

The Unintended Consequences of Sulfate Aerosols in the Troposphere and Lower Stratosphere

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Executive Summary

Sulfate aerosol injection is a geoengineering scheme that has been put forward in order to combat the rise in surface temperature of the Earth due to the build up of carbon dioxide in the atmosphere. The build up of aerosols in the atmosphere reflects sunlight away from the Earth, as shown by large volcanic eruptions such as those of Mount Pinatubo and El Chichón. Both these eruptions caused a significant decrease in regional surface temperatures for several years following the eruptions; an injection of sulfate aerosols is expected to do the same. There are potential side effects of the scheme, however, such as regional precipitation changes, ozone depletion and acid rain. In addition, sulfate aerosol injection does not address continued build-up of carbon dioxide.

In order to quantify the severity of the potential consequences and the effectiveness of the scheme at decreasing global surface temperatures, I have proposed an experiment involving a small-scale aerosol injection scheme. The experimental design is based on computer simulation models done by Robock *et al.* (2008). The goal of the experiment is to ascertain the side effects of a scheme meant to increase the amount of summer sea ice in the Arctic. Although the experiment will provide us with valuable knowledge regarding the consequences of a sulfate aerosol injection scheme, further experimentation will be necessary before any type of geoengineering scheme is undertaken.

An Introduction to Global Climate Change

Since the advent of the Industrial Revolution, societies across the globe have endeavored to increase their production capacity and, in turn, have increased their contribution to global emissions. As a result, the amount of carbon dioxide in the atmosphere has increased from 280 parts per million (ppm) to 380 ppm, and the average global surface temperature has increased by 0.8°C (Bala, 2009). These increases are the result of human perturbation, and are likely to continue unchecked, leading to significant climate change that would vastly change ecosystems all over the world.

Global warming and climate change are the result of increases in the concentrations of anthropogenic greenhouse gases in the atmosphere. Some of the most prevalent greenhouse gases are carbon dioxide, methane, water vapor, ozone and nitrous oxide. Although all of these gases play a significant role in global climate science, carbon dioxide is the one on which many models and estimates are based, and which humans play the greatest role in emitting into the atmosphere.

Natural greenhouse gases play an important role in our global climate. They act as a blanket keeping the Earth's surface at a habitable temperature. This is called the greenhouse effect. Without the presence of greenhouse gases such as water vapor and carbon dioxide, the temperature of Earth's surface would be about -19°C instead of the global mean surface temperature of 14°C (Le Treut *et al.*, 2007). This temperature has allowed for the survival and productivity of the human race and has thus permitted the industrialization of the Earth which is now contributing to global climate change and ecosystem destruction.

The increase of carbon dioxide in the atmosphere has two major components: the emissions from the burning of fossil fuels and cement production, and changes in land-use, such as deforestation and wood-harvesting. In a typical cycle, natural sinks on land and in the ocean

regulate and remove carbon dioxide from the atmosphere. However, carbon dioxide is less soluble in warmer waters, which decreases the “downward transport of anthropogenic carbon” (Bala *et al.*, 2005). In the past 20 years, the growth rate of fossil fuel emissions has increased from 1.3% per year in 1990 to 3.3% per year from 200-2006 (Canadell *et al.*, 2007). As the amount of carbon dioxide emitted into the atmosphere increases, the efficiency of natural carbon sinks decreases.

Potential consequences

If global emissions continue to grow at such rates, the consequences could be dire. Schneider (2009) presents the scenario where our atmosphere has 1,000 ppm of CO₂. This scenario would lead to a world without the ecosystems unique to Earth such as mountain glaciers and coral-reef communities. Although the scenario Schneider presents is extreme, the ideas he presents are reasonable. Even if only a few of the consequences he lays out come true, we would face a world significantly different than it is today.

For instance, an increase of 1 °C above current global temperatures could lead to coral bleaching. Coral reef systems are incredibly sensitive to environment changes, and severe coral bleaching has already occurred, such as in 1998 when nearly 16% of reef coral died (Walther *et al.*, 2002). An increase of 2.7°C may cause the Greenland ice-cap to melt and at a change of 3°C, catastrophic changes such as “reversal of the land carbon sink and possible destabilization of the Antarctic ice sheets” (Bala, 2009).

