Spotlight on risk

Using stratospheric aerosol injection to alleviate global warming: when?

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Stratospheric aerosol injection (SAI), a type of solar radiation modification (SRM), has the potential to reduce global warming caused by excessive greenhouse gases in the atmosphere. However, there is currently widespread opposition to it, because deploying it would entail a number of uncertainties and risks. Here, we present a possible decision framework to help policymakers consider using the technique. Such a framework would be necessary if concrete evidence is found that it can contribute to reducing warming and that its related risks are acceptable. Of particular importance is the establishment of strict criteria for when SAI may or should be started, and when it should be stopped.

Solar radiation modification (SRM), also known as solar geoengineering, could be one among several strategies to combat climate change. It could contribute to reducing global warming caused by increased atmospheric greenhouse gas concentrations. Readers unfamiliar with SRM are

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recommended to read "*Combatting climate change through a portfolio of approaches*"[1] before this article, written for an audience informed about the various techniques to engineer the climate.

A patchwork of international environmental norms and conventions tends to constrain the consideration of SRM, either because it is not formally part of their mandate (UNFCCC), or because it may incur risk to the ozone layer (Montreal Protocol) or biodiversity (UNCBD). As a result, there is no obvious place for deliberating on SRM. No national climate policy considers SRM in its portfolio of climate strategies. However, SRM could alleviate some of the most dramatic consequences of temperature increase, and leading scientists, including David Keith,[2] have argued that deploying SRM technology should be considered to slow the pace of global warming.

Much of the attention is currently focused on stratospheric aerosol injection (SAI),[3] one of the leading SRM technologies, which involves spraying aerosols into the stratosphere to reflect incoming solar radiation, imitating the cooling effects observed after large volcanic eruptions.[4] There is some ongoing research aiming to help scientists and policymakers better understand the technical potential of SAI, how risks and other environmental and societal challenges might adversely impact the natural environment and society, and how those could be managed. However, very limited consideration has been given to the possible timing of SAI deployment, although this might help policymakers begin to think about when SAI might be deployed and phased out, and under what conditions. The underlying assumption of this piece is that the possibility to define strict conditions could reassure decision-makers, which could trigger more support for researching SAI and more collaboration in decisions.

Expected benefits and risks from SAI deployment

There is currently a record high concentration of CO_2 — the leading greenhouse gas — in the atmosphere.[5] According to the IPCC's sixth assessment report, the residual global carbon budget to remain within 1.5°C global warming with a 66% probability is 400 Gt of CO_2 from the start of 2020.[6] Currently, the world economy emits roughly 40 Gt of CO_2 per year, emissions are still rising,[7] and about 10 Gt are naturally removed by ecosystems. Impacts from climate change are already visible, and the problem only threatens to get worse.[8] While SAI would not reduce the actual atmospheric concentrations of greenhouse gases, it would cool the planet, thereby alleviating some negative consequences of global temperature rise (see Figure 1). It could be used to 'shave a peak' of

