Introduction

Carbon dioxide concentrations in the atmosphere are higher than they have been in the last 2 million years and are increasing every year (Cenozoic CO2 Proxy Integration Project Consortium 2023). Due to this, the Earth is warming at a rate nearly twenty times faster than it did when transitioning out of the last glacial period (Eldevik et al. 2014). Global temperature changes are caused by imbalances between incoming solar energy and outgoing infrared energy from the planet (Laakso et al. 2024). Greenhouse gases (GHGs) primarily drive this imbalance by re-emitting infrared energy back to the planet (Filonchyk et al. 2024). As humans increase GHG concentrations in the atmosphere, outgoing infrared energy gets trapped in the Earth system.[1] This ultimately leads to a steady increase in the internal energy of the Earth system, which directly increases surface temperatures (Filonchyk et al. 2024). The Earth's unprecedented warming is rapidly changing the climate, exacerbating severe and catastrophic weather events, and directly threatening life within the biosphere (Glade et al. 2023).

A large segment of current global warming mitigation research focuses on restoring the Earth's energy output by reducing GHG concentrations. However, new research focuses on minimizing direct solar energy inputs into the Earth system (Laakso et al. 2024). One method involves injecting small suspended particles into the stratosphere (Laakso et al. 2024). These particles, or aerosols, scatter incoming solar radiation and reflect some of it back into space (Laakso et al. 2024). In addition, they increase the formation of clouds which have high reflectivity of sunlight (Prabhakaran et al. 2024).

Studies simulate the effects of aerosols—primarily sulfur dioxide—on the climate system through the use of coupled Earth system models (Fasullo et al. 2018). Coupled models contain large uncertainties due to the inherent difficulty of mathematically modeling the complex

[1] "Earth system" is the preferred term, as opposed to "Earth's systems."

interactions within the climate system (Fasullo et al. 2018). This review discusses the intended and unintended climatic effects of aerosols, and identifies the sources of uncertainty in models. It also lays out potential injection schemes, discussing some of the important atmospheric considerations that go into an effective injection strategy. The importance and feasibility of stratospheric aerosol injections (SAIs) in a warming climate could be more accurately assessed through the research suggested in this review.

Climatic Effects of Aerosols

SAIs have the capacity to cool the climate and largely reshape current climate systems through their sunlight reflectance capabilities (Laakso et al. 2024). Aerosols directly scatter and reflect solar radiation back to space to cool the Earth (Prabhakaran et al. 2024). In addition, aerosols act as seeds upon which water vapor can gather and become cloud droplets. Once clouds form, they have a relatively high albedo, meaning their surface is capable of reflecting a large amount of sunlight. These qualities lead to a cooling of the planet's surface as less sunlight is allowed into the Earth system. Aerosols also slow the natural transition of highly reflectant stratocumulus clouds to much less reflectant cumulus clouds. With more sunlight reflected by stratocumulus clouds for longer periods of time, aerosols have a higher net cooling effect. These aerosol physics are integrated into complex Earth System Models that can simulate interactions between aerosols and the atmosphere (Prabhakaran et al. 2024). According to Lee et al. (2019), models estimate that aerosol injections could generate sufficient temperature reductions to return the Earth's temperature back to pre-industrial times. In other words, all of the current warming from GHGs could be negated (Lee et al. 2019). However, it is important to recognize that the impact of aerosols on the non-temperature related effects of GHGs—such as ocean acidification—would be negligible (Jin et al. 2022).

Precipitation

Global precipitation generally has a positive relationship with temperature; as a result, when aerosols are applied to a simulated stratosphere and temperatures cool, global precipitation decreases in models (Laakso et al. 2024). However, when simulating an aerosol scheme that is designed to bring temperatures back to pre-industrial conditions, models show that aerosols would decrease precipitation beyond what is expected. Atmospheric models estimate that if aerosols completely negate the effects of global warming, they would reduce global precipitation by an additional .7% to 2.4% from pre-industrial times. Decreases in modeled precipitation patterns are likely driven by an energy imbalance between the stratosphere and troposphere (Laakso et al. 2024). If the magnitude of aerosol injections were to increase, aerosols would grow larger and absorb more long-wave radiation, heating the stratosphere and leading to an unexpected decline in precipitation (McGraw and Polvani 2024; Laakso et al. 2024). However, these precipitation estimates are highly uncertain due to the way they are modeled (Fasullo et al. 2019). The coupled models used in these studies are often highly simplified versions of the Earth system as a whole and potentially overlook intricate interactions within the real climate system. Until a more comprehensive understanding of the climate system develops, the climatic effects of SAIs will remain highly uncertain (Fasullo et al. 2019).

Ozone Depletion

The chemistry of the stratosphere is extremely complex and our inadequate understanding of how aerosols interact with stratospheric ozone makes it difficult to accurately simulate their impacts (Bednarz et al. 2023a). As a result, coupled models likely ignore important aspects of stratospheric chemistry (Fasullo et al. 2019). Current predictions are based on the assumption that aerosols will warm the lower stratosphere (Bednarz et al. 2023a). Stratospheric warming could exacerbate catalytic ozone depletion which could have unexpected effects on hydrological circulations and global weather patterns (Bednarz et al. 2023a). In addition, because ozone is a GHG, its removal could potentially cool the Earth further as less outgoing radiation is trapped in the atmosphere (Laakso et al. 2024). Until models can more accurately simulate aerosol interactions within the stratosphere, the implementation of SAIs will remain risky. New research must identify ways to enhance the certainty of models and limit the possibility of extreme climate consequences if SAIs are used (Laakso et al. 2024).

