Stratospheric Aerosol Removal Technology

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Abstract

Abrupt Sunlight Reduction Scenarios (ASRS) can be caused by a large injection of aerosols into the stratosphere. Despite their immense potential to cause devastating outcomes to humanity, there is currently a lack of a comprehensive plan for an effective response to mitigate the scale or duration of an ASRS. In this study, I evaluate various aerosol removal technologies, including HEPA filtration, electrostatic precipitation, cyclonic separation, chemical scrubbing, and heterogeneous nucleation enhancement, in the context of the unique challenges posed by the stratosphere. Key challenges include extreme temperatures, low pressures, low humidity, and high ultraviolet radiation, which complicate the deployment and maintenance of these systems. In view of these constraints, I propose a hybrid multi-stage system combining HEPA filters and electrostatic precipitators to efficiently remove aerosols from the stratosphere while minimising maintenance requirements. This study ultimately lays the groundwork for the development of feasible aerosol removal systems that could mitigate the potentially catastrophic impacts of an ASRS on global climate.

Introduction

An Abrupt Sunlight Reduction Scenario (ASRS) is characterised by a sudden and significant reduction in the amount of solar energy reaching the Earth's surface, which can be caused by a large injection of aerosols into the atmosphere. Depending on the properties of the aerosol particles and the altitude of the injection, these particles may rise past the tropopause into the stratosphere, where the lack of weather phenomenon allows the aerosol particles to spread globally and stay in the stratosphere for prolonged periods of time.[1] This causes the attenuation of sunlight and depletion of the ozone layer, which the stratosphere is home to. If left unaddressed, an ASRS can lead to decadal disruptions to the Earth's climate, impacting food production systems all around the world and potentially posing an existential threat to humanity.

Aerosol Injections

In this study, I have outlined four aerosol injection events that could potentially lead to an ASRS, two of which are natural and the other two are anthropogenic.

Asteroid Impact

If a sufficiently large asteroid were to strike the surface of the Earth, large amounts of soot, impact ejecta and vapourised material may be ejected into the atmosphere, giving rise to an impact winter. The Cretaceous-Paleogene extinction event that wiped out all non-avian dinosaurs on Earth approximately 66 million years ago likely involved an impact winter caused by the impact of a massive asteroid 10 to 15 kilometres wide. Today, astronomers have found 95% of all near-Earth asteroids greater than 1 kilometre and over 99% of asteroids greater than 10 kilometres, and none of them have an appreciable chance of collision with the Earth. Taking this trajectory information into account, the probability of an asteroid collision with Earth in the next century has been calculated to be about 1 in 120 000 for asteroids between 1 and 10 kilometres, and about 1 in 150 million for those above 10 kilometres.

[1] Refer to Annex A for an overview of the major layers of the Earth's atmosphere.

Volcanic Eruption

Volcanic eruptions emit large amounts of soot, volcanic ash, volcanic gases including sulfur dioxide and nitrogen oxides, as well as mineral particulates. Volcanic eruptions are especially concerning as the volcanic plumes rising out of the volcano during an eruption can extend many kilometres into the sky, thereby significantly increasing the probability that the emitted particles are able to rise into the stratosphere, giving rise to a volcanic winter. The potential of volcanic eruptions to lead to global cooling episodes have been well exemplified by the eruptions of Mount Tambora in 1815 (VEI-7), Krakatoa in 1883 (VEI-6) and Mount Pinatubo in 1991 (VEI-6), the former of which was the dominant cause of the 1816 "Year Without a Summer".[2] These eruptions emitted large amounts of sulfur dioxide into the atmosphere, leading to reductions in global temperatures by as much as 0.5 °C in the following years. While geologists have identified the remnants of dozens of supereruptions, their frequency remains very uncertain. A recent review gave a central estimate of one VEI-8 or VEI-9 eruption in 200 centuries and one VEI-9+ eruption in 8000 centuries, albeit with substantial uncertainty.

