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a call for balanced research**

Wieners, Claudia E.; Hofbauer, Ben P.; de Vries, Iris E.; Honegger, Matthias; Visioni, Daniele;
Russchenberg, Hermann W.J.; Felgenhauer, Tyler

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Editorial

Solar radiation modification is risky, but so is rejecting it: a call for balanced research

Introduction

As highlighted again by the most recent International Panel on Climate Change (IPCC) report [1, 2], climate change is an unprecedented threat. With every day of continued emissions and with every 10th of a degree of additional warming, more harm is done to people and ecosystems, and the risk of hitting tipping points is growing. Climate change affects people in all regions of the world and is impeding progress towards all UN sustainable development goals, including the eradication of poverty, inequality and injustice.

Eliminating emissions and removing carbon dioxide from the atmosphere (together 'mitigation'), and reducing damage through adaptation to climate risks and impacts, are currently accepted tools for addressing global warming and its consequences. But despite significant efforts and progress, there is no guarantee that these strategies will be sufficiently effective to keep global warming below 1.5 or even 2°C (see below). This realization has led to increasing interest in additional tools to reduce global warming and its impacts, such as solar radiation modification (SRM).

SRM aims to limit warming by reflecting a fraction of the incoming solar radiation, for example, by introducing a thin aerosol layer in the higher atmosphere or by brightening clouds [3, 4]. Modelling studies available to date suggest that SRM could deliver rapid cooling to help limit peak global warming to 1.5°C until emission reductions and carbon dioxide removal reduce greenhouse gas concentrations to tolerable levels. Models also indicate that using SRM to partially offset the assumed future warming could limit change across relevant climate variables, not just temperature, in most world regions [5].

SRM might provide an auxiliary tool to help reduce climate risk, limit suffering, lessen ecosystem degradation and improve the chances of sustainable development, but SRM is far from perfect. It does not address the root cause of global warming, does not precisely reverse all greenhouse gas-induced climate change even if the global mean temperature were restored to pre-industrial values, and is expected to come with its own set of societal and environmental risks and problems [4]. Because of this, SRM is highly controversial. Here we argue that nonetheless, thorough and critical research on SRM is a safer path than willfully neglecting it, as was recently demanded by a group of scientists proposing a 'Non-Use Agreement' that amounts to a *de facto* inhibition on SRM research [6].

Three concerns about climate mitigation call for investigating SRM

Mitigation is humanity's safest and most powerful means of fighting global warming and the only way to address its root

cause. SRM can at best complement mitigation and adaptation. However, even if humanity implements ambitious efforts in mitigation and adaptation, this may not suffice to prevent severe climate impacts and suffering. We have the following three concerns:

- Removal of CO₂ from the atmosphere may not be achieved at sufficient scale and speed. Recent IPCC scenarios [1] compatible with the Paris Agreement goal of limiting warming to 1.5°C rely on future technologies to remove CO₂ from the atmosphere, achieving global net-negative emissions by 2060. As the necessary techniques are still under development, it is uncertain whether they can be deployed in time and with sufficient intensity [7].
- The climate may react more strongly to greenhouse gases than expected. There is persisting uncertainty about the amount of warming resulting from greenhouse gases (climate sensitivity). According to the recent IPCC report [1], doubling CO₂ would warm the Earth by 2–5° (≥90% likelihood). Even the most ambitious IPCC scenario mentioned above, SSP1-19, will lead to more than 1.5°C warming if climate sensitivity is on the high end of current estimates.
- Limiting global warming to 1.5°C may not be enough to prevent serious damage. There is no certainty that severe impacts can be avoided even at this moderate warming level [2]. Adaptation may not suffice to prevent losses and suffering [8], especially if ecosystems or parts of the climate system cross tipping points [9]. But every 10th of a degree of warming we prevent reduces the probability of disastrous outcomes.

All three concerns have considerable probability; hence, the world must be prepared for the possibility that one or more of them prove true. If so, even ambitious decarbonization cannot prevent devastating climate impacts, which would disproportionately affect developing countries, induce injustice and instigate unprecedented governance challenges. And if the implementation of mitigation strategies lags behind the ambitious IPCC scenarios, climate risks will increase even more.

Hence, while SRM is risky, so is rejecting it. Ignoring either type of risk would distort judgement. We therefore recommend a 'Golden Rule' of assessing SRM: 'The risks of researching, developing and possibly implementing SRM must be balanced against the climate risks SRM would attenuate' [10, 11]. Given the severe risks of climate change, disregarding SRM may have strong repercussions for future generations. Rejecting SRM is therefore not

the obvious default option, but a choice that needs to be scrutinized both scientifically and ethically, in the same way as pursuing SRM needs scrutiny.