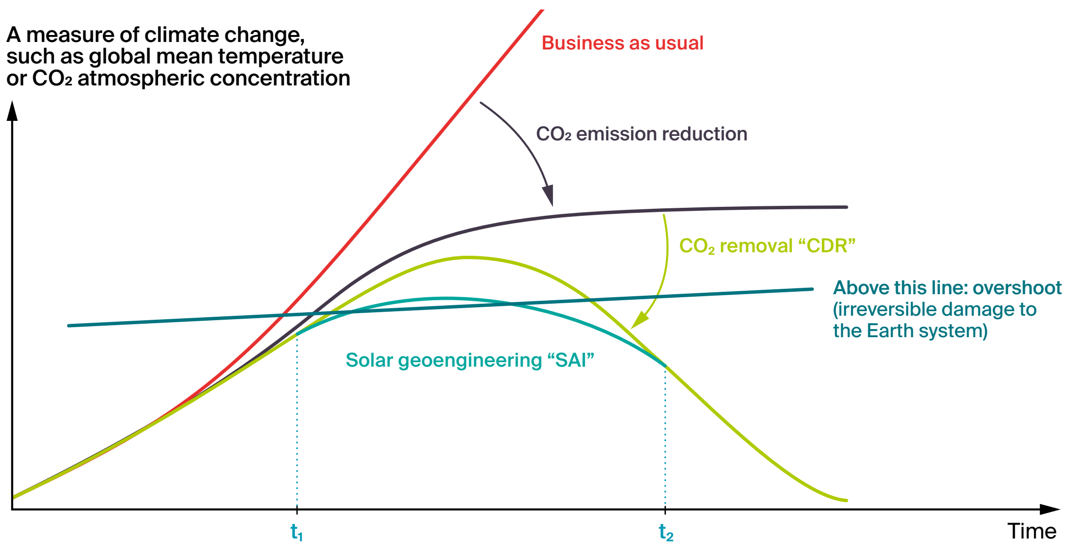

Figure 1. What is the role of CDR and SRM/SAI. Adapted from Jesse Reynolds: *Solar geoengineering to reduce climate change: a review of governance proposals*.[13] Original by Jane Long and John Shepherd: *The strategic value of geoengineering research*.[14]

temperature increase and climate impacts, buying time to address the underlying causes.[9]

'Shaving the peak' or 'buying time' is likely the only morally acceptable reason why SAI should be considered because of SAI's numerous potential risks.[10] These risks can be physical, such as potential changes to precipitation and evaporation patterns, stratospheric ozone depletion, and adverse consequences on biodiversity and ecosystems services. They also include geopolitical, security, socio-economic and ethical risks, such as the possibility of unilateral deployment by a rogue actor. In addition, there is the moral hazard concern that if SAI is seen as a solution, it might divert focus from emissions reduction.[11] If research shows that the risks of deploying the technology clearly outweigh the benefits, SAI should be taken off the table.[12]

A possible decision framework for SAI deployment

If it is not shown that the risks of SAI outweigh the benefits, and there comes a time when climate change brings ecosystems close to dangerous regime shifts, then decision-makers should consider deploying SAI.[15] Politicians, not scientists, would be in charge of making the decision, based on signals that important ecological tipping points are coming closer.[15] To prepare for this eventuality, we advise that policymakers, in collaboration with other stakeholders, have a framework in place, making clear the conditions that would permit starting SAI, and establishing ex-ante when it should be phased out. However, preparing for this possibility does not mean that SAI will ever actually be deployed, nor what type or scale would be best.

To help policymakers approach these decisions regarding SAI, we suggest three interconnected elements: research and governance, conditions for deployment, and timing.

Research and governance

This element has been widely discussed for some time. In essence, and as a prerequisite, governments and their institutions should decide on the governance of research on various SRM techniques, including small scale experimentation, and then engage in such research. This is in summary what the U.S. National Academies of Sciences, Engineering, and Medicine recommends in their Recommendations for Solar Geoengineering Research and Research Governance, published in March 2021.[16] Other national scientific institutions would be advised to consider similar approaches, and governments would be advised to support research and to stimulate discussion on SRM, rather than avoid the topic. In parallel, research and policy discussions about various options of global arrangements for the possible inclusion of SAI in climate agreements should take place. Currently, the United Nations is the most obvious place for this.[17]

Conditions for deployment

First, the conditions for possible deployment should be agreed upon in advance, based on indicators of climate change, such as CO_2 atmospheric concentration. However, this will not be easy to determine. When thresholds are reached on those indicators, the light would only turn from red to orange, not green, because other conditions should be met before deployment.

A second set of conditions concerns the requirement that SAI does not take place in isolation. It must complement emissions reduction efforts. Importantly, there would have to already be effective actions in reducing atmospheric greenhouse gas concentrations through mitigation and carbon dioxide removal (CDR). This is to avoid a 'termination shock', which is a dangerous and sudden temperature increase that would occur if SAI were ended before CO_2 atmospheric concentration had sufficiently declined.[18]

Therefore, in this framework, SAI should not be considered if mitigation efforts do not intensify. While some would see this condition as unrealistic, we believe it is necessary to agree on strict boundary conditions.