Nuclear War

A nuclear war between two nations may result in extensive firestorms in burning cities, emitting large amounts of black soot and nuclear fallout into the atmosphere. These particles are lifted high into the stratosphere by the pyrocumulonimbus clouds that form during firestorms where they cannot be rained out by precipitation, giving rise to a nuclear winter. Despite the potentially devastating effects of a nuclear winter, the phenomenon was only discovered at the height of the Cold War, a period characterised by rapid developments in nuclear weapons. Although humanity made it through the period without nuclear war breaking out, numerous close calls had occurred throughout the war that brought the world to the brink of one, largely due to human or technical error. While close calls were more frequent during times of heightened military tension, such mistakes can still occur today with the continued adoption of the launch on warning strategy of nuclear weapon retaliation, allowing missiles to be launched within just 5 minutes of a decision. Because of such human and technical errors in the complex geopolitical landscape today, studies

[2] The explosiveness of volcanic eruptions is measured on the volcanic explosivity index (VEI), a logarithmic scale which looks at the volume of ejecta and height of eruption cloud.

estimate that the probability of a nuclear war occurring can be as high as 1% per year. Nuclear modeling also predicts that a full-scale nuclear war would cause the Earth's average surface temperature to drop by about 7 °C for about five years, which is about as cool as the Earth's last glacial period. Such drastic reductions in temperature puts billions of people, especially those in the mid-latitudes, at risk of starvation. There are estimates that the resulting nuclear winter could cause more than 2 billion deaths in a nuclear war between India and Pakistan and more than 5 billion deaths in one between the USA and Russia.

Solar Geoengineering

Solar geoengineering involves the intentional injection of aerosols into the stratosphere to create a global cooling effect to offset the rise in global temperatures due to climate change. According to The Intergovernmental Panel on Climate Change (IPCC), stratospheric aerosol injection is the most researched solar geoengineering method that could limit warming to below 1.5 °C, and proposed substances include sulfur dioxide, hydrogen sulfide and gaseous sulfuric acid. However, if such technology is not used in an optimal manner, it could limit the effectiveness of the injection and possibly introduce negative outcomes on a large scale, similar to an ASRS. Such an event is especially likely in the event of misuse or miscalculation due to the very fact that the injected aerosols have been specially chosen and delivered to ensure that they are able to stay in the stratosphere for prolonged periods of time and block solar radiation to combat global warming.

Types of Aerosols

The injection events discussed above emit a wide range of aerosols, some of which are more harmful than others in the context of an ASRS. Notably, the aerosols that pose the most threat include sulfate aerosols and soot.

Sulfate Aerosols

Sulfate aerosols are secondary aerosols that are formed in the atmosphere from gas-phase precursors such as sulfur dioxide (SO_2) and hydrogen sulfide (H_2S), which are emitted from combustion and volcanic eruptions. Sulfur dioxide and hydrogen sulfide can be oxidised by oxidants such as oxygen (O_2) and hydroxyl radicals ($OH\bullet$) to produce sulfuric acid (H_2SO_4). The relevant chemical equations are as follows:

<u>Oxidation of hydrogen sulfide</u> (H_2S)

$$2H_2S + 3O_2 -> 2SO_2 + 2H_2O$$

$$H_2S + OH\bullet -> HS\bullet + H_2O$$

$$4HS\bullet + 5O_2 -> 4SO_2 + 2H_2O$$

<u>Oxidation of sulfur dioxide</u> (SO_2)

$$2SO_2 + O_2 -> 2SO_3$$

$$SO_3 + H_2O -> H_2SO_4$$

$$SO_2 + 2OH\bullet -> H_2SO_4$$

The resultant sulfuric acid vapour then condenses onto existing particles or forms new sulfate particles in the atmosphere, which are especially relevant in the context of ASRS as they are highly effective in scattering and reflecting sunlight. Combustion-derived sulfate aerosols are typically confined to the troposphere due to the relatively lower altitude of emission sources, while volcanic sulfate aerosols can be ejected high into the stratosphere, where they can effectively scatter and reflect sunlight.