Research and transparent assessment is needed to lay the groundwork for future decision making

If one or more of the aforementioned concerns materializes, there is a significant chance that a decision on the use of SRM has to be made in the future, especially if the (perceived) pressure from climate impacts calls for fast and drastic action. Should such a situation arise, ignorance would add to the risk of misguided decisions and compromise the legitimacy of the decision-making process.

Pursuing SRM in spite of lack of knowledge bears a risk of ineffective or harmful implementation strategies. Rejecting SRM *a priori* would deprive humanity of a potential auxiliary tool against climate change impacts. Rejecting SRM is the correct decision if no beneficial SRM implementation strategy exists, but it might be difficult to uphold this decision under pressure without sufficient evidence for the harmfulness of SRM. Hence, regardless of whether SRM is beneficial or detrimental, ignorance jeopardizes rational, balanced, justifiable decision making.

Currently, humanity is not well prepared for a possible decision on SRM. From 2008 to 2018, only about 52 million dollars have been spent on SRM research [4] compared to over 30 billion for climate research in general [12]. Knowledge gaps remain regarding SRM's technical implementation, effectiveness, climate and environmental effects, best implementation scenarios, and governance. Our generation has the chance and capability to perform responsible and critical SRM research in time to gain the knowledge needed for sound decision making. These research efforts should include thorough, impartial, interdisciplinary and internationally legitimized assessment by international bodies such as the IPCC.

SRM research and ethics

Besides the environmental risks associated with SRM deployment, SRM research is also not without risks, especially on an ethical, societal and political level. Three main fears are raised against SRM.

- Delayed decarbonization: The fear that the development of SRM, or even simply knowing that SRM is being considered, will lead to less ambitious mitigation efforts.
- Sleepwalking into implementation: The fear that researching and discussing SRM will almost inevitably lead to the development and eventually implementation, for example, by shifting value judgement or establishing interest groups.
- Undemocratic decision making and governance: The fear that powerful actors, such as rich and influential nations, might impose decisions on SRM in the rest of the world. This would violate procedural justice and, given the global effects of SRM, raise concerns that groups excluded from the decision-making process would be subject to unfavourable outcomes.

These are important concerns, but they may not be inevitable. Behavioural experiments found that respondents confronted

with information on SRM might actually be more willing to mitigate [13, 14] although these studies are not uncontested [15] and may not be representative of the behaviour of decision makers [16]. Also, if research exposes that SRM is infeasible or grossly undesirable, it might actually debunk unfounded hopes of a technofix. Lock-in dynamics, while possible, is far from inevitable: Many budding technology developments never make it to the implementation stage [17], so research does not automatically lead to implementation. Also, the most difficult part in SRM implementation is not technical feasibility but finding an implementation strategy that optimizes benefits and minimizes risks (which might amount to abstaining from implementation altogether). Timely SRM research, even if it increases the likelihood of implementation, may well reduce the risk of 'inappropriate' implementation. Rejecting SRM research does not necessarily prevent future undemocratic or unilateral decision making on SRM. In fact, given the current unequal distribution of SRM knowledge, rejecting further research now might mostly be a decision of privileged actors who currently have the capacity to engage in (or oppose) SRM research [18] and would thus be an undemocratic act in itself. Transparent research, outreach and capacity building, especially in vulnerable developing countries [19], can empower citizens and underrepresented regions to take part in the debate and pre-empt rogue actors from monopolizing SRM knowledge [20].

The three risks are thus not necessarily made inevitable by engaging in SRM research, nor avoided by rejecting SRM research and, in our view, do not justify ignoring the potential of SRM. Instead, SRM research should be conducted in a way that minimizes risks induced by the research itself.

Following a number of scholars who have worked on moral frameworks for SRM [4, 21], we propose the following broad principles:

- Mitigation (including removals) and adaptation need to be the primary focus of climate policy. SRM should at most serve as an addition to reducing greenhouse gas concentrations.
- Knowledge and implementation of SRM must be administered in the public interest. This entails that the provision of SRM is organized by a globally legitimized body, and not based on private interests.
- Legitimate governance processes must be adhered to, and societal values such as justice and equality must be central when considering the role SRM research can play in lessening the threat of climate change.
- Any decision about deployment should be taken on the basis of broad public participation. Special emphasis should be placed on underrepresented and vulnerable communities, such as the Global South and Indigenous Peoples.
- The research process should be transparent, reflective and cooperative (also on the international level), and provide ample space for off-ramps, in case certain findings point towards undesirable outcomes of SRM deployment.
- SRM research must aim to create a comprehensive body of knowledge covering environmental, technical, political, societal and ethical sciences and properly linking and combining these domains.
- A solid framework for the governance of SRM should be in place before implementation is seriously considered. This entails engaging in research and consultations on

governance parallel to studying the environmental and technological aspects of SRM.

