new risks of injustice on others, one might argue that it is not plausibly viewed as an injustice-reducing option.

However, as we noted above, the available evidence suggests that, on balance, SSAI could reduce aggregate risks. As a general rule, emissions-driven risks are particularly unjust because they disproportionately affect low-emitters, including the global poor, so we may reasonably expect reduction of those risks to benefit such parties to a large extent (Horton and Keith 2016). If that is the case, then deployment of SSAI *might* be justified in some case by delivering a desirable ratio of injustice alleviated to injustice imposed. In other words, if SSAI could greatly reduce risks of climate-driven injustice (e.g. due to sea-level rise, extreme heat and precipitation events, and so on), while introducing *relatively* small risks of injustice (e.g. due to ozone depletion), then justice might favor deployment of SSAI despite its obvious imperfections.

Now one might balk at this position. After all, it is not normally considered just to impose harms on innocent parties in order to avoid harms to others. But climate change is not a normal case. Due to committed climate change from past emissions, as well as the inevitability of some future emissions, it is virtually certain that many parties will be harmed in ways that are *prima facie* unjust, and this is so regardless of which policies we pursue, even those involving aggressive mitigation of emissions. The question, then, is how much total risk will be involved, as well as how the disaggregated risks will be distributed across persons. Indeed, climate justice plausibly falls within the realm of non-ideal theory, or the part of a theory of justice pertaining to cases of non-compliance with obligations of ideal justice (Heyward and Roser 2016; Valentini 2012). Had high-emitters complied with their obligations in the past, they would have pursued aggressive mitigation in the preceding decades. But this did not happen, and many high-emitters continue to oppose aggressive mitigation, committing us to some degree of climate injustice. Plausibly, in such non-ideal circumstances, it can be morally appropriate to pursue policies that, under ideal circumstances, would be unjust. Without going into the technical details, this opens the possibility that SSAI might be non-ideally just in some realistic scenarios, even if it would violate requirements of ideal justice (Morrow and Svoboda 2016).

None of the foregoing should be taken to imply that SSAI is a desirable alternative to mitigation or adaptation. On any plausible account of (non-ideal) justice, such measures are essential to avert long-term injustices. However, due to committed climate change, as well as the limits of adaptation that we have noted, SSAI has the potential to complement other measures by managing certain risks of injustice.

Caveats

Because of the many uncertainties surrounding climate change and SSAI, our claims in this paper are, of course, subject to a number of caveats.

First, the validity of our claims regarding the potential benefits and risks of SSAI depends on the results of the limited number of modeling studies conducted so far. Climate models are not perfect, and while they have improved greatly and simulate key climate features well, they all struggle to simulate observed climate precisely, such as by showing significant regional biases in precipitation (Mehran, AghaKouchak, and Phillips 2014). Climate models disagree substantially on the expected level of warming for a given GHG emissions scenario and also on the magnitude of regional climate changes. In addition, current-generation models are not good at reproducing some of the nonlinear behavior of the earth system, including the shrinkage of the Arctic sea ice (IPCC 2014a) and many of the rapid shifts in climate recorded in the paleo record, such as the Paleocene-Eocene thermal maximum (Lunt et al. 2017; McInerney and Wing 2011). It is harder to evaluate the magnitude of these uncertainties for SSAI than for climate change as fewer studies have been conducted and there is only the imperfect analogue of volcanic eruptions to test our understanding. While climate models reproduce many features of the climate response to volcanic eruptions, Driscoll et al. (2012) found that some models cannot reproduce the high-latitude winter warming observed following many volcanic eruptions (Driscoll et al. 2012). Finally, similar issues arise in the assessment of climate impacts, as imperfect models of those systems are needed to make projections. While this deep uncertainty should limit our confidence in these early projections of the effects of SSAI, there is currently no reason to believe that there is a systematic model bias that exaggerates either the benefits or the risks of SSAI.[3]

