SANDIA REPORT
SAND2010-7571
Unlimited Release
Printed October 2010

Unintended Consequences of Atmospheric Injection of Sulphate Aerosols

Barry Goldstein, Peter H. Kobos, and Patrick V. Brady

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Sandia National Laboratories

Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.

Printed in the United States of America. This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831

Telephone:	(865) 576-8401
Facsimile:	(865) 576-5728
E-Mail:	reports@adonis.osti.gov
Online ordering:	http://www.osti.gov/bridge

Available to the public from
U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Rd.
Springfield, VA 22161

Telephone:	(800) 553-6847
Facsimile:	(703) 605-6900
E-Mail:	orders@ntis.fedworld.gov
Online order:	http://www.ntis.gov/help/ordermethods.asp?loc=7-4-0#online

SAND2010-20107571
Unlimited Release
Printed October 2010

Unintended Consequences of Atmospheric Injection of Sulphate Aerosols

Barry Goldstein, Peter H. Kobos, and Patrick V. Brady
Sandia National Laboratories
P.O. Box 5800
Albuquerque, New Mexico 87185-0754

Abstract

Most climate scientists believe that climate geoengineering is best considered as a potential complement to the mitigation of CO_2 emissions, rather than as an alternative to it. Strong mitigation could achieve the equivalent of up to $-4Wm^{-2}$ radiative forcing on the century timescale, relative to a worst case scenario for rising CO_2. However, to tackle the remaining $3Wm^{-2}$, which are likely even in a best case scenario of strongly mitigated CO_2 releases, a number of geoengineering options show promise. Injecting stratospheric aerosols is one of the least expensive and, potentially, most effective approaches and for that reason an examination of the possible unintended consequences of the implementation of atmospheric injections of sulphate aerosols was made. Chief among these are: reductions in rainfall, slowing of atmospheric ozone rebound, and differential changes in weather patterns. At the same time, there will be an increase in plant productivity. Lastly, because atmospheric sulphate injection would not mitigate ocean acidification, another side effect of fossil fuel burning, it would provide only a partial solution.

Future research should aim at ameliorating the possible negative unintended consequences of atmospheric injections of sulphate injection. This might include modeling the optimum rate and particle type and size of aerosol injection, as well as the latitudinal, longitudinal and altitude of injection sites, to balance radiative forcing to decrease negative regional impacts. Similarly, future research might include modeling the optimum rate of decrease and location of injection sites to be closed to reduce or slow rapid warming upon aerosol injection cessation. A fruitful area for future research might be system modeling to enhance the possible positive increases in agricultural productivity. All such modeling must be supported by data collection and laboratory and field testing to enable iterative modeling to increase the accuracy and precision of the models, while reducing epistemic uncertainties.

CONTENTS

1. INTRODUCTION

Geoengineering is the "... large-scale engineering of our environment in order to combat or counteract the effects of changes in atmospheric chemistry" (National Academy of Sciences 1992), in particular to mediate the effects of elevated greenhouse gas, especially carbon dioxide, concentrations. The surface temperature of the Earth results from the net balance of incoming solar (shortwave) radiation and outgoing terrestrial (longwave) radiation. One category of geoengineering options attempts to rectify the current and potential future radiative imbalance via either: (1) reducing the amount of solar (shortwave) radiation absorbed by the Earth, or (2) increasing the amount of longwave radiation emitted by the Earth. The shortwave options (1) can be subdivided into those that seek to reduce the amount of solar radiation reaching the top of the atmosphere, and those that seek to increase the reflection of shortwave radiation (albedo) within the atmosphere or at the surface (e.g. Lenton and Vaughan 2009).