Temperatures would vary between regions, because maximum temperatures are increasing more slowly than minimum temperatures, meaning that there are longer freeze-free periods at high latitudes whereas the temperature change in mid-latitude regions is less noticeable (Walther *et al.*, 2002). Climate change has also caused different reactions in many species. Species whose breeding or migration depends on seasons have been arriving earlier,

such as the birds that migrate in the spring. (Walther *et al.*, 2002).

In fact, ecosystems may already be committed to long-term changes despite efforts to curb climate change. Jones *et al.* (2009) details a model involving the Amazon rainforest, which suggests that an increase in the global mean temperature increases the decomposition of soil and, coupled with the decrease in precipitation, causes plant productivity to be significantly decreased. Because some effects of climate change, such as “vegetation cover and carbon storage” (Jones *et al.*, 2009) differ in the rate of change from precipitation and temperature, it is likely that both terrestrial and marine ecosystems would continue to change even if the climate remained the same or returned to its previous state. This may mean that by 2050, the tree cover in the Amazon will be less than 50% of what it is today, as shown in Figure 1.

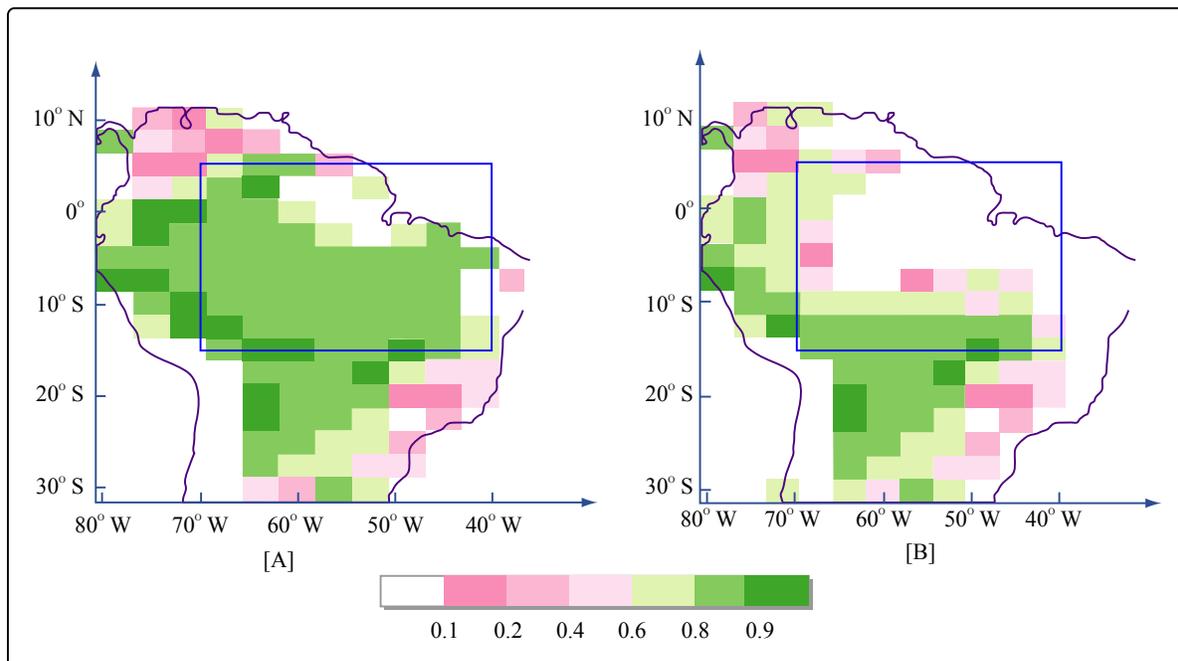


Image by MIT OpenCourseWare.

Figure 1: Amazon forest tree cover in 2050. Color gradient represents fractional coverage. **a** current **b** predicted (Jones *et al.*, 2009)

Geoengineering: history and background

Despite global efforts and treaties to curb carbon dioxide emissions, the concentration of carbon dioxide in the atmosphere is still increasing, and it is unlikely that use mitigation alone

will be enough to protect the environment. Geoengineering is the manipulation of the Earth in order to engineer a cooler climate, in order to combat the rising global temperature and carbon dioxide concentrations. Human intervention in the climate change problem has both positive and negative aspects, but may be an emergency solution in order to prevent extreme environmental change.