Second, the possibility that SSAI could be used to reduce emissions-driven injustice is no guarantee that SSAI would in fact be used in such ways. The studies we have drawn on assume SSAI is deployed to create a global aerosol cloud, but the latitudinal distribution of aerosols could be modified to some extent. For instance, the aerosols could be released in such a way that they predominate in the northern or southern hemisphere alone, or that there is a greater aerosol burden at high rather than low latitudes. Haywood et al. found that an aerosol layer isolated to one or the other hemisphere would produce very large disruptions to tropical precipitation patterns as the tropical rain belt would shift towards the warmer hemisphere (Haywood et al. 2013). Robock et al. investigated the effects of limiting the stratospheric aerosol cloud to just above the Arctic and found that the changes in climate were not limited to this region with effects felt as far away as the Tropics (Robock, Oman, and Stenchikov 2008). Furthermore, there is a concern that using SSAI as a 'band-aid' to mask GHG-driven warming could allow high-emitting countries to continue with business as usual. This would certainly be an unjust use of SSAI, though one that would be perhaps less unjust than business as usual without SSAI. We make no claim here regarding how actual decision-makers are likely to utilize SSAI, should they choose to do so in the future.

Third, It is important to point out that we have confined our discussion to the possibility for SSAI to reduce *substantive* climate injustice. It is commonly (though not universally) recognized that justice has both substantive and procedural elements. The difference between substantive and procedural justice can be understood as the difference between fairness in the result and fairness in the process, respectively (Rawls 1993).[4] For example, it is *substantively* unjust that the benefits of the activities engendering climate change have been accruing mainly to the most well-off members of the global community, while the costs of such activities have been accruing (and will continue to accrue) to those who are least well-off. In addition to this substantive injustice, the fact that those who are least well-off have had much less than their fair share of influence over the decision-making process that determines global climate policy constitutes a separate *procedural* injustice. We recognize that reductions in substantive injustice do not guarantee that SSAI would be pursued in a procedurally just fashion, but assessing SSAI on terms of procedural justice is beyond the scope of this paper.

Closing remarks

We have made the case in this paper that SSAI has the potential to be used in the future to reduce some of the injustice of climate change, specifically by reducing risks to parties who bear little or no responsibility for climate change. We do not hold that SSAI should serve as a substitute to emissions mitigation, but we have provided reasons to think that SSAI might complement mitigation and adaptation when it comes to reducing the injustice of climate change. We believe this makes SSAI worthy of further consideration.

Notes

1. We would like to thank an anonymous reviewer for pushing us to consider this point.
2. For example, see: Gardiner, A Perfect Moral Storm, ch. 10.
3. Note that our focus here is SSAI with a moderate injection of stratospheric sulfate aerosols, for which we have some observational records after large volcanic eruptions and a growing number of modeling studies. This may not be the case for other aerosol materials, such as alumina, titanium dioxide, etc.
4. This is how the difference is described in John Rawls (1993).

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References

Aswathy, V. N., O. Boucher, M. Quaas, U. Niemeier, H. Muri, J. Mülmenstädt, and J. Quaas. 2015. "Climate Extremes in Multi-Model Simulations of Stratospheric Aerosol and Marine Cloud Brightening Climate Engineering." *Atmospheric Chemistry and Physics* 15 (16): 9593–9610. doi:10.5194/acp-15-9593-2015.

Berg, Peter, Christopher Moseley, and Jan O Haerter. 2013. "Strong Increase in Convective Precipitation in Response to Higher Temperatures." *Nature Geoscience* 6 (3): 181–185.

Couce, E., P. J. Irvine, L. J. Gregoire, A. Ridgwell, and E. J. Hendy. 2013. "Tropical Coral Reef Habitat in a Geoengineered, High-CO_2 World." *Geophysical Research Letters* 40 (9): 1799–1805.

Curry, Charles L, Jana Sillmann, David Bronaugh, Kari Alterskjaer, Jason N. S. Cole, Duoying Ji, Ben Kravitz, et al. 2014. "A Multimodel Examination of Climate Extremes in an Idealized Geoengineering Experiment." *Journal of Geophysical Research: Atmospheres* 119 (7): 3900–3923.

Dagon, Katherine, and Daniel P Schrag. 2016. "Exploring the Effects of Solar Radiation Management on Water Cycling in a Coupled Land–Atmosphere Model." *Journal of Climate* 29 (7): 2635–2650.

Driscoll, Simon, Alessio Bozzo, Lesley J. Gray, Alan Robock, and Georgiy Stenchikov. 2012. "Coupled Model Intercomparison Project 5 (CMIP5) Simulations of Climate Following Volcanic Eruptions." *Journal of Geophysical Research: Atmospheres* 117 (D17): 17105.

Eastham, Sebastian D. 2015. *Human Health Impacts of High Altitude Emissions*. Boston: Massachusetts Institute of Technology.