Soot Aerosols

Soot is a carbonaceous aerosol that is mainly made up of black carbon, and is the result of incomplete combustion. Black carbon is created in large amounts in explosions and firestorms

when carbon-containing materials burn at a high temperature with insufficient oxygen, producing fine, particulate carbon that is less oxidised and more stable than other forms of carbon. Its highly ordered structure with a significant degree of graphitisation allows it to absorb light very efficiently, which leads to the warming of the stratosphere by trapping heat, as well as the cooling of the Earth's surface by reducing the amount of solar radiation reaching it.

Other Aerosols

Apart from sulfate and black carbon aerosols, ejections of dust, ash and soil are able to make a substantial contribution to an ASRS. Dust and soil may be ejected into the atmosphere by the impact of an asteroid or by the force of nuclear explosions, especially by ground-burst detonations. Volcanic ash refers to materials that were blasted into the atmosphere during a volcanic eruption, including pumice, tephra and volcanic glass. While these particles are able to contribute to short-term cooling and visibility issues, their impact is typically more localised and less sustained, as the larger size and mass of the particles causes them to fall out of the atmosphere quickly.

Effects of Aerosols

The impact of aerosols on the climate of the Earth can be divided into direct effects and indirect effects.

Direct Effects

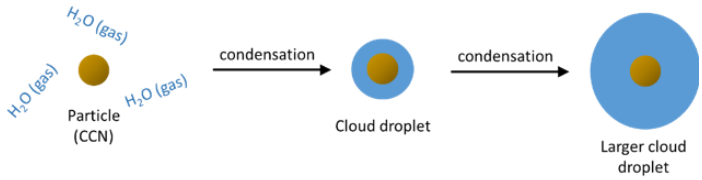
Aerosols directly lead to the attenuation of sunlight through light scattering and light absorption. The scattering of light occurs when scattering aerosols like sulfate and nitrate aerosols reflect shortwave radiation, causing negative radiative forcing and reducing the amount of solar radiation reaching the surface of the Earth. There are two different types of scattering – Rayleigh scattering occurs in very small particles and causes scattered light to travel in all directions approximately equally, while Mie scattering occurs in larger particles and causes a larger proportion of the scattered light to travel in the same direction as the incident light. Most

scattering falls on a spectrum between both, with larger particles exhibiting a higher degree of Mie scattering. On the other hand, the absorption of light occurs when absorbing particles like black carbon absorb sunlight, which warms the stratosphere by trapping heat but also reduces the amount of solar radiation reaching the surface of the Earth.

Indirect Effects

Aerosol particles indirectly affect the climate by acting as cloud condensation nuclei (CCN), on which water vapour can condense to form cloud droplets. In cloud formation processes, cloud droplets are able to form as soon as a relative humidity of 100% is reached. Heterogeneous condensation is energetically favourable compared to homogeneous condensation, hence the water molecules will almost always condense onto CCN in a supersaturation of water vapour. However, not all particles can act as CCN, and the activation of CCN based on the level of supersaturation depends largely on their physical and chemical properties. The process of heterogeneous condensation is illustrated in Figure 1:

Figure 1: Heterogeneous condensation on a CCN



When a large number of CCN are present, water will be distributed across a greater number of aerosol particles, resulting in smaller but more numerous cloud droplets. There are two effects associated with such a phenomenon – the Twomey effect explains that the smaller cloud droplets exhibit a higher degree of Rayleigh scattering when scattering light, while the Albrecht effect explains that the more lightweight cloud droplets are less likely to fall out of clouds as rain, therefore leading to delayed precipitation and a longer lifetime of clouds. Consequently, aerosol particles are able to stay in the atmosphere for a longer period of time and reflect less solar radiation towards the surface of the Earth. However, the high altitude and low humidity of the stratosphere compared to the troposphere renders it unconducive for typical water cloud formation, which explains its relative lack of clouds. Furthermore, the stratosphere is

