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Sulfur injections for a cooler planet

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To keep global temperature rise in check, annual stratospheric sulfur injections would have to be similar in scale to the eruption of Mount Pinatubo on 12 June 1991.

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Achieving the Paris Agreement's aim to limit the global temperature increase to at most 2°C above preindustrial levels will require rapid, substantial greenhouse gas emission reductions together with large-scale use of “negative emission” strategies for capturing carbon dioxide (CO₂) from the air (1). It remains unclear, however, how or indeed whether large net-negative emissions can be achieved, and neither technology nor sufficient storage capacity for captured carbon are available (2). Limited commitment for sufficient mitigation efforts and the uncertainty related to net-negative emissions have intensified calls for options that may help to reduce the worst climate effects (3). One suggested approach is the artificial reduction of sunlight reaching Earth's surface by increasing the reflectivity of Earth's surface or atmosphere.

Research in this area gained traction after Crutzen (4) called for investigating the effects of continuous sulfur injections into the stratosphere—or stratospheric aerosol modification (SAM)—as one method to deliberately mitigate anthropogenic global warming. The effect is analogous to the observed lowering of temperatures after large volcanic eruptions. SAM could be seen as a last-resort option to reduce the severity of climate change effects such as heat waves, floods, droughts, and sea level rise. Another possibility could be the seeding of ice clouds—an artificial enhancement of terrestrial radiation leaving the atmosphere—to reduce climate warming (5).

SAM technologies are presently not developed. Scientists are merely beginning to grasp the potential risks and benefits of these kinds of interventions (6). Earth-system model simulations have been used to explore idealized scenarios and thereby improve the

understanding of the climatic impacts of such approaches within the geoengineering model intercomparison project (GeoMIP). Results suggest that use of SAM would mitigate greenhouse gas–induced changes in global temperatures and extreme precipitation. However, different models consistently identify side effects; for example, the reduction of incoming solar radiation at Earth's surface reduces evaporation, which in turn reduces precipitation (7). This slowing of the hydrological cycle affects water availability, mostly in the tropics, and reduces monsoon precipitation.

Model studies have helped to improve the understanding of sulfur aerosol microphysics and transport; for example, models have successfully reproduced aerosol distributions after recent volcanic eruptions (8). It has also become clear that the cooling efficiency—that is, the cooling per injected unit of sulfur—falls with increasing injection rate (9). Thus, the more SAM is done, the less effective further injections are at reducing temperatures (see the figure, left panel). But the extent of injection required for a given level of cooling is uncertain, varying widely between models (10). The magnitude of the cooling effect also depends on injection location, height, and area and differs between models of different complexity.

Furthermore, the aerosol distribution patterns that result from SAM are uncertain and depend on aerosol microphysics and transport in the models. Stratospheric sulfate absorbs terrestrial radiation and thereby warms the stratosphere. This warming affects stratospheric dynamics; for example, it may increase the wind velocity in the equatorial wind systems of the stratosphere, increasing the tropical confinement of the aerosols and reducing the poleward transport of aerosols (11). This has consequences not only for sulfate but for the transport of all stratospheric constituents. In models, changes in stratospheric chemistry caused by SAM have been shown to affect stratospheric ozone concentrations and cause a delay of the Antarctic ozone recovery by several decades (12).

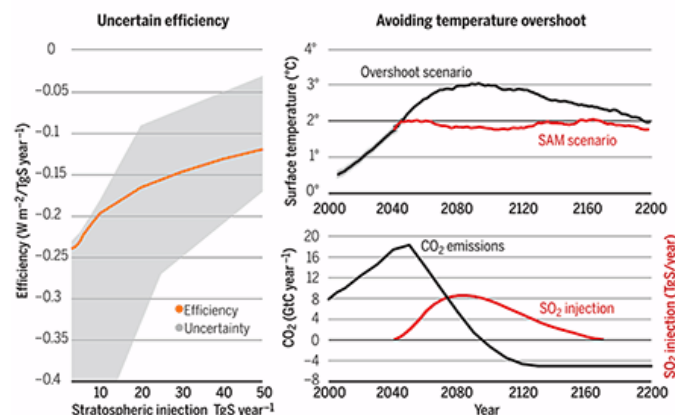
Aerosols with different characteristics than sulfur may eventually be developed to reduce some side effects (13). Small-scale experiments in the stratosphere have been proposed to further understand chemical and aerosol microphysical characteristics of sulfur and alternative aerosols (14). Those experiments, however, will not contribute to the understanding of largescale climate impacts of SAM due to SAM-related changes in stratospheric temperature and dynamics. Global changes and impacts can only be assessed with Earth system models, although it is difficult to attribute impacts to SAM.

