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Would solar radiation modification exacerbate conflict?

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Abstract

Solar radiation modification (SRM) or solar geoengineering is a set of proposed technologies to directly intervene in the Earth's radiation budget to reduce surface temperatures in order to alleviate risks from anthropogenic climate change. SRM could, however, present novel environmental and societal risks, or a risk-risk tradeoff. Recent advances in scientific understanding suggest that using SRM moderately would alleviate some climate risks and bring the climate back closer to preindustrial levels when compared with not deploying SRM. This could, in turn, reduce the risks of climate-induced conflicts. Though the intention behind using SRM could complicate the prospects for conflict, the potential contribution of SRM to lessening conflict should be further investigated.

Keywords

Solar radiation modification (SRM), solar geoengineering, climate engineering, climate change, conflict

1. Introduction

The effects of climate change are increasingly being felt across the globe (World Meteorological Organization, 2020), ranging from extreme heat waves to recurring forest fires in California and Australia to the bleaching of the Great Barrer Reef, to name a few. Over the past few years, climate-related issues have been at the top of the list of the global risks outlined in the annual *Global Risks Report* (World Economic Forum, 2021). In response to the looming climate crisis, policymakers, businesses, and stakeholders are accelerating their actions to reduce the greenhouse gas (GHG) emissions that contribute to global warming. For instance, as of this writing, about 450 cities, 23 regions, and about 570 universities have pledged some form of carbon neutrality (UNFCCC, 2021), and these numbers continue to grow.

And yet, despite these ambitions, scientific analysis (United Nations Environment Programme, 2020) reveals a large gap in emissions between what the world wants and what is occurring. For instance, to contain the increase in the global mean surface temperature (GMST) to below 2°C, economically efficient pathways suggest that the world has to reduce annual emissions to 41 billion metric tons of carbon dioxide (CO_2) equivalent by 2030 (median of the assessed scenarios). On the other hand, emissions are expected to grow up to 53 billion metric tons per year by 2030 if the nationally determined contributions (NDCs) of the parties to the 2015 Paris Agreement are fully implemented. This gap increases further for more ambitious targets, such as the 1.5-degree target.

Against this background, a new set of interventions is receiving increasing traction: geoengineering, climate engineering, or climate intervention. These interventions are intended to directly intervene in the climate system on a large enough scale to counteract global warming (Shepherd et al., 2009; National Research Council, 2015b, 2015a; IPCC, 2018; National Academies of Sciences, Engineering, and Medicine, 2021). Solar radiation modification (SRM), solar radiation management, or solar geoengineering, in particular, could act quickly and cool the Earth's surface temperature relatively inexpensively, although imperfectly (Keith et al., 2010). Scientists have considered SRM as taboo for a long time because using SRM might deter people from acting to reduce emissions. This taboo has been lifted due to influential academic papers and an authoritative report (Crutzen, 2006; Wigley, 2006; Shepherd et al., 2009).

As with many emerging technologies, such as artificial intelligence and synthetic biology, SRM has been controversial, as it represents a risk-risk tradeoff: reduced climate risks are traded off with novel environmental and societal risks (Grieger et al., 2019). In fact, SRM could reduce the global mean surface temperature, but what matters to people and nature are changes in the *regional* climate. One of the first modeling studies on SRM (Robock et al., 2008) noted that injections of sulfur dioxide (SO_2) would lower the global mean surface temperature but would also simultaneously disrupt the Asian and African monsoons, potentially affecting food production for billions of people. On the other hand, a burgeoning literature on climate and conflict implies that changing the climate would exacerbate intra-state (civil) armed conflicts, albeit in a small and complex way (Koubi, 2019; Mach et al., 2019). If this is true, SRM would increase the risk of armed conflicts in those areas.

The prospect of impacting agriculture is not an inherent property of SRM (Keith & MacMartin, 2015), however. If SRM was implemented on a moderate scale, some recent studies suggest that it could *improve* the regional climate without making (almost) anybody worse off (Irvine et al., 2019). If that is true, would SRM ameliorate climate-related conflicts? This paper will make the argument that SRM could reduce conflict, a point that has not been explicitly dealt with in the literature, though the contribution of the present paper is modest.

This paper is organized as follows. Section 2 reviews the current status of ways to mitigate climate change and SRM; Section 3 discusses the contribution of SRM to alleviating climate-induced conflicts; and finally, conclusions are presented in Section 4, along with the limitations of this study.

