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COMMENTARY
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A Living Assessment of Different Materials for Stratospheric Aerosol Injection—Building Bridges Between Model World and the Messiness of Reality

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Key Points:

- Vattioni et al. (2023, https://doi.org/10.1029/2023gl105889) demonstrated large uncertainties in the projected impacts of alumina particles in the stratosphere
- We use the results to discuss more broadly how to better think about the climate impacts and side effects of Stratospheric Aerosol Injection
- We propose the idea of a "living assessment" of Stratospheric Aerosol Injections that can constantly integrate useful experimental results with modeling work

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Abstract

There are obstacles in better understanding the climate impacts associated with new materials that could be used for Stratospheric Aerosol Injections (SAI), like the lack of an integrated framework that combines climate modeling across scales, laboratory studies and small-scale field experiments. Vattioni et al. (2023, https://doi.org/10.1029/2023gl105889) explored one aspect of using alternative, non-sulfate materials for SAI. They investigated how uncertain the response of stratospheric ozone would be to alumina injections for SAI. In their study, they quantify chlorine activation rates in the presence of alumina, and then cascade these uncertainties into estimates of ozone depletion, concluding that alumina might have less detrimental impacts on stratospheric chemistry than sulfate, but with large uncertainties. Their results provide a useful basis upon which future research endeavors combining indoor and outdoor experiments and modeling may be structured to produce robust assessments of SAI impacts, benefits and uncertainties, together with clarifying what kind of research needs to be prioritized.

Plain Language Summary

We could use tiny particles injected into the higher atmosphere to reflect a small portion of incoming sunlight and thereby cool the planet. But doing so comes with risks and uncertainties: for instance, one might wonder how do we select which kind of particles to use. Sulfate is present in nature, for instance during the aftermath of volcanic eruptions followed by an observable surface cooling. However, we know that mimicking that effect would come with some drawbacks, for example, it heats the upper layer of the atmosphere and affects ozone. Alumina, supposedly, would impact atmospheric chemistry less than sulfate and so might be considered "preferable," but not being naturally present in the atmosphere, there are lots of things we don't know. For example, Vattioni et al. (2023, https://doi.org/10.1029/2023gl105889) demonstrate that even potential implications for atmospheric chemistry are highly uncertain when looking at alumina particles as a candidate for Stratospheric Aerosol Injections (SAI). Therefore, their study is a good opportunity to think more broadly about intended SAI-associated climate impacts and unwanted side effects, and how to better coordinate research activities in this space.

As the effects of anthropogenic climatic change become more evident by the year, and as its future threats and risks are elucidated by climate science (for instance, when thinking of tipping points looming in on us, McKay et al. (2022)), discussions around Solar Radiation Modification (SRM), that is, reducing the amount of incoming sunlight, are likely to become more prominent. For now, such discussions have been often either confined to debating the abstract concept of climate interventions or limited to the scientific investigation of expected higher-level Stratospheric Aerosol Injections (SAI) impacts, for example, through climate model experiments or, in a more limited capacity, some indoor laboratory experiments. Therefore, the details of SAI impacts not only on surface temperatures and precipitation, but also on ecosystems and human livelihoods are underexplored (Zarnetske et al., 2021).

But as the interest grows, and as international institutions and countries put the issue on their agenda, a through and balanced evaluation of SAI-associated climate impacts and unwanted side effects needs to be based on a more realistic assessment of potential deployment scenarios. Governments and citizens may ask, for instance, if there is an optimal choice in SAI materials.

The study by Vattioni et al. (2023) clearly highlights how difficult responding to this question will be. The vast majority of the modeling studies trying to investigate the physical impacts of SAI tend to use sulfate (and overwhelmingly, the sulfate aerosol precursor SO_2) (Visioni et al., 2021) to mimic the effect of big volcanic eruptions. However, there have been multiple studies suggesting that other materials might be similarly effective in reflecting solar light (Crutzen, 2006; Ferraro et al., 2015; Keith et al., 2016; Pope et al., 2012). Some of these materials may not interfere as much with atmospheric processes, either chemically or radiatively, and might be therefore have fewer detrimental side effects. However, it is currently unclear how to analyze these different trade-offs between effectiveness and (partially undesirable) changes in atmospheric chemistry.