characterised by stratified temperature zones with limited vertical movement of air, and this lack of convection currents means that moisture does not easily rise to higher altitudes within the stratosphere, thereby inhibiting cloud formation. Because of this, the indirect effect of aerosols is largely applicable in the troposphere, which contains 99% of all water vapour and clouds. Nonetheless, stratospheric aerosols can still participate in cloud formation under specific conditions. The primary clouds in the stratosphere are polar stratospheric clouds (PSCs), or nacreous clouds, which form at very low temperatures below -78 °C in the polar stratosphere in the presence of ice, nitric acid or water-ice mixtures. However, PSCs facilitate reactions on their surfaces that convert inactive chlorine compounds into their active forms, which are able to take part in reactions that lead to the depletion of the ozone layer. It is for this reason that the ozone hole is over the Antarctic region.

Theory of Change

The phenomenon of an ASRS has been a topic for research since the height of the Cold War. However, the majority of current interventions fall into two distinct groups – prevention and relief. Measures centered on prevention aim to reduce the probability of an ASRS occurring altogether, such as through policy making and disarmament agreements. Measures centered on relief aim to increase humanity's ability to weather through an ASRS, such as through nuclear bunker construction, large-scale food stockpiling and research into alternative food sources. While these are impactful, there is an aspect of the problem that has received relatively little attention in comparison—reducing the scale or duration of the ASRS so as to mitigate the extent of the disaster and prevent it from posing an existential threat to humanity. My project hence intends to shed light on this aspect of the problem by assessing the feasibility and efficiency of potential aerosol removal methods inspired by current air purification technology, before proposing a design that incorporates the most promising ones. Subsequently, I will suggest future action to take in order to make the deployment of these technologies a feasible reality.

Removal Processes

The processes involved in the natural removal of the aerosols in the atmosphere include dry and wet deposition. Dry deposition refers to the removal of particles by collision with surfaces, and involves Brownian diffusion, gravitational settling, interception and impaction. Wet deposition refers to the scavenging of particles from the atmosphere by solid or liquid water and their subsequent removal by precipitation, and involves in-cloud scavenging, also known as rainout, and below-cloud scavenging, also known as washout. In-cloud scavenging refers to the process in which a particle acting as a cloud condensation nucleus (CCN) or ice nucleus (IN) induces the formation of a droplet at altitudes above the cloud base before being removed by precipitation. In contrast, below-cloud scavenging refers to the removal of a particle by collision and coalescence with falling hydrometeors at altitudes below the cloud base.

Despite these processes, stratospheric aerosols can take years to settle out of the stratosphere naturally. Only diffusion and gravitational settling are relevant in dry deposition as the removal processes take place in the stratosphere where there are no terrestrial or hydrological surfaces to act as collectors. Wet deposition is also less useful due to the low humidity and high altitude of aerosols in the stratosphere, leaving the stratosphere mostly cloud- and weather-free.

Crucially, the main goal of the removal technology is to facilitate the descent of aerosol particles into the troposphere, where they are more susceptible to wet deposition processes that can further remove them from the atmosphere.

Removal Technology

Due to the slow rate of aerosol removal by natural processes, inspiration can be sought from available air purification technology in order to accelerate this process. Before doing so, it is worth obtaining a better understanding of the stratosphere so as to understand the challenges involved in addressing the problem.

Key Challenges

The stratosphere poses significant challenges that render the deployment of removal technologies difficult or ineffective. Aerosol particles can stay up to 50 kilometers above sea level, complicating deployment. Extreme conditions like temperatures ranging from -50°C at the tropopause to -15°C at the stratopause can impact the technology's structural integrity, while low pressures ranging from 100 millibars to 1 millibar can hinder the efficiency of removal mechanisms. Additionally, high levels of ultraviolet radiation and the presence of the ozone layer introduce further challenges, necessitating extensive pilot testing before large-scale use. Understanding these stratospheric conditions is crucial for evaluating potential aerosol removal methods.