Most climate scientists believe that climate geoengineering is best considered as a potential complement to the mitigation of CO_2 emissions, rather than as an alternative to it. Strong mitigation could achieve the equivalent of up to $-4Wm^{-2}$ radiative forcing on the century timescale, relative to a worst case scenario for rising CO_2. However, to tackle the remaining $3Wm^{-2}$, which are likely even in a best case scenario of strongly mitigated CO_2 releases, a number of geoengineering options show promise. Only placing sunshades in space or increasing planetary albedo by injecting stratospheric aerosols have the potential to roughly cancel the projected mitigated CO2 radiative forcing. (Lenton and Vaughan 2009). The costs of constructing and placing sunshades into orbit are obviously much greater than land-based injection of inexpensive sulphate aerosols into the atmosphere. The ability to rapidly "titrate" sulphate atmospheric concentrations is also a distinct advantage when attempting to control complex and interacting global systems. Because it is the most likely form of geoengineering to be implemented, an examination of the possible unintended consequences of the implementation of atmospheric injections of sulphate aerosols is needed.

2. UNINTENDED CONSEQUENCES

A change in one factor in any dynamic and tightly coupled complex system may well influence other factors. The resulting changes in these other factors may be positive and the intended result of the action upon the system, or negative and not the intended consequence. This is certainly true of geoengineering which acts upon the entire earth, including land, sea and air. The possible unintended consequences of sulphate aerosol injection discussed in this report include:

1. Changes in amount and location of global precipitation,
2. Changes in the color and brightness of the sky,
3. Delay in the mitigation of ozone loss,
4. Increase in acid rain,
5. Rapid warming if atmospheric sulphate aerosol injection abruptly stopped,
6. Decreasing insolation for energy production from solar thermal and photovoltaic technologies,
7. Increase in plant productivity,
8. Differential change in regional climates,

9. Worsening of negative health effects,

Changes in amount and location of global precipitation

Model simulations show that the temperature response pattern due to greenhouse gas forcing and due to solar insolation reduction (such as sulphate aerosol injection) is similar despite the imbalance in spatial and temporal distribution of the forcing (See below). The response of the hydrological cycle to sulphate aerosols, however, shows distinct differences. The hydrological sensitivity, defined as the change in global mean precipitation per one degree temperature change, is considerably higher for aerosol than for greenhouse gas forcing (Liepert, Feichter et al. 2004). This is because the aerosol forcing primarily affects the surface radiation budget, whereas a major part of the greenhouse gas forcing is felt within the troposphere. Surface waters and moisture in the land and air evaporates less if solar insolation is reduced and precipitation declines accordingly (Feichter and Leisner 2009).

Trenberth and Dai (2007), analyzed observed precipitation following the eruption of Mount Pinatubo in June 1991 and found a substantial decrease in precipitation over land and a record decrease in runoff and river discharge into the oceans in the period October 1991 to September 1992. They conclude that major adverse effects, including drought, could arise from solar insolation reduction. Eliseev et al. (2009) concluded that when the global mean surface air temperature is stabilized by sulphate aerosol injection, global precipitation decreases by about 10%. Globally averaged precipitation was calculated to decrease during the twenty-first century by 12–13 cm/year relative to 2000–2010 for the case of complete mitigation of global warming. Despite a very similar globally averaged value, geographical patterns of precipitation change differ between different latitudinal distributions of sulphate aerosols. For the uniform latitudinal distribution of stratospheric sulphates, annual precipitation decreases by 5–10 cm/year compared to the first decade of the twenty-first century in the tropical areas and in the southern storm tracks (Eliseev, Chernokulsky et al. 2009).

Similar precipitation response has been calculated by Brovkin et al. (2009) . Marked reduction in precipitation over the tropical west Pacific as a response to the combined anthropogenic and geoengineering forcing was also simulated by Robock et al. (2008), and the reduction of precipitation over the near-equatorial continental areas under a similar scenario was predicted by Matthews and Caldeira (2007). For the case of complete global warming mitigation in the twenty-first century and for the triangular latitudinal distribution of stratospheric sulphates peaked at 50◦N or at 70◦N, annual precipitation was predicted to decrease by 5–10 cm/year relative to 2000–2010 in the northern subtropics (in particular, in the region of the South-Asian monsoon) and respectively **increase** by 5–10 cm/year in the southern storm tracks. The predicted precipitation **decrease** in the south-east of Asia is in agreement with the suppression of summer monsoon there. A similar precipitation decrease was also simulated by Brovkin et al. (2009) and Eliseev et al. (2009).