Gardiner, Stephen. 2011. *A Perfect Moral Storm: The Ethical Tragedy of Climate Change*. New York: Oxford University Press.

Glienke, Susanne, Peter J Irvine, and Mark G Lawrence. 2015. "The Impact of Geoengineering on Vegetation in Experiment G1 of the GeoMIP." *Journal of Geophysical Research: Atmospheres* 120 (19): 10196–10213.

Goes, Marlos, Nancy Tuana, and Klaus Keller. 2011. "The Economics (or Lack Thereof) of Aerosol Geoengineering." *Climatic Change* 109 (3–4): 719–744.

Haywood, Jim M., Andy Jones, Nicolas Bellouin, and David Stephenson. 2013 March. "Asymmetric Forcing From Stratospheric Aerosols Impacts Sahelian Rainfall." *Nature Climate Change* 3 (7): 660–665. doi:10.1038/nclimate1857.

Heyward, C., and D. Roser. 2016. *Climate Justice in a Non-Ideal World*. New York: Oxford University Press.

Horton, Joshua, and David Keith. 2016. "Solar Geoengineering and Obligations to the Global Poor." In *Climate Justice and Geoengineering: Ethics and Policy in the Atmospheric Anthropocene*, edited by Christopher Preston. New York: Rowman & Littlefield International.

IPCC. 2012. *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*. Cambridge: Cambridge University Press.

IPCC. 2014a. *Climate Change 2013 – The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Chap. 12. New York: Cambridge University Press.

IPCC. 2014b. *Climate Change 2014 – Impacts, Adaptation and Vulnerability: Part A: Global and Sectoral Aspects: Volume 1, Global and Sectoral Aspects: Working Group II Contribution to the IPCC Fifth Assessment Report*, 59–60. New York: Cambridge University Press.

Irvine, Peter J, Ben Kravitz, Mark G. Lawrence, Dieter Gerten, Cyril Caminade, Simon N. Gosling, Erica J. Hendy, et al. 2017. "Towards a Comprehensive Climate Impacts Assessment of Solar Geoengineering." *Earth's Future* 5 (1): 93–106.

Irvine, P. J., B. Kravitz, M. G. Lawrence, and H. Muri. 2016. "An Overview of the Earth System Science of Solar Geoengineering." *Wiley Interdisciplinary Reviews: Climate Change* 7: 815–833. doi:10.1002/wcc.423.

Irvine, P. J., Daniel J Lunt, Emma J Stone, Andy Ridgwell. 2009. "The Fate of the Greenland Ice Sheet in a Geoengineered, High CO_2 World." *Environmental Research Letters* 4 (4): 045109. doi:10.1088/1748-9326/4/4/045109.

Ito, Akihiko. 2017. "Solar Radiation Management and Ecosystem Functional Responses." *Climatic Change* 142: 53–66. doi:10.1007/s10584-017-1930-3.

Jones, Andy, Jim M. Haywood, Kari Alterskjaer, Olivier Boucher, Jason N. S. Cole, Charles L. Curry, Peter J. Irvine, et al. 2013. "The Impact of Abrupt Suspension of Solar Radiation Management (Termination Effect) in Experiment G2 of the Geoengineering Model Intercomparison Project (GeoMIP)." *Journal of Geophysical Research: Atmospheres* 118 (17): 9743–9752.

Keith, David W, and Peter J Irvine. 2016. "Solar Geoengineering Could Substantially Reduce Climate Risks—A Research Hypothesis for the Next Decade." *Earth's Future* 4: 549–559.

Kravitz, Ben, Ken Caldeira, Olivier Boucher, Alan Robock, Philip J. Rasch, Kari Alterskjaer, Diana Bou Karam, et al. 2013. "Climate Model Response from the Geoengineering Model Intercomparison Project (GeoMIP)." *Journal of Geophysical Research: Atmospheres* 118 (15): 8320–8332.

Kravitz, Ben, Alan Robock, Luke Oman, Georgiy Stenchikov, and Allison B. Marquardt. 2009. "Sulfuric Acid Deposition from Stratospheric Geoengineering with Sulfate Aerosols." *Journal of Geophysical Research: Atmospheres* 114 (D14).