High-Efficiency Particulate Air (HEPA) Filtration

High-Efficiency Particulate Air (HEPA) filters capture particles as small as 0.3 microns with an efficiency of 99.97% while maintaining low air flow resistance. They use three mechanisms to capture particles: inertial impaction captures large particles by forcing them to collide with filter fibers when they follow the stream of air flow, hence this mechanism dominates with stronger air flow; interception captures mid-size particles when they come close to fibers while following the air stream through individual fibers; and Brownian diffusion captures small particles through random Brownian motion between the particles and air molecules, hence this mechanism dominates with weaker air flow.

HEPA filters are highly efficient at capturing small particles, including sulfate and black carbon aerosols in the 0.1 to 1.0 microns range. However, they require regular maintenance because used filters increase air flow resistance and decrease filtration efficiency. While HEPA filters are effective in enclosed spaces and industrial processes, scaling them up for stratospheric use presents challenges due to the vast air volume needed to be filtered and maintenance difficulties at high altitudes. Low temperatures and pressures in the stratosphere further complicate filter operation as the reduced Brownian motion due to low air density decreases capture efficiency, while filter media fiber materials like polypropylene and fiberglass may become brittle or lose performance in extreme cold. To address these issues, research into durable materials and

protective coatings is needed. Additionally, using pre-filters could help by eliminating large particles and reducing maintenance costs by increasing the duration between filter replacements.

Electrostatic Precipitation

Electrostatic precipitation involves electrically charging the aerosol particles before collecting them on oppositely-charged collection plates. Electrostatic precipitators have been used industrially for almost a century and stand out for their versatility, high efficiencies, low maintenance requirements and resistance to high temperatures. They operate by passing the aerosol through a previously ionised region, where ions will transfer charge to the aerosol particles, causing them to migrate to collection plates where they are removed from the gas.

Electrostatic precipitation boasts high efficiencies over a wide range of particle sizes. Removal efficiency for fine particles can also be improved by agglomeration of particles. However, the implementation of electrostatic precipitators in the stratosphere presents challenges due to the size, complexity and energy demands of the systems. In addition, the low temperature and pressure in the stratosphere introduce complications in the system's performance. The high-voltage components and collection plates may be susceptible to material stress from the cold, potentially suffering from icing and other forms of degradation, while the low pressure may reduce the ionisation efficiency and lead to problematic electrical discharge issues. To overcome these challenges, durable materials can be used to withstand the low temperatures, while heating elements may be incorporated to prevent freezing and ensure consistent operation. Design improvements must also be made to the ionisation system to avoid electrical discharge problems and ensure that it is able to function efficiently at low pressures.

Cyclonic Separation

Cyclone separators use centrifugal, gravitational and inertial forces to separate particles from a gas. Aerosols enter the cyclonic chamber tangentially along an angled inlet port, creating a swirling motion that forms a vortex within the chamber. Larger particles within the air are separated by centrifugal forces and pushed against the walls of the chamber at high velocity before settling by gravity at the bottom of the chamber where they can be collected by an

accumulator. Meanwhile, the swirling air creates a vortex in the centre where air flow turns upwards, allowing the remaining air and any particles too fine to be removed by centrifugal force to exit at the top of the chamber.

Cyclone separators contain few moving parts, are inexpensive to manufacture and require little maintenance, as the cyclonic effect within the chamber keeps it clean. This method of removal may be efficient for particles larger than 10 microns, but efficiency quickly drops as particle size decreases below that threshold. In addition, deployment of cyclone separators in the stratosphere will be difficult due to the high altitude. The low pressure in the stratosphere may also lead to complications in the strength of the centrifugal force and cyclonic effect, causing a reduction in the removal efficiency. To overcome these challenges, the design of the separators may be optimised to enhance removal efficiency in low pressure environments. The separation mechanism may also be implemented in multiple stages or in hybrid designs with other mechanisms so as to capture finer particles.