As noted, application of geoengineering in the case of complete mitigation of globally averaged warming results in a decrease of global precipitation by about 10% relative to the mean value for the years 2000–2010. In absolute units, the largest decrease of annual precipitation is simulated in the tropics and in the Southern Hemisphere storm tracks. This agrees with other empirical and model-based studies (Groisman 1985; Matthews and Caldeira 2007; Trenberth and Dai 2007; Robock, Oman et al. 2008; Brovkin, Petoukhov et al. 2009; Eliseev, Chernokulsky et al. 2009).

A substantial precipitation decrease in the Amazon and Congo valleys may trigger a dieback of tropical forests with corresponding suppression of carbon uptake from the atmosphere (see e.g. Cox, Betts et al. 2004) which would result in additional greenhouse warming. The latter, in turn, would require additional sulphur emissions to mitigate the additional warming (Eliseev, Chernokulsky et al. 2009).

Changes in the color and brightness of the sky

To compensate for a doubling of CO_2, which causes a greenhouse warming of 4 W/m^2, the required continuous` stratospheric sulphate loading would be a sizeable 5.3 Tg S (1 Tg=1^{12} g), producing an optical depth of about 0.04. The Rayleigh scattering optical depth at 0.5 μm is about 0.13, so that some whitening on the sky, but also colorful sunsets and sunrises would occur. It should be noted, however, that considerable whitening of the sky is already occurring as a result of current air pollution in the continental boundary layer (Crutzen 2006).

Absorption by carbon in single and composite particles decreases as the wavelength is increased in the visible band, thus resulting in redshifts of the color of the sky. Single atmospheric soot grains are very absorbing, but when they interact with sulphate droplets they become even more absorbing. Single sulphate droplets contribute very little to light absorption. As a rule of thumb, carbon dims and redshifts daylight through selective absorption, whereas sulfuric acid enhances the aforesaid effect of carbon on light through microlensing (Dogras, Ioannidou et al. 2004).

Delay in the mitigation of atmospheric ozone loss

Crutzen (2006) calculated that roughly 5.3 Tg of stratospheric sulfur (S) would counteract surface warming due to doubled atmospheric CO_2. This assumed that volcanic-sized particles require injections of 2 Tg S/year to maintain the effect. Rasch et al. (2008), calculated that an injection of 1.5 Tg S/year, using particles considerably smaller than those assumed by Crutzen (2006), would achieve the same radiative effect. Smaller aerosols are expected to cool more efficiently than large aerosols because of the dependence of backscattering on particle size. Furthermore, smaller aerosols have a smaller effect on stratospheric temperature. Murphy (2009) suggests that any intentional enhancement of the stratospheric aerosol layer would need to produce particles between about 0.2 and 1 μm in diameter: smaller particles do not efficiently scatter light, and larger particles are quickly lost from the stratosphere due to gravitational settling. Tilmes et al (2008) concluded that the continuous injection of an amount of sulfur large enough to compensate for surface warming caused by the doubling of atmospheric CO_2 would strongly increase the extent of Arctic ozone depletion during the present century for cold winters and would cause a considerable delay, between 30 and 70 years, in the expected recovery of the Antarctic ozone hole.

Increase in acid rain

Kravitz et al. (2009) calcualted that the additional acid deposition that would result from geoengineering (using sulphate aerosols) will not be sufficient to negatively impact **most** ecosystems. With the exception of waterways, every region has a critical loading value a full order of magnitude above the total amount of acid deposition that would occur under the geoengineering scenario. Even waterways would receive at most 0.05 $mEq/m^2/acre$ in additional sulphate deposition meaning only those waterways most sensitive to small amounts of additional deposition would be negatively impacted.