Kwiatkowski, Lester, Peter Cox, Paul R. Halloran, Peter J. Mumby, and Andy J. Wiltshire. 2015. "Coral Bleaching Under Unconventional Scenarios of Climate Warming and Ocean Acidification." *Nature Climate Change* 5 (8): 777–781.

Lunt, Daniel J, Matthew Huber, Eleni Anagnostou, Michiel L. J. Baatsen, Rodrigo Caballero, Rob DeConto, Henk A. Dijkstra, et al. 2017. "The DeepMIP Contribution to PMIP4: Experimental Design for Model Simulations of the EECO, PETM, and Pre-PETM (Version 1.0)." *Geoscientific Model Development* 10 (2): 889–901.

McClellan, Justin, David W Keith, and Jay Apt. 2012. "Cost Analysis of Stratospheric Albedo Modification Delivery Systems." *Environmental Research Letters* 7 (3): 034019.

McCormack, Caitlin G, Wanda Born, Peter J. Irvine, Eric P. Achterberg, Tatsuya Amano, Jeff Ardron, Pru N. Foster, et al. 2016. "Key Impacts of Climate Engineering on Biodiversity and Ecosystems, with Priorities for Future Research." *Journal of Integrative Environmental Sciences* 13 (2–4): 103–128.
McInerney, Francesca A, and Scott L Wing. 2011. "The Paleocene-Eocene Thermal Maximum: A Perturbation of Carbon Cycle, Climate, and Biosphere with Implications for the Future." *Annual Review of Earth and Planetary Sciences* 39: 489–516.
Mehran, Ali, Amir AghaKouchak, and Thomas J Phillips. 2014. "Evaluation of CMIP5 Continental Precipitation Simulations Relative to Satellite-Based Gauge-Adjusted Observations." *Journal of Geophysical Research: Atmospheres* 119 (4): 1695–1707.
Mercado, Lina M, Nicolas Bellouin, Stephen Sitch, Olivier Boucher, Chris Huntingford, Martin Wild, and Peter M. Cox. 2009. "Impact of Changes in Diffuse Radiation on the Global Land Carbon Sink." *Nature* 458 (7241): 1014–1017.
Moellendorf, Darrel. 2015. "Climate Change Justice." *Philosophy Compass* 10 (3): 173–186.
Moore, John C, Svetlana Jevrejeva, and Aslak Grinsted. 2010. "Efficacy of Geoengineering to Limit 21st Century Sea-Level Rise." *Proceedings of the National Academy of Sciences* 107 (36): 15699–15703.
Moriyama, Ryo, Masahiro Sugiyama, Atsushi Kurosawa, Kooiti Masuda, Kazuhiro Tsuzuki, Yuki Ishimoto. 2016. "The Cost of Stratospheric Climate Engineering Revisited." *Mitigation and Adaptation Strategies for Global Change*, 23, 145–146.
Morrow, David R., and Toby Svoboda. 2016. "Geoengineering and Non-Ideal Theory." *Public Affairs Quarterly* 30: 85–104.
Murphy, Daniel M. 2009. "Effect of Stratospheric Aerosols on Direct Sunlight and Implications for Concentrating Solar Power." *Environmental Science & Technology* 43 (8): 2784–2786.
Niemeier, Ulrike, H. Schmidt, K. Alterskjær, and J. E. Kristjánsson. 2013. "Solar Irradiance Reduction via Climate Engineering: Impact of Different Techniques on the Energy Balance and the Hydrological Cycle." *Journal of Geophysical Research: Atmospheres* 118 (21): 11905–11917.
Niemeier, U., H. Schmidt, and C. Timmreck. 2011. "The Dependency of Geoengineered Sulfate Aerosol on the Emission Strategy." *Atmospheric Science Letters* 12: 189–194. doi:10.1002/asl.304.
Niemeier, Ulrike, and Claudia Timmreck. 2015. "What Is the Limit of Climate Engineering by Stratospheric Injection of SO_2?" *Atmospheric Chemistry and Physics* 15 (16): 9129–9141.
O'Neill, Brian C., Michael Oppenheimer, Rachel Warren, Stephane Hallegatte, Robert E. Kopp, Hans O. Pörtner, Robert Scholes, et al. 2017. "IPCC Reasons for Concern Regarding Climate Change Risks." *Nature Climate Change* 7 (1): 28–37.
Parker, Andy, and Peter J. Irvine. 2018. "The Risk of Termination Shock From Solar Geoengineering." *Earth's Future* 6 (3): 456-467.
Pitari, Giovanni, Valentina Aquila, Ben Kravitz, Alan Robock, Shingo Watanabe, Irene Cionni, Natalia De Luca, et al. 2014. "Stratospheric Ozone Response to Sulfate Geoengineering: Results from the Geoengineering Model Intercomparison Project (GeoMIP)." *Journal of Geophysical Research: Atmospheres* 119 (5): 2629–2653.
Pongratz, Julia, D. B. Lobell, L. Cao, and K. Caldeira. 2012. "Crop Yields in a Geoengineered Climate." *Nature Climate Change* 2 (2): 101–105.
Preston, Christopher J. 2013 January. "Ethics and Geoengineering: Reviewing the Moral Issues Raised by Solar Radiation Management and Carbon Dioxide Removal." *Wiley Interdisciplinary Reviews: Climate Change* 4 (1): 23–37. doi:10.1002/wcc.198.
Rawls, John. 1993. *Political Liberalism*. New York: Columbia University Press.
Robine, Jean-Marie, Siu Lan K. Cheung, Sophie Le Roy, Herman Van Oyen, Clare Griffiths, Jean-Pierre Michel, and François Richard Herrmann. 2008. "Death Toll Exceeded 70,000 in Europe during the Summer of 2003." *Comptes Rendus Biologies* 331 (2): 171–178. doi:10.1016/j.crvi.2007.12.001.
Robock, A., L. Oman, and G. L. Stenchikov. 2008. "Regional Climate Responses to Geoengineering with Tropical and Arctic SO_2 Injections." *Journal of Geophysical Research-Atmospheres* 113 (D16): D16101. doi:10.1029/2008jd010050.
Rogelj, Joeri, Michel den Elzen, Niklas Höhne, Taryn Fransen, Hanna Fekete, Harald Winkler, Roberto Schaeffer, et al. 2016. "Paris Agreement Climate Proposals Need a Boost to Keep Warming Well Below 2 C." *Nature* 534 (7609): 631–639.