Vattioni et al. (2023) builds on those studies and asks: would one of these proposed alternate aerosols, alumina, actually be less harmful to stratospheric ozone? They try to answer this question by combining available literature on what would happen to such alumina particles under stratospheric conditions, performing their own experiments of its behavior and then finally analyzing the outcome in a state-of-the-art climate model. Their well-crafted answer is "alumina injection is fraught with significant uncertainties" or, in layman's terms, "it depends." It might result in a few percent points less reduction of the overall ozone column compared to sulfate injections if such particles were to be fully coated by naturally-present H_2SO_4. Or it might not, if the reaction probability (γ_{ClONO2}) of one of the ozone-depleting chemical reactions once the alumina is added turns out to be particularly high, and actually result in a far larger depletion (over 30% over the South Pole, and over 10% in the tropics) than could ever be expected under sulfate injections. Furthermore, the relevance of such uncertainties will depend on when such injections would happen: in 2090, when hopefully and thanks to the Montreal Protocols ozone depleting substances (ODS) will be far less in the stratosphere, the depletion potential would be far, far less independently of the more or less pessimistic chemical scenario (Figure 1a).

Some of these aforementioned uncertainties may be unresolvable (we don't know what humanity will do, be it with the governance of SAI or with carbon or ODS emissions) while some of them might be narrowed down with more research. Hence, a particular risk should not be just evaluated in terms of trade-offs (for instance, a 5% reduction in stratospheric ozone vs. a further warming of 0.5°C) (Felgenhauer et al., 2022), but also taking into account the (deep) uncertainties associated with these trade-offs within a wider context (Keller et al., 2021) (Figure 1b). Following the example, this would mean thinking about whether ozone might actually be reduced by 1% or 12% or not at all, and what would this entail for actual impacts (for instance, how they would change surface UV exposure, compared to previous ozone levels during higher chlorine loads in past decades). A probabilistic view on deep uncertainties would also give room to exploring what might be catastrophic risks, because sometimes the tails of the distribution might be of far more concern that the median ever could. An example, could be the probability that the Atlantic Meridional Overturning Circulation (AMOC) might shut down due to anthropogenic warming (Ditlevsen & Ditlevsen, 2023), and the chance that SAI might prevent it if started early enough (Pflüger et al., 2024).

Hence we think that a reader of the Vattioni et al. (2023) study should not conclude that "The risks are too high, we should never think about alumina (or SAI in general) ever again" but rather they should wonder "What can we do to evaluate these uncertainties and trade-offs as part of a decision-making process?". Not all uncertainties can be narrowed down indefinitely: most studies focus on SO_2 injection because simulating a natural analog can both yield precious information for the case under analysis and because it offers some upper bounds for what's the worst that could happen. Mt. Pinatubo's eruption in 1991 injected roughly four time as much SO_2 in a day than what Vattioni et al. (2023) consider in their study. The stratosphere did warm, ozone was affected (Aquila et al., 2013) and, ultimately, the surface was cooled. While there are many differences between the actual eruption event and continuous SAI (Plazzotta et al., 2018), the climatic response to Pinatubo is still incredibly valuable in bounding how wrong can we be when considering the outcomes of sulfate-based SAI, and demonstrating how adequate our climate modeling tools are (Quaglia et al., 2023).

Alternate SAI materials such as alumina might offer advantages but also need even more scrutiny and a multipronged approach covering engineering challenges as well as a physical sciences view before even being able to develop a more comprehensive impacts assessment. For marine cloud brightening, Diamond et al. (2022) defined six topics linking science and engineering developments (e.g., cloud microphysics) to other challenging questions, such as ecosystems responses (Zarnetske et al., 2021), which then in turn have further reaching implications related to justice and precaution (Buck et al., 2020). These topics serve as checkpoints to bring together researchers and stakeholders in policy making, and facilitate decisions about continuing research toward a certain direction, for example, a specific aerosol delivery method.