Rapid warming if stratospheric sulphate aerosol injection stops

If geoengineering proceeds for a finite time interval and ceases afterwards, a large disparity between the applied radiative forcing and current state of the climate system develops. Even larger surface air temperatures (SAT) changes are predicted to occur after the geoengineering stops at the regional level. One of the models used by Eliseev et al. (2009) shows that for complete CO_2 mitigation, these SAT changes could be as large as 3 K/decade in the interiors of Eurasia and North America for the uniform latitudinal distribution of stratospheric sulphates, and up to 5 K/decade for other distributions with a maximum at 70◦N (Eliseev, Chernokulsky et al. 2009).

Brovkin et al. (2009) calculated that within 30 years after the emissions breakdown, the Arctic region would be 6–10◦C warmer in winter while northern landmasses would be roughly 6◦C warmer in summer. This warming would be much more rapid than one of the most abrupt and extreme global warming events recorded in geologic history, the Paleocene–Eocene Thermal Maximum (PETM) event about 55 Myr ago, when sea surface temperatures rose between 5 and 8◦C over a period of a few thousand years (Zachos, Pagani et al. 2001). In one simulation by Brovkin et al. (2009) a warming of similar magnitude was predicted to occur within a few decades. An unprecedented abruptness of climate change as a consequence of a failure in geoengineering was stressed recently by Matthews and Caldeira (2007) who pointed out that the warming rates in this case could be up to 20 times greater than present-day rates.

Decrease in the amount of power production from concentrating solar collectors

Light scattering calculations based on data from the Mauna Loa, Hawaii Observatory (with a data record spanning the eruption of Mt. Pinatubo), show that stratospheric aerosols reduce direct sunlight by about 4 W for every watt reflected to outer space. The balance becomes diffuse sunlight. One consequence of deliberate enhancement of the stratospheric aerosol layer would be a significant reduction in the efficiency of solar power generation systems using parabolic or other concentrating optics. The impact on concentrating solar power is surprisingly large: peak power output was reduced by about 20% during a year when the stratospheric aerosol layer from the Mt. Pinatubo eruption reduced total sunlight by less than 3% (Murphy 2009).

Because flat solar hot water and photovoltaic panels utilize diffuse as well as direct sunlight, the performance losses are not as large as for concentrating solar collectors. However, the performance loss will still exceed the reduction in total sunlight because a tilted panel does not capture diffuse sunlight as efficiently as direct sunlight. A potentially important effect is that any shift from direct to diffuse sunlight makes a passive solar design less effective: in winter diffuse sunlight is harder to capture with south-facing windows, and in summer, shading windows with overhangs is less effective (Murphy 2009). Murphy (2009) used observations of direct solar energy generation in California after the 1991 Pinatubo eruption and showed that generation went from 90% of peak capacity in non-volcanic conditions to 70% in summer 1991 and to less than 60% in summer 1992.

Increase in plant productivity

An unintended positive consequence of geoengineering – increased plant productivity - might also occur. Gu et al. (1999; 2002; 2003), Roderick et al. (2001), and Farquhar and Roderick (2003) suggested that increased diffuse radiation allows plant canopies to photosynthesize more efficiently, increasing the CO_2 sink. Gu et al. (1999) actually measured this effect in trees following the 1991 Pinatubo eruption. While some of the global increase in CO_2 sinks following volcanic eruptions may have been due to the direct temperature effects of the eruptions, Mercado et al. (2009) showed that the diffuse radiation effect produced an increase sink of about 1 Pg C/yr for about one year following the Pinatubo eruption. The effect of a permanent geoengineering aerosol cloud would depend on the optical depth of the cloud, and these observed effects of episodic eruptions may not produce a permanent vegetative response as the vegetation adjusts to this changed insolation. Nevertheless, this example shows that stratospheric geoengineering may provide a substantial increased CO_2 sink to counter anthropogenic emissions. This increase in plant productivity could also have a positive effect on agriculture (Mercado and al. 2009).