The idea of geoengineering has been around in earnest since the 1950s and 60s. The two major players were the USA and the USSR, both of whom sought to control the climate, often for military reasons (Keith, 2000). The Soviet Union considered climate-control to be one of “the most urgent problems of Soviet science” (Keith, 2000), and proposed many solutions akin to those being proposed today. These included cloud seeding and using aerosols in the atmosphere to change climate patterns both in northern Russia and at the equator. The US similarly experimented with cloud seeding in the 1950s, and during the Vietnam war used cloud seeding to achieve their military goals. This led to an international treaty prohibiting the use of “Environmental Modification Techniques” (Keith, 2000) for hostile goals.

After this era, geoengineering was often seen in a negative light, and it wasn't until the 1990s that the mainstream scientific community considered the idea again. Research showed that the current levels of carbon dioxide could take 1,000 years to dissipate, and interest in alternate solutions began to peak. Even when geoengineering reappeared in mainstream publications, few scientists were willing to put their career on the line to research geoengineering schemes. Geoengineering was not included in reports on anthropogenic climate change, such as those by the Intergovernmental Panel on Climate Change, until the past several years.

Now the majority of geoengineering proposals fall into two categories : reducing the amount of solar radiation that reaches the surface of the Earth, and removing carbon dioxide from the atmosphere. Proposals that involve reducing the amount of radiation generally involve

increasing the Earth's albedo, or reflectivity. This can be done either on the surface of the Earth by genetically engineering more reflective plants or crops, or in the atmosphere, with schemes such as cloud seeding, launching aerosols into the atmosphere and launching space shields to reflect the sun. Proposals that involve removing carbon dioxide from the atmosphere include iron fertilization of the oceans, underground sequestration of carbon dioxide and marine carbon capture.

A Brief Look at Individual Schemes

One way of removing CO₂ from the atmosphere, iron fertilization of the oceans, aims to decrease the carbon dioxide concentration by storing it in biomass, namely phytoplankton. By providing additional iron, one of the key nutrients that phytoplankton need to photosynthesize and grow, one can increase the phytoplankton population, which in turn, increases the amount of carbon dioxide taken by phytoplankton from the atmosphere. While it seems to be a relatively simple scheme, there is no indication that it will work, and a recent experiment shows that much of the added iron will be eaten by krill.

Another often proposed scheme is a sun shield. It is on the extreme end of the proposed scheme due to both cost and feasibility. While a sun shield may be a more 'green' solution than other schemes, it has potential detrimental effects of its own. The concept of a sun shield is that the sun's rays need to be deflected only a few degrees to reduce the global mean surface temperature. This would be achieved by putting small translucent disks "sunward of the L1 Lagrange point" (Keith, 2000). A space shield screen, however, is one of the most expensive of the schemes proposed.

Problems with Geoengineering

In general, the potential problems and complications that accompany geoengineering are

vast. They range from political conflicts due to the implementation and control of schemes, to the ability of the geoengineering schemes to work, because our current climate prediction methods, on which many geoengineering models are based, lack accuracy (Bala, 2009). In addition, any undertaken scheme would have to be maintained indefinitely because otherwise the Earth could undergo a rapid increase in global temperature or carbon dioxide concentration.

Stratospheric Aerosols

The remainder of this paper will focus on the geoengineering scheme that involves launching sulfate aerosols into the troposphere and lower stratosphere. This scheme falls under the solar radiation management category. The goal of sulfate aerosols is to reduce the global mean surface temperature by accumulating aerosols in the atmosphere that will reflect sunlight away from Earth. The basis for these observations comes from volcanic eruptions such as Mt. Pinatubo and El Chichón.