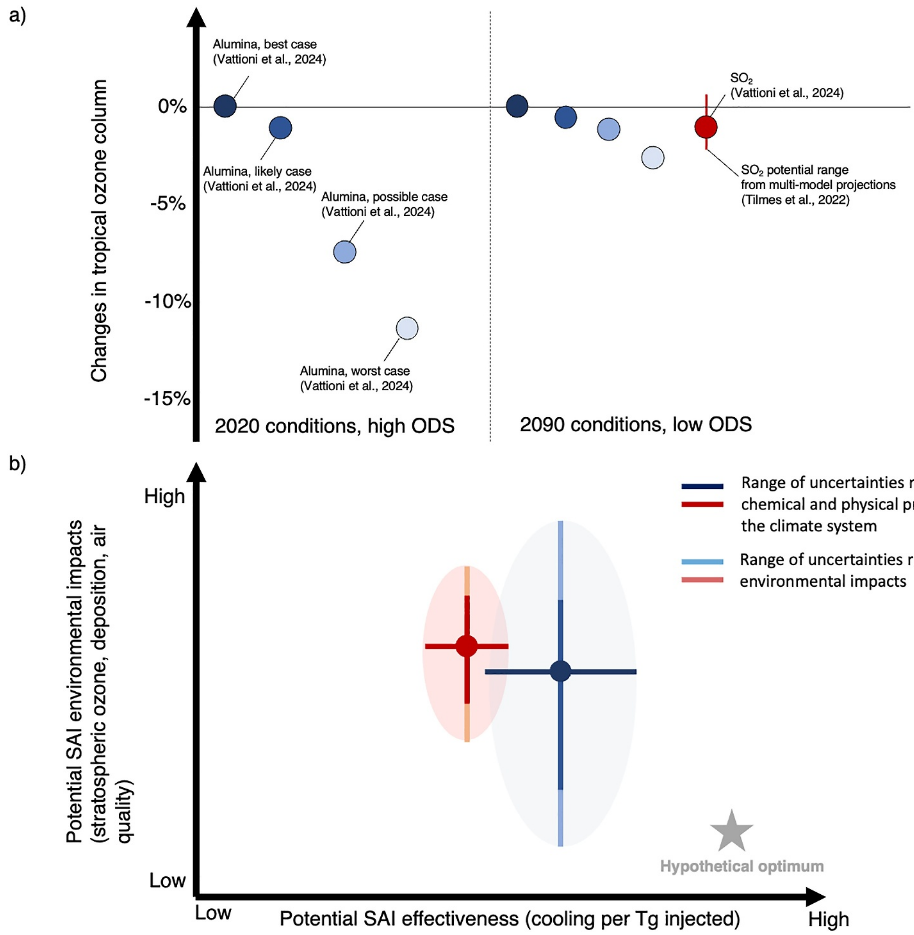

Figure 1. (a) A simplified summary of the results in Vattioni et al. (2023), focusing on tropical ozone changes. For SO_2 (red dot), an uncertainty bar derived using multi-model results from Tilmes et al. (2022) has been added, even if the injection magnitude are higher in that case. (b) Schematic of potential uncertainty ranges that would be associated with sulfate or alumina (or other materials) in the case of SAI for both effectiveness and environmental impacts. Due to the lack of natural analogs, physical and environmental uncertainties might be larger for alumina compared to sulfate, but with the potential for the central value to be lower for a close to ideal material, as shown in panel (a). Some uncertainties can be narrowed down with further observations, or with direct tests. Scenario uncertainty, which depends on factors that might not be related directly to chemistry or physics, such as the underlying emission scenario of ozone depleting substances, or other sources that are not within direct control, and that require more holistic assessments, are also relevant to an overall assessment.