Regional imbalances in weather impacts

If the injected sulphate aerosols are not uniform throughout the atmosphere, whether due to inadequate placement, due to non-uniform mixing by winds, or due to differential removal by wet deposition, some regions of the earth could experience more extreme drought and other regions could potentially experience floods. Even if uniformly distributed, shortwave radiation management to stabilize climate in one region might amplify the impact of increasing GHG concentrations elsewhere (Blackstock, Battisti et al. 2009). Indeed, even in the case of complete global warming mitigation, substantial anomalies of annual mean surface air temperature (SAT) develop in different regions. Their magnitude basically increases with time in accordance with growth of the sulphur emissions in the stratosphere. The geographical pattern of these anomalies depends on latitudinal distribution of atmospheric sulphates (Eliseev, Chernokulsky et al. 2009). For both uniform and triangular latitudinal distributions of atmospheric aerosols, the SAT response on geoengineering mitigation consists of anomalies of one sign in the northern middle latitudes and anomalies of another sign in the middle and subpolar latitudes of the Southern Hemisphere (Eliseev, Chernokulsky et al. 2009).

Feichter and Leisner (2009) caution that it should be kept in mind that the concept of solar insolation reduction does not neutralize the greenhouse effect which acts on long-wave radiation and, thus, unintended regional climate response may occur. As demonstrated by Govindasamy et al. (2003) green house gas warming is effective at all latitudes and throughout the year, while an enhanced short wave albedo cools preferentially where and when the sun shines most.

Globally averaged annual changes in air surface temperature are zero, but regional and seasonal temperature changes are substantial. During winter, polar regions are warmer by up to 2°C in both the northern and southern hemispheres. The aerosol forcing is almost absent in high latitudes during winter time when the solar radiation flux is very small, while the longwave radiative CO_2 forcing is active during all seasons. In summer, negative radiative forcing of aerosols leads to about 1◦C cooling over North America and Eurasia. At the same time, a warming of 0.5–1◦C is calculated over the Tibetan plateau and North Africa. These regions have a relatively high surface albedo and adding an aerosol layer does not make their planetary albedo higher, but lower. Aerosols over bright surfaces increase the multiple scattering of light between the surface and the atmosphere thereby enhancing the absorption of solar radiation. As a result, the air temperature over the regions with high surface albedo increases. In monsoon regions in East and South-East Asia, cooling leads to a reduction in precipitation. This is caused by a reduction in monsoon intensity associated with surface cooling and a reduced temperature gradient between ocean and land. In southern Europe and subtropical North America, summer aridity is increased as well. Precipitation is predicted to be lowered over tropical land masses during all seasons, except for tropical Asian regions during June–August (Brovkin, Petoukhov et al. 2009).

Rasch et al (2008) calculated that sulphate mass formed in the stratosphere is concentrated in low and in high latitudes. In mid-latitudes and the subtropics sulphate concentrations are lower because downward transport into the troposphere takes place in these latitudes. Although the sulphate amount is higher in winter, the forcing is highest when solar insolation is at maximum. In summer, radiative forcing is highest in Polar Regions. The regional pattern of the temperature response due to sulphate injections is similar to that due to an increase of greenhouse gases with stronger cooling over the continents and at polar latitudes and less cooling over the oceans. These regional differences could lead to regional climate "winners" and "losers" should such geoengineering occur, exacerbating possible societal disruptions.

Negative health effects

Fossil fuel burning releases about 25 Pg of CO_2per year into the atmosphere, which leads to global warming. However, it also emits 55 Tg S as SO_2 per year (Stern 2005), about half of which is converted to sub-micrometer size sulphate particles, the remainder being dry deposited. Recent research has shown that the warming of earth by the increasing concentrations of CO_2 and other greenhouse gases is partially countered by some backscattering to space of solar radiation by existing sulphate particles, which act as cloud condensation nuclei and thereby influence the micro-physical and optical properties of clouds, affecting regional precipitation patterns, and increasing cloud albedo (e.g. Rosenfeld 2000; Ramanathan, Crutzen et al. 2001). Anthropogenically enhanced sulphate particle concentrations thus cool the planet, offsetting an uncertain fraction of the anthropogenic increase in greenhouse gas warming. However, this fortunate coincidence is "bought" at a substantial price. According to the World Health Organization, the pollution particles currently affect health and lead to more than 500,000 premature deaths per year worldwide (Nel 2005).