The respective eruptions of 1991 and 1982 were the two largest volcanic eruptions of the 20th century (Robock *et al.*, 2007). Volcanic eruptions inject sulfur dioxide and other particulate matter into the stratosphere. The Pinatubo eruption in the Philippines injected nearly 20 Tg of SO₂ into the lower stratosphere (Robock *et al.*, 2009), and caused a nearly 1 °C decrease in the global temperature from 1991 to 1993 (Lane *et al.*, 2007). Although volcanic eruptions may be analogous to a stratospheric aerosol geoengineering scheme, one important difference is that an eruption injects aerosols over the course of several days, whereas a geoengineering scheme would require constant, gradual injection.

Injecting sulfate aerosols into the stratosphere would have a profound effect because the natural concentration of sulfur in the stratosphere is roughly 0.1 Tg S per year, as opposed to the 20 Tg S that the eruption of Mt. Pinatubo forced into the stratosphere. Sulfate aerosols

occur naturally in the stratosphere because of transport of sulfur compounds from the troposphere, though the concentrations introduced by volcanic eruptions are much higher than those that occur naturally. Aerosols have a much longer residence time in the stratosphere than they do in the troposphere. A residence time of several years as opposed to several days means that fewer aerosols need to be introduced into the stratosphere in order to maintain the climatic effects (Rasch *et al.*, 2008). The characteristics of the stratosphere lead to the dispersion of the aerosols over an area larger than the launch site, causing a global, rather than local, effect, an important aspect of geoengineering. Figure 2 shows the location of the stratosphere, troposphere and the tropopause, the layer separating the two. Any sulfate aerosol geoengineering scheme would aim to launch aerosols into the lower stratosphere, between 10 and 15km above the surface of the Earth.

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Figure 2: Schematic of atmosphere. The troposphere is located from 0 to 10 km, the tropopause is at about 10 km and the stratosphere is located from 10 to 50 km. The lower stratosphere is from 10-15 km above the surface of the Earth. http://www.windows.ucar.edu/earth/Atmosphere/images/stratosphere_diagram_sm.jpg

The sources of atmospheric aerosols can be both natural and anthropogenic sources. Examples include dimethyl sulfide, sulfur dioxide, hydrogen sulfide and carbonyl sulfide (OCS). OCS contributes roughly half of the sulfur present in the stratosphere, whereas the other gases play a larger role in the troposphere. The majority of sulfate aerosols in the stratosphere exist in the form of sulfuric acid. The dispersion of aerosol particles over a large area results mainly from wind, though the lifetime of a sulfate particle is related to more variables, including meteorological conditions, particle size and concentration (Rasch *et al.*, 2008).

Before implementing any geoengineering scheme, it is important to weigh the risks. Geoengineering with sulphate aerosols specifically can result in changes to the global ecosystem, the most detrimental of which are perturbations to the hydrological cycle, changes in atmospheric circulation, continued ocean acidification and acid rain. Robock (2008) outlines many more potential consequences that cut across all schemes including political and superficial problems, such as conflicts with current treaties and whitening of the skies.

Unintended Consequences of Sulphate Aerosols

In order to understand what may happen when sulfate aerosols are injected into the atmosphere, and therefore predict the unintended consequences of such a geoengineering scheme, we can analyze large scale volcanic eruptions. For example, the Mount Pinatubo eruption decreased air temperatures and reduced the total amount of water vapor present in the atmosphere (Trenberth & Dai, 2007). In 1992, following the eruption of Pinatubo, a significant percentage of the world experienced drought conditions, a fact attributed to the eruption (Dai *et al.*, 2004). In addition, precipitation changes in 1992 were much larger than for other years, indicating a relationship between the increase in sulfate aerosols in the atmosphere and the hydrological cycle (Trenberth & Dai, 2007). Moreover, volcanic eruptions in the tropics have

been shown to cause warming in Northern Hemisphere summers while eruptions at high latitudes cause warming in Northern Hemisphere winters (Oman *et al.*, 2006). The seasonal temperature changes are due to changes in atmospheric circulation. Sulphate aerosols have the potential to cause global changes in precipitation, temperature and water vapor, even if released from a singular location.