While there exists no complete framework yet to ensure adherence to these principles, the US National Academies of Sciences, Engineering and Medicine have recently published a collection of recommendations for scientists, states and the international community to promote fair and balanced SRM research [4]. These include: self-governance by the scientific community, for example, by establishing a code of conduct; transparency and commitment to open access; public engagement, outreach and inclusive international consultation; international collaboration and capacity building; regulating (large-scale) outdoor experiments; and non-commerciality.

The above principles are not intended to be the last word on the ethics of SRM research and deployment. Any ongoing ethical deliberation requires an open mind for criticism, debate and amendment. This is particularly important since the discussion around SRM research has thus far not been sufficiently representative nor global. However, this lack of representation only underscores the need for more inclusive thorough and systematic research into SRM and its impacts. By calling for ethical SRM research, we recognize that ethics has to be a central part of the research process itself.

Conclusions

Given the most recent projections of the IPCC, immediate and decisive action is necessary to reduce the threats of climate change. Rapid emission reduction and carbon dioxide removal are essential to keep and stabilize the climate system in a liveable state, and any further delay will increase climate-induced risks. Meanwhile, SRM might help to meaningfully reduce climate-induced risks, but it may also introduce new ones. When assessing SRM, all these risks must be fairly balanced. However, knowledge of SRM is as yet insufficient to achieve this.

Given the severity of the climate crisis, there is a significant chance that humanity will eventually have to take a decision in favour or against the use of SRM, and this possibility will not vanish if we now choose to ignore the issue or prohibit SRM research and assessment. If a choice on the use of SRM has to be made, ignorance increases the risk of inadequate decisions. We believe that society has a moral obligation to engage in SRM research—and to set up this process in such a way as to minimize potential risks stemming from the research itself. We therefore call for international, inclusive, transparent, reflective and comprehensive research efforts to enable a balanced assessment of SRM.

Supplementary material

A version of this paper with additional footnotes and an updated list of all signatories can be found on the website: <https://www.call-for-balance.com>.

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Authors' Contributions

Claudia Elisabeth Wieners (Conceptualization, Writing—original draft [equal]), Ben Paul Hofbauer (Conceptualization, Writing—original draft [equal]), Iris E. de Vries (Conceptualization, Writing—original draft [equal]), Matthias Honegger (Conceptualization, Writing—original draft [equal]), Daniele Visioni (Conceptualization, Writing—original draft [equal]), Herman W.J. Russchenberg (Conceptualization [equal]), and Tyler Felgenhauer (Conceptualization [equal]). All authors contributed to initial discussions and outline of manuscript. Claudia Elisabeth Wieners, Ben Paul Hofbauer, Iris E. de Vries, Matthias Honegger, and Daniele Visioni wrote manuscript.

Claudia E. Wieners^{1,2*}, **Ben P. Hofbauer**³, **Iris E. de Vries**⁴, **Matthias Honegger**⁵, **Daniele Visioni**⁶, **Hermann W.J. Russchenberg**⁷, **Tyler Felgenhauer**⁸

¹Institute for Marine and Atmospheric Research, Utrecht University, Utrecht 3584 CC, The Netherlands

²Centre for Complex Systems Studies, Utrecht University, Utrecht 3584 CE, The Netherlands

³Faculty of Technology, Policy and Management, Delft University of Technology, Delft 2628 BX, The Netherlands

⁴Institute for Atmospheric and Climate Science, ETH Zürich, Zürich 8092, Switzerland

⁵Perspectives Climate Research gGmbH, Freiburg i.B. 79106, Germany

⁶Sibley School of Mechanical and Aerospace Engineering, Cornell University, Freiburg i.B. 79106, Germany

⁷Department of Geoscience and Remote Sensing, Delft University of Technology, Delft 2628CN, The Netherlands

⁸Pratt School of Engineering, The Duke Center on Risk, Duke University, Durham NC 27705, USA

*Correspondence address. Institute for Marine and Atmospheric research, Utrecht, Utrecht University, Princetonplein 5, Utrecht 3584 CC, The Netherlands. E-mail: c.e.wieners@uu.nl

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