Lastly, although not an unintended consequence, the fact that sulphate aerosol injection does not address ocean acidification, another consequence of CO_2 loading of the atmosphere, must be noted. Presently, ocean pH is buffered by, in part, by reactions involving CO_2 dissolution into the ocean and calcite dissolution/growth. Each reaction depends on both atmospheric CO_2 levels and temperature. In the past, CO_2 and temperature were themselves linked; with sulphate injection, they will not be. Decoupling of temperature and CO_2 would therefore lead to different, and potentially less predictable changes in ocean pH in the future.

3. UNINTENDED ECONOMIC CONSEQUENCES

Characterizing the economic impacts of climate change is highly dependant upon the scale and resolution of what impacts analyses consider. For example, economic impacts can often be divided into direct effects on the production of goods and services (G&S), direct impact on nonmarket G&S, indirect impacts within the regional economy, and indirect impacts that operate through other regions of the world (Abler, Shortle et al. 2000). By region, economics often refers to either a reasonably geographically isolated portion of several economies (e.g., the Austrialasia subcontinent) or simply a singular country. This division of definitions is important for global discussion regarding the impact of climate change because it helps put the 'costs' or 'benefits' of climate change into context in terms of impact (e.g., $), and nonmarket effects. A key example of the direct and indirect effects of say, a decreasing regional supply of precipitation will directly affect the region or country within the preceipitation's extent (e.g., local drought), yet it may also affect other regions or countries if say, this particular region undergoing a chronic or permanent drought was a productive staple agricultural basin for many parts of the world. Market impacts often referred to as 'primary' economic sectors include agriculture, forestry and fisheries. Examples of nonmarket impacts include ecosystem damage, impacts to humans such as potential changes in morbidity and hardship due to pollution, migration, political instability (Abler, Shortle et al. 2000).

Changes in amount and location of global precipitation

The effects of a potential change in precipitation tied to an increase in extreme weather patterns has been developed by Rose et al. (2000). Rose et al. (2000) found that using an Input Output (I-O) model for a 5.2% decrease in forestry production, the regional economy may see a reduction of only 0.0035% which represents approximately $62.9 million ($US=1995). For context, the Mid-Atlantic Region (MAR) of the United States under consideration by Rose et al. (2000) represented 13% of the total national output in 1995. The low percentage of economic impact due to a decrease in the forestry sector's productivity is primarily due to the nature of the regional model, relative size of the forestry sector in the region, and it's ties with the global economy. Also, it is important to note that this represents the economy *at a single point in time* and that the additive (and potentially cumulative) effects across the decades is to be determined (Rose, Cao et al. 2000).

For larger, more rural regions of the world that could be affected by increase prevelance of fire, the consequences of changes in climate may be more acute. The work of Sedjo (2010) suggest that for larger geographic region, such as the forests of Brazil fires in the Amazonian regions may require and additional annual $2 million to combat these fires. However, the overall net economic effect of climate change to changes in the rainforest remain to be determined (Sedjo 2010).

Lastly, reductions (or substantially shifted) in precipitation leading toward higher degrees of drought-like phenomenon will also lead to groundwater loss thereby detrimentally affecting water-stressed (e.g., due to population growth) and relatively poor regions of the world (Ranjan, Kazama et al. 2006).