Stratospheric aerosol injection could also cause an increase in acid rain. Some aerosols find their way to the troposphere and hydrate to form sulfuric acid, leading to an increase in acid deposition in a variety of ecosystems (Kravitz *et al.*, 2009). These increases will be most noticed in pristine as opposed to urban areas and areas with significant rainfall will be the most affected (Kravitz *et al.*, 2009). Although sulfur is a necessary nutrient in some ecosystems, for other ecosystems it can be extremely harmful in excess quantities. Acid rain has led to a decrease in biodiversity in aquatic ecosystems and acidic soils can limit the amount of nutrients available to trees (Kannan & James, 2009). It is not possible to control the areas affected by acid rain because sulfate aerosols cause changes in cloud chemistry across the globe.

Another significant potential consequence of this scheme is an increase in ozone depletion. The seasonal ozone hole over Antarctica is caused by chemical reactions on the surface of water and nitric acid particles, and injecting sulfate aerosols would increase the surface area on which these chemical reactions can occur (Robock, 2008). As a result, the ozone hole would become larger, causing even more ultraviolet radiation to reach the Earth. UV radiation has negative effects and can cause skin cancer in humans as well as damage to DNA and photosensitizers in plants (Stapleton, 1992).

Finally, combating the rise in global temperature with stratospheric aerosols does not address continued carbon emissions, a significant side effect of global warming. The continued build up of greenhouse gases in the atmosphere leads to ocean acidification. The ocean uptakes a significant portion of excess carbon dioxide in the atmosphere (Robock, 2008)

because when CO₂ is dissolved it forms dissolved carbon dioxide, carbonic acid, bicarbonate and carbonate. Ocean acidification significantly affects marine ecosystems such as coral reefs, and would have repercussions through the entire biological chain (Robock, 2008).

These are only a few of the consequences that may stem from a sulfate aerosol geoengineering scheme. The breadth and severity of their effects need to be considered along with the potential benefits from any scheme.

Hypothesis

In order to judge the actual effects of stratospheric sulfate aerosols, it will be necessary to run an experiment and gather data. Since there are many potential consequences, no one experiment can analyze them all. The experiment I propose will be designed to test specifically for those consequences which might result from a geoengineering scheme meant to increase the amount of summer sea ice in the Arctic.

I hypothesize that a sulfate aerosol scheme aimed at increasing the amount of summer sea ice in the Arctic will indeed successfully increase the level of ice, but will also cause a drastic change in regional precipitation patterns. Specifically, I expect that the monsoons in Africa and Asia will be weakened. I base my hypothesis on the analysis of high-latitude volcanic eruptions, events which produce changes in atmospheric circulation in Northern Hemisphere summers (Oman *et al.*, 2006), and are followed by weakened monsoons (Graf, 1992; Oman *et al.*, 2006). Since a high-latitude sulfate injection scheme would be a parallel event to a volcanic eruption, I expect similar changes to follow.

Monsoons are caused by a temperature gradient between the ocean and land. An increase in the amount of aerosols in the atmosphere has been shown to decrease the temperature gradient and reduce cloud cover over land (Oman *et al.*, 2005). These two consequences lead to an increase in temperature because of a decrease in cloudiness and soil

moisture (Graf, 1992; Oman *et al.*, 2005). Less rain and increased temperatures during the former rainy season can lead to droughts, affecting the food production of hundreds of thousands of people who depend on subsistence agriculture. This is a secondary consequence of the proposed scheme, but is one that has potential to affect the livelihood and survival of people on many continents.

Experimental Design

I will base my experimental design on the models done by Robock *et al.* (2008). These models will guide the amount of material injected, the region it is injected from and the size of the aerosols. For the launching mechanism, I rely on recommendations by Budyko (1977) and Robock *et al.* (2009).

The model used by Robock *et al.* (2008) is the National Aeronautics and Space Administration Goddard Institute for Space Studies ModelE atmosphere-ocean general circulation model. This model has correctly simulated the conditions following volcanic eruptions such as the 1783 Laki eruption in Iceland and 1912 Katmai eruption in Alaska (Robock *et al.*, 2008; Oman *et al.*, 2005). In fact, Robock *et al.* (2008) conducted multiple simulations, including a control experiment, a simulation of tropical aerosol injection and an arctic aerosol experiment. Moreover, the model simulates a dynamic as opposed to slab ocean, a reason for which I believe that the set up can be relayed onto a real experiment. As stated in the hypothesis, the proposed experiment will focus on the Arctic in an effort to ascertain the effects of sulphate aerosol injection on the summer sea ice, and related climatic responses, particularly those impacting precipitation in Africa and Asia.