Chemical Scrubbing

Chemical scrubbers use scrubbing solutions to neutralise or react with gases or particles into less problematic compounds, such as compounds which have a smaller impact on the Earth's climate or are less likely to remain airborne for prolonged periods of time. Different scrubbing mechanisms include spray scubbers, where the scrubbing liquid is sprayed into an air stream through nozzles or misting devices; packed bed scrubbers, where the air flows through a bed of packing material that is wetted by the scrubbing solution, providing a large exposed surface area for contact; and venturi scrubbers, where the air and scrubbing solution are mixed together under high pressure, creating a high-velocity air stream that enhances contact between the solution and the particles. These interactions dissolve gases and capture particles, causing them to become suspended in the solution or become sludge. After contact with the scrubbing solution, the clean air exits the system while the scrubbing solution, now containing the absorbed or reacted compounds, can be recirculated, treated or discharged as waste.

The effectiveness of chemical scrubbing varies with the chemical composition of different aerosols. While wet scrubbers can effectively neutralise sulfate aerosols, black carbon is

relatively unreactive and inert and therefore less susceptible to chemical removal. Deployment of scrubbers in the stratosphere will also be difficult due to the complexity of the systems and the extreme conditions which may compromise on the efficiency of the chemical reactions. Low temperatures may cause scrubbing solutions to freeze while low pressures may reduce efficiency by shifting the equilibria of the chemical reactions. To overcome these challenges, reagents must be selected for performance under extreme conditions, while the use of modular systems may enable chemical replenishment to be carried out more efficiently.

Heterogeneous Nucleation Enhancement

Heterogeneous nucleation enhancement technology involves facilitating the condensation or freezing of water vapour onto aerosol particles acting as CCNs and INs. Potential solutions can be directed at increasing the activation rate of the aerosol particles or introducing nucleating agents and chemical additives into the stratosphere to promote the formation of cloud and ice droplets. Local atmospheric conditions can also be manipulated to achieve favourable environments for nucleation, such as by increasing the humidity through the injection of water vapour.

However, manipulation of atmospheric conditions presents a multitude of challenges. The stratosphere's extremely low humidity requires a massive injection of water vapour to achieve the supersaturation necessary for cloud and ice formation. Additionally, cloud formation in the stratosphere is largely only viable in the polar regions where the conditions for the formation of PSCs are met. While the polar vortex may confine aerosol particles to high-latitude regions during winter, facilitating PSC formation may drastically increase the rate of ozone depletion in the polar regions due to the activation of ozone-depleting chlorine compounds on their surfaces. Furthermore, due to low temperatures, any potential cloud formation outside of the polar regions would be in the form of ice crystals. However, the processes of ice nucleation differ from that of cloud nucleation and require specific particles with strong ice-nucleating abilities that facilitate the arrangement of water molecules into ice. While sulfate aerosol particles may act as effective CCN due to their high hygroscopicity, their chemical composition is not conducive for them to act as effective IN. On the other hand, black carbon particles are both poor CCN and IN due to

their hydrophobic nature and low hygroscopicity. Lastly, altering atmospheric conditions, even on a local scale, is extremely complex and could result in unforeseen environmental side-effects.

Others

Other widespread and well-researched air purification technologies have been considered as well, but they have ultimately been ruled out due to their inability to remove airborne particles. These include activated carbon, UV-C light and ozone generation technologies, which are most effective in eliminating odours, viruses, bacteria and mould spores, but have limited efficiency in eliminating airborne particulate matter.

Delivery Technology

Investigating potential aerosol removal methods only addresses one side of the problem, the other side of which entails the feasibility of deployment. This involves examining methods of delivering the removal systems into the stratosphere, where they can operate efficiently.

Aircraft

High-altitude aircraft offer a way to deliver the systems into the stratosphere. While commercial airplanes typically operate between 9 and 12 kilometres in altitude, specialised high-altitude jets can be designed to operate in the lower stratosphere, above commercial flight altitude. However, the low air density in the stratosphere makes it difficult for airplanes to generate lift with traditional wing designs, while the low temperature and pressure may affect the structural integrity and the systems of the aircraft. Nonetheless, stratospheric flight has been achieved in the past, as exemplified by the United States Air Force's U-2 high-altitude reconnaissance aircraft which operates at the altitude of 21.3 kilometres. Additionally, potential high-altitude aircraft includes airships and dirigibles, which can be designed to serve as platforms for the deployment of aerosol removal technologies due to their ability to provide a large working surface area for a multitude of systems and remain aloft in the stratosphere for prolonged periods of time.