Shue, Henry. 1993. “Subsistence Emissions and Luxury Emissions.” *Law & Policy* 15 (1): 39–60. doi:10.1111/j.1467-9930.1993.tb00093.x.

Stott, P. A., D. A. Stone, and M. R. Allen. 2004. “Human Contribution to the European Heatwave of 2003.” *Nature* 432 (7017): 610–614. doi:10.1038/nature03089.

Svoboda, Toby, Klaus Keller, Marlos Goes, and Nancy Tuana. 2011. “Sulfate Aerosol Geoengineering: The Question of Justice.” *Public Affairs Quarterly* 25 (3): 157–180.

Tilmes, Simone, John Fasullo, Jean-Francois Lamarque, Daniel R. Marsh, Michael Mills, Kari Alterskjær, Helene Muri, et al. 2013. “The Hydrological Impact of Geoengineering in the Geoengineering Model Intercomparison Project (GeoMIP).” *Journal of Geophysical Research: Atmospheres* 118 (19): 11036–11058.

Valentini, Laura. 2012 September. “Ideal vs. Non-Ideal Theory: A Conceptual Map.” *Philosophy Compass* 7 (9): 654–664. doi:10.1111/j.1747-9991.2012.00500.x.

Warren, R., J. Van Der Wal, J. Price, J. A. Welbergen, I. Atkinson, J. Ramirez-Villegas, T. J. Osborn, et al. 2013. “Quantifying the Benefit of Early Climate Change Mitigation in Avoiding Biodiversity Loss.” *Nature Climate Change* 3 (7): 678–682.

Xia, Lili, Alan Robock, Jason Cole, Charles L. Curry, Duoying Ji, Andy Jones, Ben Kravitz, et al. 2014. “Solar Radiation Management Impacts on Agriculture in China: A Case Study in the Geoengineering Model Intercomparison Project (GeoMIP).” *Journal of Geophysical Research: Atmospheres* 119 (14): 8695–8711.

Yang, Huiyi, Steven Dobbie, Julian Ramirez-Villegas, Kuishuang Feng, Andrew J. Challinor, Bing Chen, Yao Gao, et al. 2016. “Potential Negative Consequences of Geoengineering on Crop Production: A Study of Indian Groundnut.” *Geophysical Research Letters* 43 (22): 11786–11795.