2. Review of SRM

2.1. Call for new responses to climate change

While climate change mitigation initiatives are gaining momentum, they have not yet reached the requisite speed and scale. This is the motivation for assessing novel interventions, such as geoengineering or climate engineering.

One of the lessons learned from the ongoing novel coronavirus pandemic is how hard it is to reduce greenhouse gas emissions. COVID-19 wreaked havoc with the global economy and only modest emissions reductions were observed. According to the International Energy Agency, global CO_2 emissions reduced by 5.8% relative to the previous year due to urban lockdowns and the economic contraction associated with the new coronavirus pandemic (IEA, 2021). A modest reduction of several percentage points is in stark contrast to the ambitions expressed by governments across the world. The slow progress is one of the reasons why scientists and policymakers have begun paying closer attention to climate engineering.

Geoengineering (Shepherd et al., 2009), climate engineering (Keith, 2013), or climate intervention (National Research Council, 2015a, 2015b) are generic terms for solar radiation modification (SRM) and carbon dioxide removal (CDR) (IPCC, 2018). Although earlier assessments tended to lump these two categories together (Shepherd et al., 2009), they have very different scientific mechanisms, societal issues, and environmental risks. The Intergovernmental Panel on Climate Change (IPCC) therefore recommends avoiding the loose category of geoengineering and treats SRM and CDR separately (IPCC, 2018).

SRM and CDR can be contrasted with conventional responses to climate change, such as mitigation (for example, cutting greenhouse gas emissions by introducing solar and wind power and by using electric vehicles) and adaptation (for example, building dikes to cope with rising sea levels) (Figure 1). A similar classification scheme was presented in prior works (Keith, 2000; Caldeira et al., 2013). However, the distinctions between SRM and CDR are sometimes blurry. Afforestation and reforestation are considered conventional mitigation techniques and have been long promoted, even aside from climate change. In the IPCC definition, CDR is part of mitigation. Sometimes SRM is considered as adaptation, since it does not directly counteract the GHG-induced radiative balance. In Figure 1, regional climate interventions could be considered as adaptation. In fact, a research program in Australia to ameliorate damage to the Great Barrier Reef is called the Reef Restoration and

Adaptation Program (Brent et al., 2020).

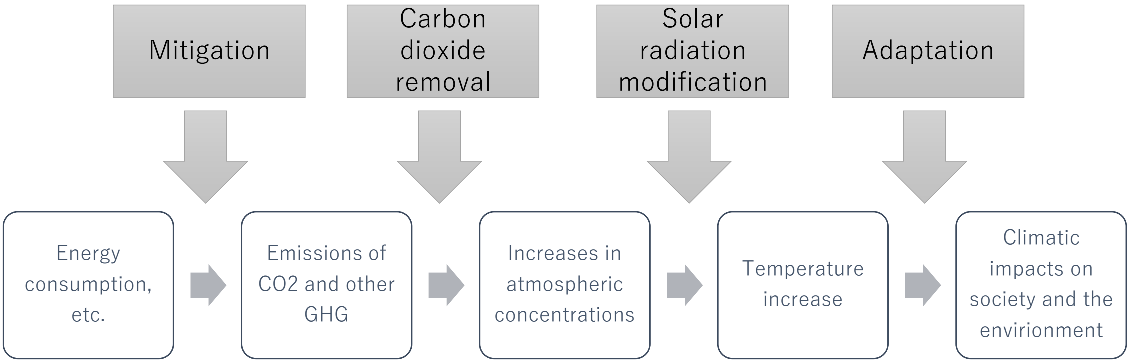

Figure 1. Classification of human responses to anthropogenic climate change

One of the robust messages from the literature on SRM, CDR, and human responses to climate change is that these options should not be viewed in isolation; a portfolio of options should always be considered (Long & Shepherd, 2014; MacMartin et al., 2018). In other words, SRM and CDR cannot and should not replace conventional approaches, such as mitigation or adaptation. (SRM could be excluded from such a portfolio.)

To appreciate a portfolio approach, consider the following scenario: If the world does not take action to prevent global warming, the temperature increase could reach about 3.5°C in 2100, and rise after that. In reality, however, countries are already implementing climate policies to a certain extent, and we might be able to limit the temperature rise to about 2.5°C. In addition, if we can capture a large amount of CO_2 from the atmosphere, we might be able to keep the temperature increase below 2°C. However, even in that case, the temperature rise could temporarily exceed 1.5°C. This is where solar radiation modification comes in. SRM would allow us to achieve the 1.5°C target agreed upon in the Paris Agreement.