Timing

All this points to the importance of timing, both when to start and when to stop, as SAI must not be used indefinitely.[18] Policymakers would thus need to see SAI as a way to help fill a gap, or bridge two moments, which we call t_1, before which SAI is neither needed nor desirable (and should perhaps be prohibited), and t_2, after which SAI must be discontinued. t_1 and t_2 would be determined by a policy decision based on scientific evidence and collaborative deliberation with stakeholders to make it a legitimate decision.

Timing considerations

In determining when to start and stop SAI, several important factors must be considered, using the conditions described above.

When to start (t_1)

This proposed framework suggests three conditions for policymakers to decide when it is time to begin SAI (t_1). t_1 can only exist when all three of the following conditions are met:

1. We are close to crossing one or more dangerous ecological thresholds ('overshoot'), beyond which irreversible shifts and damage would occur in ecosystems. Such thresholds would need to be specified in advance (but might evolve with new science). Deployment would not wait until the tipping points have occurred, which would be too late, but start when early warnings are detected[19] that important socio-ecological systems are coming close to a regime shift.[15]
2. We are quite sure that we are on the path to sufficient CO_2 emissions reduction globally.
3. There is clarity as to when SAI can be stopped (t_2).

t_1 only exists if all three conditions above are met (including that t_2 can be identified).

When to stop (t_2)

t_2 is the time when the danger of irreversible damage has been avoided, and CO_2 concentration has started to decline. t_2 can only exist when the following conditions have been met:

4. It can be identified before t_1, i.e., before SAI is started.
5. Emissions will continue to be reduced during SAI deployment (should not go up again).
6. Sustainable large-scale CDR has been implemented effectively (CO_2 atmospheric concentration continues to decline).

t_2 only exists if conditions 4 to 6 are met. If this is not the case, deployment cannot be considered. t_2 must be clearly indicated in the policy decision to avoid continuing SAI for an undetermined period of time, which would increase the risk of a termination shock. In other words, using SAI is only reasonable and acceptable if linked to a serious reduction of CO_2 emissions and concentration.

This suggestion is neither complete nor perfect, but...

This piece suggests that it could be possible to create very strict conditions for SAI deployment. More work is needed to refine the details of the criteria, triggers and thresholds. Nevertheless, we hope this could contribute to reassuring decision-makers and encourage more active support of research, as well as efforts towards engaging in more collaborative international decisions. Before concluding, a few more observations:

- The framework described above does not include the case when climate impacts would become extremely severe, and some of these criteria for SAI deployment would not be met. It does not adopt the 'SRM for emergency' framing, because decision frameworks used in times of emergency, catastrophe or crisis are different from those for risk prevention and management. This suggestion is for deciding in the context of risk management, not crisis management. The analogy would be the management of nuclear safety or proliferation risk, in contrast to the management of a nuclear accident. The risk is tightly regulated at the international level and, even if its enforcement is sometimes difficult, nobody would say that international regulation to prevent nuclear proliferation risk is not needed.
- The framework does not rule out the possibility of deviations from pre-agreed plans. However, today, we are in the worst possible situation where there is no plan at all, so the first priority is to collaborate to design a plan.
- The framework does not include the case when governments would not behave as planned. The fact that some international agreements are not implemented is not a sufficient reason for not making international decisions.

Conclusion

When considering SAI, its risks must be compared to the climate risks of not deploying SAI, which we discussed in our previous Spotlight on risk article.[20] Both sets of risks are characterised by uncertainties and ambiguities. In May 2021, Nature published an editorial concluding that "if solar geoengineering [aka SRM] is harmful, leaders will need evidence so that they can rule out the technology," suggesting that until such evidence is found, a blanket decision to ban SAI is not appropriate.[21] We add that not deciding at all is not good either.

The decision framework presented in this article is certainly not perfect, but we hope it could create some confidence that considering SAI is not unreasonable. We suggest it is possible to make sensible, careful and stringent decisions about possible SAI deployment while continuing to prioritise CO_2 emission reduction.

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IRGC invites feedback with the goal to, if possible, refine the proposed decision framework through an open conversation. We are in particular interested in what contributes to establishing effective conditions for policy-science collaboration, or what kind of specific support policy needs from science. Please send commentaries to irgc@epfl.ch.

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