It is important to remember, however, that this is an experiment and not a true geoengineering scheme. Consequently, it will be important to keep sulfate levels within a range of what the Earth has dealt with before. The Mt. Pinatubo volcanic eruption launched 20 Mt of

SO₂ into the stratosphere (Bluth *et al.*, 1992), and therefore the sulfate levels for this experiment will be kept below this level.

Technical Details

There are many variables that must be taken into account in this experiment, including particle size, altitude and location of launch as well as the lifetime of the aerosol. The particles from the Mt. Pinatubo eruption had a 0.35 µm radius, however smaller particles have longer stratospheric lifetimes, so fewer injections would be needed (Rasch *et al.*, 2008). Thus, this experiment will use particles with a 0.25 µm radius, which have an average stratospheric lifetime of two years (Budyko, 1977). I propose launching the aerosols at latitude 68°N in an effort to confine the effects of the scheme to the Arctic. The longitude is arbitrary due to the atmospheric properties (Robock *et al.*, 2008). Robock *et al.* (2009) suggests the Gunnbjørn Fjeld in Greenland, located at 68°N, because it is the highest point in the Arctic, thus requiring less energy to get the material to the stratosphere. Because aerosols have a longer lifetime in the stratosphere than troposphere, they will be launched into the lower stratosphere, an altitude between 10-15 km (Robock *et al.*, 2008).

In an effort to confine the climatic response to geoengineering, a lower rate of injection is used, and again, following the simulation of Robock *et al.*(2008), the sulfate aerosols will be injected at a rate of 3 Mt/annum. This is suitable for an experiment, because it is equivalent to a Pinatubo eruption every 6.67 years, and would cause a sulfate level that would not overburden the Earth's natural capacity. The experiment will be continued for 10 years, long enough to see a decrease in global average surface temperature according to Robock *et al.* (2008). This would mean over 10 years, a total of 30 Mt SO₂ will be introduced into the lower stratosphere.

Due to the dark Arctic winter, the frequency of injections through the fall and winter would not need to be as great because aerosols have no effect in the dark winter (Robock *et al.*,

2009). However, the lifetime of particles in the Arctic is shorter than it would be in the tropics because aerosols are removed primarily in the Arctic, whereas tropical aerosols first must be transported poleward (Robock *et al.*, 2008). This is a benefit to this experiment because we are striving to confine the effects only to the Arctic region, a reasonable effort because high-latitude volcanic eruptions generally have aerosols confined to the hemisphere in which the eruption took place (Oman *et al.*, 2005).

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Figure 3: Proposed methods of sulfate aerosol injection into the stratosphere. Drawing by Brian West. (Robock *et al.*, 2009).

Launching Mechanism

So far, little experimentation has been done with different launching mechanisms. However, many possibilities, such as airplanes, artillery shells and stratospheric balloons have been proposed (Robock *et al.*, 2009). Figure 3 illustrates these ideas.

Of all these options, the most practical one to use is airplanes. The reason is that technology capable of flying into the lower stratosphere in both the tropics and the Arctic already

exists. In fact, larger planes with a larger payload can be used in the Arctic due to a lower stratospheric altitude in that region. Robock *et al.* (2009) suggests planes such as the KC-135 Stratotanker or the KC-10 Extender, both of which have a large payload and can be operated continuously. A large fleet of these craft would be available at a minimal additional cost because they are currently used in the military.

Another aspect of the experiment that needs to be considered is the method of sulfur dispersal. Budyko (1977) originally suggested adding sulfur to plane fuel. This method, however, would require that the fuel used in the stratosphere be separated from the fuel used below the tropopause in order to minimize pollution of the troposphere (Robock *et al.*, 2009). A more practical option is to attach a nozzle to the plane running from a separate tank. In fact, both of the suggested aircraft already have a nozzle, as shown in Figure 4, because of their use as mid-flight refuelers, so no additional alterations would be required.