This is an idealized scenario. Countries may succeed or fail in mitigation. If one option in the portfolio fails, other options would have to take up the slack. Given the slow pace of mitigation, there is an increasing role for CDR and SRM.

2.2. SRM and stratospheric aerosol injection (SAI)

SRM is intended to cool the climate by reflecting a few percent of sunlight back into space (Caldeira et al., 2013). SRM has four subcategories, which can be distinguished by the location of the sunlight reflection (Shepherd et al., 2009; National Research Council, 2015b; de Coninck et al., 2018) (Table 1). Scientists have proposed space-based methods (Early, 1989; Angel, 2006), stratospheric aerosol injection (Crutzen, 2006; Robock et al., 2008), marine cloud brightening (Latham et al., 2008), and surface albedo (reflectivity) enhancement (in the order of the distance from the Earth's surface). There is a related proposal for cirrus cloud thinning (Mitchell & Finnegan, 2009) but this method cuts infrared radiation, not solar radiation, and so is not technically an SRM technique. Although all these approaches have similarities in that they block sunlight from entering the climate system, they differ greatly in their underlying scientific principles, engineering requirements, efficacy, and side effects.

Table 1. Types of SRM

Location of sunlight reflection	Method
Space	Space-based sunlight reflector (at the Lagrange point or in low Earth orbit)
Stratosphere	Stratospheric aerosol injection
Troposphere	Marine cloud brightening (spraying sea salts as cloud condensation nuclei)
Surface	Increasing albedo (reflectivity) of rooftops, grasslands and croplands, or deserts

The most often discussed method of SRM is stratospheric aerosol injection (or stratospheric aerosol geoengineering). The scientific principle is similar to that of the climatic impact of a major volcanic eruption. It is well known that a major volcanic eruption creates a layer of aerosols in the stratosphere that cool the entire climate system. For instance, the 1991 eruption of Mount Pinatubo on the island of Luzon in the Philippines injected about 20 Mt of sulfur dioxide (SO_2) into the stratosphere (Robock, 2000), and the SO_2 was oxidized into sulfuric acid. The clouds of sulfuric acid cooled the atmosphere by about 0.5°C (Soden et al., 2002). In SAI (stratospheric aerosol injection), technologies such as aircraft are used to inject aerosols at an altitude of about 20 kilometers. Injection materials can be aerosol precursors (rather than aerosols), which would become aerosol particles in the stratosphere.

Research into SRM used to be scant, but there has been substantial progress over the past decade not only in natural sciences but also in social sciences and humanities. Especially, there has been significant progress in climate and Earth system modeling. The Geoengineering Model Intercomparison Project (GeoMIP) (Kravitz et al., 2015) is now part of the Coupled Model Intercomparison Project (CMIP) Phase 6, which is a major contributor to the climate science reviewed by IPCC. Professors Keutsch and Keith of Harvard University, with funding from philanthropists such as Bill Gates, are planning a small-scale field experiment called the Stratospheric Controlled Perturbation Experiment (SCoPEx) (Dykema et al., 2014; Shyur et al., 2019) that was going to launch a test engineering flight in the summer of 2021 (Greenfield, 2021). But the plan was cancelled after consultation with stakeholders in March, 2021 (Swedish Space Corporation, 2021). Though there has been rapid progress in SAI over the past decade, it is far from being able to be deployed.

In the following sections, we primarily focus on SAI because it is the most widely discussed approach and because other techniques have some problems: marine cloud brightening intervenes in clouds, which continue to be the greatest source of uncertainty in the climate system; and surface albedo enhancement has limited effectiveness and is thought to be prohibitively expensive (Shepherd et al., 2009). Though a new generation of space companies are making steady progress in reducing the costs of space travel, space-based SRM methods are technically very challenging in the short term (Keith et al., 2020).