Delay in the mitigation of ozone loss

The impact of additional sulfate aerosols in the upper atmostphere may contribute to additional ozone loss whether through natural (e.g., volcanoes) or anthropogenic (geoengineering) means. Rasch et al. (2008) describe reduction in the ozone column of 2 percent in the tropics following the Mount Pinatubo eruption and 5 percent in the ligher lattidudes. Kelfkens et al. (1990) concluded that, for a 1% decrease in the total column atmosphere ozone, an increase of non-melanoma skin cancer may be 2.7%. While ozone layer degradation affects many regions throughout the world, Australia has been particularly affected due to its proximity to the Antacrtica 'ozone hole'. Certain regions of Australia has been measured to have an incident rate of melanoma and non-melanoma skin cancer of 20 – 2055 incidents per 100,000 population as compared to 8 – 407 in some regions of the U.S., and 3-128 in certain areas of Europe. Given the high incidence of of skin cancer, Australia instituded several pulic awareness programs to focus on skin cancer prevention. The 'Slip, Slop, Slap' campangin of the 1980s, and the 'SunSmart' campangin later may now prevent up to 28,000 disability-adjusted life-years (e.g., benefit) as compared to the cost of the campaigns. The general return on this government investment has been described to be 2.30 $AU (2003 levels) for every dollar invested (Ting-Fang Shih, Carter et al. 2009).

Rapid warming if atmospheric sulphate aerosol injection abruptly stopped

The introduction of sulphate aerosols beyond current rates of emissions result in either a decrease in the insulating capacity of the atmostphere – thereby leading to global cooling, or increase the global temperature due to an overcapacity of atmospheric aerosols (e.g., based on expanded SO_2 emissions) (Ward 2009). Alternatively, as pointed out by Kunzig (2008), deploying large-scale sulfur aerosols may have a direct effect on decreasing insolation in the short term. However, drastic consequences including rapid, relatively large global warming may result if and when the continual deployment of sulur aerosols stops abrubly. One can imagine many scenarios that may lead to such an abrubt stop including global economic depressions, wars, acute and therefore abrubt use of the funding used for sulfur aerosols being diverted to address pandemics, and many others. Thus, as discussed by Robock et al. (2008) and many others in the research community, it is not necessarily the global warming that has dire consequences for humanity, rather, it is the speed of and region in which it occurs and thereofore allows for subsequent adaptation.

Increase in plant productivity

One concern of reducing the relative solar radiation reaching the Earth's surface due to geoengineering is the effects on plant productivity. In theory, a decrease in solar radiation, at first glance, could decrease photosynthesis in select regions of the world that may or may not be offset by increases in traditionally less productive regions. Stanhill and Cohen (2001) reviewed data from the global network of the surface radiation balance published by the World Radiation Center, also sponsored by the World Meterological Organization. Their findings suggest a 10-20% decrease in solar radiation reaching the earth may only have a minor effect on plant productivity and subsequent crop yields. The degree of water stress in the affected regions will drive plant productivity moreso than these potential decreases in solar radiation.

Differential change in regional climates

According to Chhetri (2008), an underlying notion as to the extent of climate change impacts on agriculture is the combined effects of the physical changes of the climate as well as society's ability to innovate and adapt to it. Central to their thesis is the direction and size of feedbacks amongst the climate-technologial interaction. Specifically, when climate changes give farmers the appropriate signals to induce innovation, their ability to undertake such innovations is a function of their ability (e.g., socioeconomic) to adapt to change. A more salient example is the dominantly rain-fed rice cultivation in Nepal. Due to limited irrigation infrastructure, one may suspect limited flexibility for agricultural innovation. Chhetri's examination of the district data, however, supports a hypothesis that innovation, spurred in part through programs instituted in the 1990s, has allowed less productive sites to 'catch up' to their more productive counterparts more quickly than one might otherwise have thought.

To address a more global perspective on the ability to adapt in a timely manner to climate change Fisher et al. (2005) developed a global integrated assessment model. Global simulations suggest that agricultural production in developing countries may decrease 5-10% along with similar reductions in developed regions of North America and Russia. The number of undernourished people of the world, changing from a base level of roughly 800 million people, may change 0 – 15% in the decades following substantial climate change. The variability in climate change effects between regions will likely be substantial especially in damange to arable land and water resources which will thereby affect food production. Fisher et al. (2005) highlight the importance of enhancing individual nations' ability to adapt to climate change.