Effects of stratospheric aerosol modification (SAM)

(Left) The cooling efficiency per injected unit of sulfur falls as more sulfur is injected. Furthermore, the overall effectiveness of SAM is uncertain. [Adapted from (7)] (Right) In a model study, CO₂ emissions were assumed to fall from 2040, becoming negative around 2095. Without SAM, temperatures rose to 3°C above preindustrial

Effects of stratospheric aerosol modification (SAM)

(Left) The cooling efficiency per injected unit of sulfur falls as more sulfur is injected. Furthermore, the overall effectiveness of SAM is uncertain. [Adapted from (7)] (Right) In a model study, CO₂ emissions were assumed to fall from 2040, becoming negative around 2095. Without SAM, temperatures rose to 3°C above preindustrial levels before falling back to 2°C above preindustrial levels by 2200. Use of SAM kept temperature increases to 2°C above preindustrial levels. [Adapted from (15)]



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levels before falling back to 2°C above preindustrial levels by 2200. Use of SAM kept temperature increases to 2°C above preindustrial levels. [Adapted from (15)]

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Most current Earth system models do not adequately capture important interactions, such as the coupling between stratospheric aerosols, chemistry, radiation, and climate. They cannot, therefore, simulate the full impact of the interventions. A comprehensive description of these interactions in models as well as coupling with ice, ocean, and land are expected to provide a better estimation of the uncertainties and risks. Processes in Earth system models can be further improved through expanded continuous observations of the atmosphere's composition. Such observation capability would also ensure high-quality measurements after rare large volcanic eruptions.

Beyond the scientific assessments of possible impacts, it is crucial to understand the economic costs and technological requirements of stratospheric sulfur injection. Assuming a scenario in which aggressive mitigation and large-scale carbon capture and removal start as late as 2040, sulfur must be injected for 160 years, with a peak injection of 8 TgS/year, to limit the temperature increase to 2°C above preindustrial levels (see the figure, right panel) (15); this injection amount is equivalent to one Mount Pinatubo eruption per year (see the photo). Without the intervention, temperatures would have risen by 3°C. The estimated delivery cost of sulfur into the

stratosphere for $\sim 1^\circ\text{C}$ of cooling with aircraft newly developed for SAM is US\$20 billion/year (**10**), requiring 6700 flights per day. The cost would increase for higher injection rates because of the decreasing cooling efficiency (**9**).

Additional costs arise from the need to set up a comprehensive observation system with which to monitor atmospheric changes, including aerosol distribution, impact on chemistry, and climate. The necessary amount of sulfur injection would need to be estimated according to comprehensive forecast models, requiring extensive modeling capabilities. The total cost of SAM would also need to include compensation for potential side effects and would thus be much higher than the delivery costs (**16**).

Currently, a single person, company, or state may be able to deploy SAM without in-depth assessments of the risks, potentially causing global impacts that could rapidly lead to conflict. As such, it is essential that international agreements are reached to regulate whether and how SAM should be implemented (**3**). A liability regime would rapidly become essential to resolve conflicts, especially because existing international liability rules do not provide equitable and effective compensation for potential SAM damage (**17**). Such complexities will require the establishment of international governance of climate intervention, overseeing research with frequent assessments of benefits and side effects.

Climate intervention should only be seen as a supplement and not a replacement for greenhouse gas mitigation and decarbonization efforts because the necessary level and application time of SAM would continuously grow with the need for more cooling to counteract increasing greenhouse gas concentrations. A sudden disruption of SAM would cause an extremely fast increase in global temperature. Also, SAM does not ameliorate major consequences of the CO_2 increase in the atmosphere, such as ocean acidification, which would continue to worsen.

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