2.3. Risks from SAI

While modeling studies have demonstrated that SAI could lower the global mean surface temperature and reduce many climate risks associated with global warming, SAI could also bring about a wide range of novel environmental and societal risks. Previous studies have compiled lists of the risks and benefits of SAI (Robock, 2016; Robock et al., 2009). Here I cite the list of ten major concerns (Grieger et al., 2019) verbatim, which was originally produced by an earlier study (Olson, 2011):

1. *Unintended negative consequences to the Earth's complex geophysical and ecological systems (e.g., ozone layer depletion, regional droughts, changes in precipitation patterns, extreme weather responses);*
2. *Potential ineffectiveness arising from a lack of information on field scale efficacy;*
3. *Risk of undermining mitigation efforts by redirecting research and political effort;*
4. *Risk of sudden catastrophic warming if SAI were discontinued as GHG concentrations continue to rise in the meantime;*
5. *Inequality in receiving the benefits of SAI, potentially resulting in conflicts;*
6. *Even greater difficulty in reaching international agreement than for mitigation;*
7. *Potential for weaponization given past experiences with weather modification being used for military purposes;*
8. *Reduced efficiency of solar energy from decreased incoming solar radiation;*
9. *Danger of corporate interests overriding the public interest; and*
10. *Danger of research driving inappropriate deployment, as experienced with other technologies.*

Though this list is broad and covers some elements mentioned by critics of the technology (Hamilton, 2013; Hulme, 2014), it is 10 years old. Advancements in research have since clarified the magnitude of the risks and their preconditions. Some risks appear no longer to be major concerns in light of this new understanding.

First, environmental risks need clarification. As the climatic risks and benefits depend on how, when, where, and what kind of SAI is deployed, there are few inherent properties of SAI. Besides, there are many technological choices, ranging from the magnitude of cooling to the materials for injection to the latitude and the height of the injection. Earlier studies assumed idealized scenarios in which SAI was deployed to offset 100% of global warming. In such a simple scenario, the models revealed completely cancelling global warming leading to a decrease in mean precipitation. The tropics would likely be over-cooled (Kravitz et al., 2013). Also, if halted suddenly, SRM would result in sudden unmasking of hidden warming, resulting in a rapid increase in the global mean surface temperature, an effect referred to as termination shock or termination effect (Matthews & Caldeira, 2007). Other side effects include the loss of stratospheric ozone, a decrease in direct sunlight, and an increase in diffuse sunlight.

Recent studies, however, have demonstrated that there is no need to deploy SRM to completely cancel global warming and that a more moderate deployment strategy could reduce climate risks while containing the side effects (Keith & MacMartin, 2015). For instance, the termination shock is proportional to the magnitude of SRM cooling, and a moderate use could render SRM "fail-safe" (Kosugi, 2013). Choosing sulfuric aerosol particles would result in stratospheric ozone destruction, but spraying calcium carbonate particles would increase, rather than decrease, stratospheric ozone (Keith et al., 2016). Especially, a strategy to halve global warming with SAI seems to ameliorate many of the risks previously identified (Irvine et al., 2019) (see below).

Second, for the societal risks too, some risks might have been overstated. The list above includes the weaponization of SAI as a possible risk, but a recent article (Smith & Henly, 2021) rejected this concern. Engineering studies have discovered that the climatically meaningful operation of SAI would involve hundreds, if not thousands, of aircraft flights, and would be highly conspicuous and easily detected (Moriyama et al., 2017; Smith, 2020), rendering covert operation impossible. In addition to the conspicuousness of the technology, SAI has imprecise targeting. A modeling study (Dai et al., 2018) showed that the effect of SAI at a specific latitude impacts on that region poleward of the injection latitude. Because of prevailing east-west winds, the impact cannot be confined longitudinally. Such an imprecise property makes it hard to deploy SAI as a weapon.

Note that this does not negate all concerns about SAI. Two researchers (Smith & Henly, 2021) provided support for concerns about the moral hazard or mitigation deterrence (SAI reducing the motivation for mitigation), infiltration of fossil fuel interests into the SAI complex, unilateral subscale deployment as political expression, heterogeneous preferences, and conflicts, among others.

2.4. Current state of SRM governance

Despite the high risks of SRM, there is no dedicated legal framework (Biniaz & Bodansky, 2020;

Reynolds, 2019). There are many treaties and fora relevant to SRM, including the United Nations Framework Convention on Climate Change, the Vienna Convention for the Protection of the Ozone Layer, the Montreal Protocol on Substances that Deplete the Ozone Layer, the Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques (ENMOD), the Outer Space Treaty, and the United Nations Security Council. None of these, however, directly regulates SRM.

Instead, we have seen many bottom-up initiatives, such as the Oxford Principles (Rayner et al., 2013) and the Code of Conduct for Responsible Scientific Research involving Geoengineering (Hubert & Reichwein, 2015). In addition, a number of social scientists have entered the discourse, enabling interdisciplinary (Kreuter et al., 2020) and transdisciplinary research (Sugiyama et al., 2017) in the spirit of responsible innovation (Stilgoe et al., 2013).