Balloons

High-altitude balloons or stratostats can be modified from weather balloons to carry specialised equipment into the stratosphere. These uncrewed balloons are typically filled with hydrogen or helium, and can reach altitudes as high as 50 kilometres. They are mainly used for research purposes and generally contain electrical equipment such as cameras, transmitters and satellite navigation systems, hence attaching aerosol removal systems may not be a huge leap from the technology that is available today. These balloons can also be connected to the ground via a tether, allowing altitude adjustments as needed.

Drones

Drones and unmanned aerial vehicles (UAVs) could also be designed to carry aerosol removal systems. Their long endurance and high-altitude capabilities make them ideal for operating as platform stations in the stratosphere, while their potential for autonomous deployment and remote operation offers flexible deployment strategies in an ASRS.

Assessment

Based on the pros and cons of each of the technologies discussed above, I seek to assess their deployability, on a scale of 1 to 5, using 6 factors: removal efficiency in the critical size range, energy consumption, maintenance requirements, operational complexity, technological readiness and environmental considerations. This is reflected in the following assessment matrix.

Table 1: Assessment matrix of stratospheric aerosol removal technologies

	Removal Efficiency	**Energy Consumption**	**Maintenance Requirements**	**Operational Complexity**	**Technological Readiness**	**Environmental Impact**	**Total**
HEPA Filtration	5	3	3	4	5	4	24
Electrostatic Precipitation	5	3	3	4	5	3	23

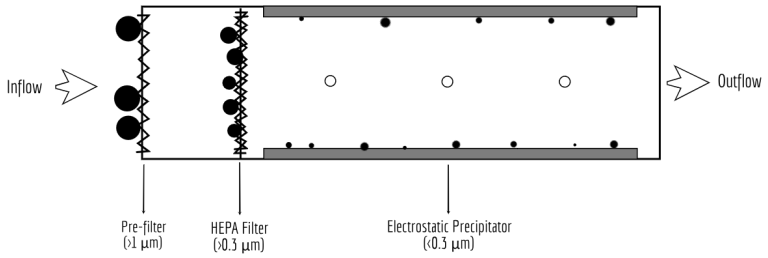
Cyclonic Separation	2	2	4	3	5	4	20
Chemical Scrubbing	4	4	4	3	4	3	22
Heterogeneous Nucleation Enhancement	3	3	3	2	3	3	17

From this matrix, it is clear that HEPA filtration and electrostatic precipitation are the most promising due to their high removal efficiency, low operationality complexity as well as the availability of the technology required. On the other hand, cyclonic separation and heterogeneous nucleation enhancement scored poorly due to the former's low removal efficiency in the required size range and the high operational complexity of the latter.

Proposal

Therefore, I propose a hybrid multi-stage design implementing HEPA filtration and electrostatic precipitation, as well as a pre-filter that helps to eliminate large particles so as to reduce the maintenance requirements of the HEPA filter. The two mechanisms are arranged such that small particles that are able to pass through the HEPA filter can be effectively removed by the electrostatic precipitator. The system should also be designed for easy maintenance and durability in the harsh stratospheric environment. The proposed design is as follows:

Figure 2: Proposed hybrid removal system



Potential enhancements to the design include the utilisation of chemical surfactants to enhance agglomeration between aerosol particles in a pre-filtration process. Sensors can also be incorporated into the system to measure the performance of each component, and the data can be used to adjust the operation and maintenance of the system to ensure optimal performance. Additionally, the power requirements of the system could be met by energy sources available in the stratosphere, such as solar energy. Lastly, the mechanism of enhancing heterogeneous nucleation may be applied to particles that have descended into the troposphere to facilitate their further removal by wet deposition.