For SAI, similar checkpoints could be defined. We suggest that four topical areas should be investigated in more detail and across disciplines: (A) Climatic projections under SAI—direct and indirect radiative effects on temperature, precipitation and large scale dynamics, (B) Aerosol delivery, (C) Changes in atmospheric chemistry, and (D) Ecosystem impacts linked to particle deposition, quality of light and climatic changes. This list of topics is not meant to exhaustive but should rather serve as a starting point to inform the political debate. Comparing two different SAI materials then would constitute a multiple-objective decision problem where trade-offs could be made between different metrics linked to these different topics. For example, a material could score higher on not affecting precipitation through large scale dynamical changes, but could have more detrimental impacts on ozone depletion—which prompted the study by Vattioni et al. (2023). Within this multi-option decision making space, uncertainties will play a key role in order to better evaluate trade-offs between different options. To better quantify uncertainties and highlight interactions between different topics, we need a broader, collective effort by the SAI research community with the aim of not just producing great science, but to form the backbone of a robust and transparent process that builds global confidence in the overall results. What steps could we take to make this happen? We think that mostly two things are needed:

1. *A clear communication of research aims, overall framing and possible limitations of any SAI research approach*: offering more clarity for each experiment over which uncertainty is expected to be explored, and reduced, by outlining which targeted parameter or mechanism would be modified or improved in a climate model projection, or how our basic understanding of a physical process would be modified. In Vattioni et al. (2023), this equates to being clear about what would be changed in the climate model with the new γ_{ClONO2} values. Proposed improvements in climate models, and their prioritization, could also be framed around how they might reduce specific uncertainties and better integrated novel information from observations and experiments.
2. *Converge on a list of modeling experiments of broad relevance with a clear backbone in laboratory studies and observations*: This would mean having a "before" and "after" of Figure 2 in Vattioni et al. (2023), except repeated over multiple potential impacts other than ozone, and clearly explaining the whole range of uncertainties associated with model assumptions as well as experimental inputs and constraints. Another example would be that observations serve as inputs for improved parameterizations of critical processes such as the aerosol delivery and as constraints for modeling frameworks used for detection and attribution. Standardized climate model experiments of SRM are nothing new (it's something the Geoengineering Model Intercomparison Project has been doing for a decade, see Visioni et al. (2023)), but they might look different if they are explicitly aimed at robustly quantifying (and ideally reducing) specific uncertainties in an operational, iterative way.

We believe a "living assessment" of SAI would be capable of building confidence in the projected outcomes, and that can be constantly re-assessed once new information (be it good or bad) comes in. An integrated and transparent framework combining modeling efforts, laboratory studies and both existing and novel observations (which should include also small outdoor tests, if deemed necessary, useful and with low environmental impacts) would also help to distinguish these efforts better from actions of rogue players aiming to 'sell' SRM, especially if new scientific results can be linked to impacts and policy relevant information. It would also make clear to modeling centers what kind of improvements, theoretical research and modeling experiments are necessary to narrow down specific uncertainties and how to integrate experimental results and novel observations better. A starting point for collecting information on SAI related research activities could be the NASA Panel for Data Evaluation (Burkholder et al., 2019), that offers multi-year updates on chemical data to be used by atmospheric modelers, and whose structure could somewhat be replicated. We acknowledge that such steps would obviously also add a burden, together with the benefits we imagine below; on this, we remand to the vigorous discussions around the benefits in terms of public trust, and the burdens, of pre-registering clinical trials and observational studies in the medical field (Krleža-Jerić et al., 2005; McDermott, 2023; Nosek et al., 2018; Zarin & Tse, 2008). The ambitiousness in not lost on us, nor are its related requirements in terms of time and personnel; but for us this underscores the dire need for more resources to be devoted to SRM research (National Academies of Sciences Engineering and Medicine, 2021).

This "living assessment" would provide valuable information to everyone: it can highlight what needs to be prioritized for funding bodies, it can better motivate researchers and foster research collaborations across disciplines, and it can provide decision-makers and the public with a robust base for informed deliberation around the topic of SAI. Climate models' results will constitute the outward facing part of such an assessment: as SAI is not deployed anywhere, we will always need models to build the counterfactual world of what would happen with or without it in hypothetical futures. But model robustness and trust in models are not inherent properties, are not solely a function of models' complexity, and are not something that can be derived from a mathematical demonstration (Lloyd, 2010): rather, they are emerging qualities of a research endeavor that can fully demonstrate a commitment to transparency, inclusivity (geographical, and in terms of expertizes represented) and clarity of intents.

Data Availability Statement

Data were not used, nor created for this research.

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