Governments are gradually getting serious about climate engineering; it was on the agenda at the fourth UN Environment Assembly in Nairobi, Kenya, in March 2019. A draft resolution was proposed by 12 countries, led by Switzerland, requesting the secretariat of the UN Environment Assembly to review the current state of science and governance. However, the draft resolution was opposed by the United States, Saudi Arabia, and other countries, and unfortunately no agreement was reached (Jinnah & Nicholson, 2019). Nevertheless, this proposal can be seen as a harbinger of more serious international attention to come in the future.

3. SRM and within-state conflict

3.1. Climate change and conflict

The preceding discussion showed that SRM could reduce some of the climatic impact. If that is the case, would SRM help reduce climate-related conflicts as well?

There is a growing literature on the relationship between climate change and conflict (Ide, 2017; Koubi, 2019), and recognition of the climate-conflict relationship has not been limited to academia. High-ranking officials, such as President Barak Obama and UN Secretary-General Ban Ki-moon, have made the connection between climate change and conflict. The literature, however, presents diverse and conflicting views, with some researchers claiming a strong relationship and others doubting any link at all.

And yet, there is an emerging understanding that while the cause of conflict is far from certain, climate can act as a threat multiplier and does influence conflict, albeit to a small extent. Recently, a structured expert elicitation (Mach et al., 2019), from 11 leading scholars in a wide range of research fields, probed the role of climate in armed conflicts within states. (Notably, there were researchers in this study with opposing views, for example, Marshall Burke and Halvard Buhaug). The structured expert elicitation found that the experts agreed that climate plays an uncertain but small role, and that further warming will likely increase the risk of climate-related conflict. Therefore, the current understanding is that climate change influences conflict, but that other factors, such as low socioeconomic development and low state capability, are more important.

Similarly, an article in the *Annual Review of Political Science* (Koubi, 2019) presented a synthesis of the literature, broadly in agreement with Mach et al.'s findings. The author noted that the literature is unclear about the relationship between climate and the onset of conflict, but that climate contributes to conflict under certain conditions in areas that are prone to conflict, including those dependent on rain-fed agriculture.

According to two reviews (Ide, 2017; Koubi, 2019), many of these studies used large-*N* statistical analysis. These studies basically frame conflict as a function of deviations in temperature and precipitation from a certain climatic condition. In a semi-arid region, for instance, climate change will increase local temperature and likely decrease precipitation, which could decrease agricultural output, consequently, raising the prospect of conflict.

3.2. Would reducing climate change lessen intra-state conflicts?

It is instructive to look at similarities between the literature on climate and economic damage with the literature on climate change and conflict.

As with the literature on the climate-conflict nexus, econometric models have been developed to analyze the impact of climate on economies. Since the seminal work of William Nordhaus (1991), a 2018 Nobel economics laureate, and others, scholars have defined the damage from climate change as a function of anomalous temperature and other climate variables, such as precipitation. Recent studies using an ever-larger dataset have identified a robust relationship between temperature increase and economic damage to different sectors (within the American context, see Hsiang et al. (2017)). In other words, the damage from climate change can be reduced if we can bring the climate closer to preindustrial levels. Note that in some locations, the preindustrial climate is not optimal and even moderate global warming could increase public wellbeing in those regions. For instance, moderate global warming might improve the wellbeing of Russians.

If the damage caused by climate change is an increasing function of the deviation of climate from the original position, how would SRM affect the climate and the economy? To investigate that question, Harding et al. (2020) adopted state-of-the-art macroeconomic models and applied them to the case of SRM offsetting global warming. Cancelling a large, 4-degree warming with SRM would lead to substantially equal economic prospects compared with the warming-only scenario.[1] In other words, SRM would improve public wellbeing in developing countries more than (relatively speaking) in developed countries.

Note that these results (Harding et al., 2020) are based on total cancellation and the full reversal of global warming with a massive deployment of SRM. These researchers found their results to be robust when investigated against different specifications, etc., but their results could change if factors other than temperature and precipitation are significant.

This study (Harding et al., 2020) was predicated on the large-scale deployment of SRM, but there are many ways to deploy SRM, and as indicated above, there is a risk of termination shock if SRM is used on a large scale (though there are many countermeasures). Keith and Irvine (Keith & Irvine, 2016) hypothesized that countering half of global warming could substantially reduce climate risks. Irvine et al., using a high-resolution climate model and a suite of models participating in GeoMIP, (Irvine et al., 2019) explored the climatic impact of using SRM to offset half of the warming from a doubling of atmospheric CO_2 concentrations. In their models, the sun was artificially dimmed slightly to counteract the radiative forcing by CO_2.