Possible Schemes

Despite the large-scale global climatic uncertainties associated with SAIs, researchers have proposed methods to optimize the cooling effect of aerosols. Laakso et al. (2024) explain that with atmospheric CO_2 concentrations of 500 ppm, optimal sulfur injection rates to negate projected warming vary. Models suggest that sulfur injections of anywhere from 5 to 19 TgS (teragrams of sulfur) per year would be necessary to achieve pre-industrial temperatures based on these concentrations (Laakso et al. 2024). This wide range is due to the fact that different injection sites would have different impacts on aerosol longevity and effectiveness (Zhang et al. 2024). For instance, Zhang et al. (2024) show that subtropical latitude injections would produce more global cooling per unit aerosol than polar and equatorial injections. Furthermore, because poleward winds are asymmetrical across different longitudes, injecting aerosols at specific longitudes—depending on the time of year—could increase their lifetime (Sun et al. 2023). Both studies also note potentially beneficial secondary effects of higher-latitude injection sites. For instance, summer Arctic sea ice, which is rapidly declining, would experience the greatest recovery from a polar-latitude injection scheme because of the shifting temperature gradient (Zhang et al. 2024). Thus, potential climate tradeoffs need to be considered in aerosol injection schemes and clear objectives must be established. Differing schemes may have the potential to work in tandem, with some tailored towards global climate regulation, and others customized for regional climatic changes.

When developing efficient schemes, managing the lifetime of aerosols would also be beneficial (Sun et al. 2023). Aerosols injected higher in the stratosphere typically have a longer lifetime because they slowly descend through the atmosphere. However, higher altitude injections also require significantly more resources to be executed effectively and are associated with greater costs. The latitude and longitude of injection sites can be optimized by identifying air circulation patterns with strong poleward wind at specific locations and during certain times of the year. Injecting aerosols into air-flow patterns such as the Brewer-Dobson circulation would promote persistent circulation in the atmosphere. By targeting these areas, injection schemes could be designed for lower altitudes while still achieving the same aerosol cooling capacity (Sun et al. 2023). However, models indicate that SAIs could significantly change the intensity and magnitude of current air circulations, including the Brewer-Dobson circulation (Bednarz et al. 2023b). To ensure that aerosol injections can be optimized and adapted over time, developing a comprehensive understanding of these changing atmospheric dynamics is crucial.

Research Uncertainties and Potentials

Beyond their simplification of the climate system, coupled climate models used in SAI simulations are rendered inherently uncertain by their predictor variables (Maattanen et al. 2024). Earth's climate sensitivity—how intense temperature changes are for a given amount of GHGs—is a largely ambiguous variable that can differ greatly among models (Laakso et al. 2024). Small changes in climate sensitivity can have large impacts on temperature uncertainties (Laakso et al. 2024). Elastic variables, such as the magnitude of future emissions, further complicate models because they are geopolitically-dependent (Maattanen et al. 2024). As a result, *predictive* models are informed by already uncertain *predictions* of future climate (Maattanen et al. 2024). Laakso et al. (2024) acknowledge this uncertainty, explaining that across models there is a discrepancy in how aerosol injections might affect temperature and precipitation responses globally. These discrepancies create the potential for extreme weather or climatic changes to be overlooked (Laakso et al. 2024). For instance, the effect that SAIs might have on the depletion of stratospheric ozone by increasing stratospheric water vapor is highly uncertain (Bednarz et al. 2023a). While it is known that increases in stratospheric water vapor can lead to catalytic ozone depletion, the extent of ozone loss is not fully understood (Bednarz et al. 2023a). Future studies should work to increase knowledge about how the ozone layer will respond to aerosols. In addition, to improve their accuracy, predictive climate models—such as those regarding precipitation and circulation patterns—must include statistical terms for uncertainty about interactions within the climate system. Although it is impossible to accurately predict how elastic variables will change in the future, model uncertainty can be decreased by incorporating new variables and narrowing the scope of current ones.

Conclusion

Researchers focus on SAIs for their potential use in reversing the global warming caused by GHGs. Current research shows the potential for aerosols to negate GHG warming and lower temperatures to pre-industrial levels. Despite the uncertainties discussed in this review, the research clearly indicates that SAIs should at least be considered a tool of last resort. If climate accelerates beyond a tipping point, SAIs could be used to curb extreme changes in global temperatures, even if their own effects are not well understood. Incorporating a more comprehensive understanding of the climate system into coupled climate models is essential in assessing the true usefulness of SAIs as a tool in fighting climate change. Understanding the climate's intricacies will require further studies on atmospheric dynamics with a strong emphasis on stratospheric chemistry. Future studies should also identify the long-term effects of aerosols on stratospheric ozone and global precipitation patterns. Through these studies, uncertainties could be meaningfully reduced in current models and more informed decisions could be made about if, how, and for what specific purpose aerosol injections should be implemented.