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Figure 4: KC-10 Extender refueling a plane in mid-flight. Adapted from *Robock et al.*, 2009.

Experimental Details

Because this experiment uses the Earth system, a replicate experiment is not possible. However, the data collected will be compared to climate data for the ten years preceding the ten year experiment in order to form recommendations on the feasibility, practicality and worthiness of a sulfate aerosol geoengineering scheme. The majority of the data necessary to understand the implications of the geoengineering scheme is already collected on a regular

basis, so it would only be a matter of collating all data sources into one central location or database.

Because the goal of this experiment is to understand the unintended consequences of geoengineering, the data collected will include information on Arctic sea ice, such as square mileage, depth, sea level pressure and Arctic coastal precipitation, but also extensive data on precipitation patterns over Africa and Asia. Data points over Africa and Asia will include annual average surface air temperature, solar radiation (downward shortwave radiation), monthly global precipitation and the latitudinal spread of aerosols over the course of each year. In addition, regional data will be taken in order to show the regional changes in surface air temperature and precipitation. Using this data, it will be possible to evaluate the effects that the geoengineering scheme has had on various regional ecosystems and to make recommendations about further use.

Conclusions and Recommendations

Results

It is very likely that a sulfate aerosol geoengineering scheme carried out similarly to the experiment described in the previous section would significantly increase the amount of Arctic sea ice, by between 10-25% of current levels, according to Robock, *et al.* (2008). However, in the process of increasing sea ice level, it is certain that other regions of the world would experience variable climates. There would be a precipitation change associated with a weaker summer monsoon over India and Northern China, as well as a reduction in precipitation over the Sahel desert in Western Africa. These changes are depicted in Figure 5. Although the figure shows that there is an increase in precipitation in some regions of the world, the increases generally occur over open ocean and have little effect on land masses, whereas the negative

changes in precipitation would severely impact large human populations. In East Africa, for example, monsoons control the two rainy seasons, and farmers in the region are dependent on this rain in an otherwise dry region (Nairobi, 1979). In India, not only do monsoons provide the majority of rain for the sub-continent, but they also have cultural importance and symbolize romance and beauty. Undertaking a sulfate aerosol scheme could potentially cause many negative consequences on global environments.

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Figure 5: Precipitation changes following a sulfate aerosol geoengineering scheme. Brown color depicts negative changes. Green color depicts positive changes. Adapted from Robock, *et al.* (2008).

Recommendations

Although the proposed experiment tests many aspects of a sulfate aerosol scheme, there are many more unknowns. It would be unwise to implement a global, long-term geoengineering scheme without further experimentation or political negotiation on a global scale. Any geoengineering scheme would have to be taken on for an indefinite length of time because of the risk of rapid temperature and carbon dioxide increases if it were halted. The

global environmental impacts mean that every country must be in agreement of the indefinite nature of the scheme and of the environmental impacts.

Detailed documentation is needed on the environmental impacts on different global environments and whether any negative effects that may occur can be mitigated. This will require cooperation from researchers outside the field of geoengineering. A global organization, perhaps the United Nations, would need to be in charge of a geoengineering scheme and the approval process could potentially take years. Negotiation must be started soon because global warming is reaching a critical level and global warming is beginning to reach a critical level in which some type of action must be undertaken in the next several years.

Conclusion

Geoengineering is one way to combat global climate change. There are many types of geoengineering and before any scheme is implemented, much more research has to be done into its effectiveness and side effects. We cannot say at this point whether geoengineering is better or more effective than decreasing the cause of global warming, carbon dioxide emissions, but it is one possibility and could provide a relatively quick solution.

Geoengineering with sulfate aerosols has potential to mitigate the effect of rising surface temperatures; it is relatively cheap compared to other methods aiming to reduce solar radiation and has a somewhat assured effectiveness due to the parallel with volcanic eruptions. However, although the experiment presented in this paper details its effectiveness, it also presents potential consequences. These consequences need to be considered and retested, along with possible political and social consequences before a definitive decision on implementation can be made.

We cannot yet discount the possibility of geoengineering nor can we proceed with a full-

fledged implementation. Instead, the global scientific and political communities need to continue working together to develop experiments and treaties regarding geoengineering.

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