Irvine et al. (2019) examined how climatic variables (temperature, annual maximum temperature, precipitation minus evaporation, maximum annual 5-day precipitation) were affected by temperature offsets from SRM. If we define *improvement* as a shift of climate closer to preindustrial levels, then SRM substantially improves climatic conditions. More importantly, few regions would experience a worsening of climatic conditions. In the high-resolution model, only 0.4% of global surface area (excluding Greenland and Antarctica) experienced a worsening of water availability as well as precipitation extremes. Coarser GeoMIP models reveal that some areas would experience degradation but the inter-model medians indicate that 1.9% and 0.8% of the land surface would experience a worsening due to hydrological changes. Also, this study, using their high-resolution model, found that half the amount of SRM could offset most of the increase in tropical cyclone intensity as measured by the power dissipation index (PDI).

Although this study represented SRM in an idealized way (for example, solar dimming), another, follow-up study (Irvine & Keith, 2020) used the results from the geoengineering large ensemble (GLENS) project (Tilmes et al., 2018) where stratospheric aerosol injection was explicitly modeled. They estimated the climatic impact of half SRM by linearly combining the SRM scenario with the global warming scenario (close to the 4-degree increase). Their conclusion was broadly in agreement with the previous analysis, identifying the potential of half SRM for mitigating climate change.

[1] Technically speaking, the study used Representative Concentration Pathway (RCP) 8.5, which corresponds to a radiative forcing of about 8.5 W/m^2 in 2100. This scenario shows a warming of approximately 4°C in 2100.

These studies assumed 50% of the warming offset, but 50% is not a magic number. In addition, many parameters can be chosen to adjust SRM (Ban-Weiss & Caldeira, 2010; Kravitz et al., 2016; Tilmes et al., 2018).

If we combine the results from the two studies outlined above (Irvine et al., 2019; Harding et al., 2020), it is possible to deduce that a moderate use of SRM could reduce the physical climatic impact as well as economic damage originating from climate change. Moderate use, then, could reduce the chance of intra-state armed conflicts being exacerbated.

SRM does not have the same effect as anthropogenic global warming, and there are other key variables, such as increases in ultraviolet radiation due to stratospheric ozone destruction and the ratio between direct and diffuse sunlight. Atmospheric CO_2 concentrations would remain high and ocean acidification would not be mitigated. Nevertheless, to the extent that these are small effects (because of the constrained size of SRM), the impact through these channels might not be a reason for concern.

4. Conclusions and discussion

This working paper makes the argument that SRM could reduce the risk of armed conflicts within states. A growing literature, mostly based on large-*N* statistical analyses, identified a weak, though complex, link between climate and conflict (not the onset but rather the severity, duration, etc.). In these studies, the risk of conflict was modeled as a function of deviations of climate-related variables from a certain, original position. To the extent that SRM could ameliorate those deviations of climate, it would reduce the risk of conflict.

There are many limitations to the present argument. First, it is an argument that has not been quantitatively demonstrated. That will be left for future research. Second, a more serious issue is that this argument does not take into account the fact that SRM is an act of political states, not a natural phenomenon. Whether a local climatic condition is improved or not, people who are subject to the change in climate due to SRM can easily pinpoint the actor who initiated SRM, and that perception could affect the prospect of conflict. This has already been pointed out by a study (Ide, 2017) looking into the climate-conflict nexus. There are potential remedies for this issue, such as parametric insurance (Horton & Keith, 2019), but this approach needs to be further explored.

This paper did not touch on the possibility of conflicts among major powers with reference to SRM, a topic extensively covered in the literature (Schelling, 1996; Bodansky, 2013; Flegal et al., 2019). The literature has often characterized the issues as related to unilateral action because of SRM's relative low cost and a free-driving externality (Weitzman, 2015), though countries could form a coalition for SRM implementation (Ricke et al., 2013). This subject obviously requires more thorough investigation. One thing that the current literature omits is the interconnectedness among the different issues. In a standard setting, the payoff function is formulated as a function of climate. In reality, states face multiple issues simultaneously. Currently, US–China relations have reached a new level of tension, but under the new Biden administration, climate change is being considered as an area for cooperation. These countries' decisions would certainly be affected by considerations in other areas.

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