The hybrid system can be delivered into the stratosphere via high-altitude aircrafts, balloons or drones. However, further tests must be conducted to assess the practicality and potential risks of attaching and operating bulky aerosol removal technology on these platforms for prolonged periods of time.

Future Work

Building on the potential of the identified aerosol removing technologies for addressing an ASRS, future research will focus on several key areas to address their limitations and enhance their efficiency. Advanced materials will be explored for improved performance and durability, and ways to better facilitate the integration of multiple mechanisms into one cohesive system will be developed. Small-scale tests will also be conducted to validate the system's performance, while methods to increase the system's energy efficiency will be explored. It is also crucial to develop monitoring and data analysis tools to continuously assess and improve the system.

Conclusion

This study has explored the potential causes of ASRS and evaluated various stratospheric aerosol removal technologies, laying the groundwork for future innovations that could enhance our ability to mitigate an ASRS. While promising, these findings underscore the presence of

significant technical and scientific challenges that need to be overcome before these technologies can effectively be deployed. The assessment of current technologies reveal the multitude of issues related to efficiency, material durability and environmental impact that we currently lack a comprehensive understanding of, hence it is crucial that future research addresses these uncertainties through advancements in material science and aerosol dynamics. By systematically addressing these hurdles, we can work towards developing viable solutions to mitigate the impacts of an ASRS and enhance our preparedness for such scenarios. Overall, this study highlights the need for ongoing innovation and rigorous evaluation to ensure the safe and effective application of aerosol removal technologies in the stratosphere.

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Annex A

The Earth's atmosphere consists of five major layers, which, from the lowest to the highest, are the troposphere, stratosphere, mesosphere, thermosphere and exosphere.

Troposphere

The troposphere extends from Earth's surface to 12 kilometres in altitude on average, with its height lower at Earth's poles and higher at the Equator. Despite being the thinnest layer, it contains 99 percent of all water vapour, aerosols and air required for the survival of all living organisms. As a result, most of Earth's clouds and weather are confined to the troposphere. Temperature decreases with increasing altitude with an average environmental lapse rate (ELR) of 6.5°C per kilometre, as most of the heat in the troposphere is generated by transfer of heat from the Earth's surface. The troposphere may also be further divided into the planetary boundary layer (PBL), which refers to the lowest part of the atmosphere that is directly influenced by the Earth's surface, and the free troposphere, where the wind is approximately geostrophic and unaffected by surface drag. The troposphere and the stratosphere is divided by the tropopause, an isothermal layer that is defined as the lowest level at which the ELR decreases to 2°C per kilometre or less.

Stratosphere

The stratosphere is located between approximately 12 and 50 kilometres above Earth's surface, and is nearly cloud and weather free, apart from polar stratospheric clouds that may form in the polar lower stratosphere. It is home to the Earth's ozone layer, and the absorption of ultraviolet radiation from the sun by stratospheric ozone explains why temperature increases with increasing altitude.

Mesosphere

The mesosphere is located between 50 and 80 kilometres above Earth's surface, and gets progressively colder with increasing altitude. In fact, the top of the mesosphere is the coldest

place found within the Earth's system, with an average temperature of -85°C. This is also the layer at which most meteors burn up.

Thermosphere

The thermosphere is located between 80 and 700 kilometres above Earth's surface, and temperature increases with increasing altitude here due to the very low density of molecules. The lowest part of the thermosphere also contains the ionosphere, where ultraviolet and x-ray solar radiation ionises atoms and molecules into charged particles. The aurora borealis and aurora australis are sometimes found here, and The International Space Station also orbits the Earth in this layer.

Exosphere

The exosphere is located between 700 and 10000 kilometres above Earth's surface, and is the highest layer of the Earth's atmosphere, merging with solar wind at its top. With an extremely low density of molecules here, the exosphere does not behave like a gas, with particles escaping into space. The aurora borealis and aurora australis may be found in the lowest part of the exosphere, and most Earth satellites also orbit in this layer.