4. CONCLUSIONS

The risks of unintentional consequences of geoengineering can be minimized by targeting research in several areas. New computer simulations should better quantify the potential economic consequences of changes in precipitation, potential changes in the ozone layer. The research should address these unintended consequences in three stages by answering the questions, (1) Will the said change be an acute or chronic global effect, (2) What are the direct and indirect effects on the biosphere of these changes and (3) Are these changes reversible in a time scale relevant to humanity (e.g., 100's of years vs. several millenia)? An example of an acute change would be the unintended effects of immediately turning off injection of sulphate aerosols into the atmosphere. The effects would be relatively pronounced and immediate and reversible relative to other effects such as affecting the ozone layer. A chronic effect may be changes in global precipitation patterns because, from an anthropogenic standpoint, many societies may not have adequate water supplies with the underlying political stability it may provide for generations to come.

Research should also include lab-scale, paper-based scenario studies (e.g., input output-like economic impact scenarios) and larger, field experiments such as those associated with atmospheric studies in the arctic. Future research should include modeling the optimum rate and particle type and size of aerosol injection, as well as the latitudinal, longitudinal and altitude of injection sites, to balance radiative forcing to decrease negative regional impacts. Similarly, future research might include modeling the optimum rate of decrease and location of injection sites to be closed to reduce or slow rapid warming upon aerosol injection cessation.

A last area for future research would be system modeling to enhance the possible positive increase in agricultural productivity. All such modeling must be supported by data collection and laboratory and field testing to enable iterative modeling to increase the accuracy and precision of the models, while reducing epistemic uncertainties.

5. REFERENCES

Abler, D., J. Shortle, et al. (2000). "Characterizing regional economic impacts and responses to climate change." Global and Planetary Change **25**: 67-81.

Blackstock, J. J., D. S. Battisti, et al. (2009). Climate Engineering Responses to Climate Emergencies (Novim, 2009), archived online at: http://arxiv.org/pdf/0907.5140.

Brovkin, V., V. Petoukhov, et al. (2009). "Geoengineering climate by stratospheric sulfur injections: earth system vulnerability to technological failure." Clim. Change **92**: 243-259.

Chhetri, N. B. (2008). Understanding the Process of Agricultural Adaptation to Climate Change: Analysis of Climate-Induced Innovation in Rice Based Cropping System of Nepal - Interim Report IR-08-028, International Institute for Applied Systems Analysi.

Cox, P. M., R. A. Betts, et al. (2004). "Amazonian forest dieback under climate–carbon cycle projections for the 21st century." Theor. App. Climatol. **78**: 137-156.

Crutzen, P. J. (2006). "Albedo enhancement by stratospheric sulphur injections: A contribution to resolve a policy dilemma? ." Climatic Change **77**: 211-219.

Dogras, C. K., M. P. Ioannidou, et al. (2004). "Analytical study of the changes in the color of daylight due to sulfate droplets and soot grains in the atmosphere, ." Journal of Quantitative Spectroscopy & Radiative Transfer **84**: 223-238.

Eliseev, A. V., A. V. Chernokulsky, et al. (2009). "Global warming mitigation by sulphur loading in the stratosphere: dependence of required emissions on allowable residual warming rate, ." Theor Appl Climatol **DOI 10.1007/s00704-009-0198-6**

Farquhar, G. D. and M. L. Roderick (2003). "Pinatubo, diffuse light, and the carbon cycle " Science **299**: 1997-1998.

Feichter, J. and T. Leisner (2009). "Climate engineering: A critical review of approaches to modify the global energy balance." Eur. Phys. J. Special Topics **176**: 81-92.

Fisher, G., M. Shah, et al. (2005). "Socio-economic and climate change impacts on agriculture: an integrated assessment, 1990–2080." Philosophical Transactions of The Royal Society **360** 2067-2083.
Govindasamy, B., K. Caldeira, et al. (2003). "Geoengineering Earth's radiation balance to mitigate climate change from a quadrupling of CO2." Global Planet. Change **37**: 157.
Groisman, P. Y. (1985). "Regional climatic consequences of volcanic eruptions." Soviet Meteorol. Hydrol. **10**: 39-45.
Gu, L., D. Baldocchi, et al. (2002). " Advantages of diffuse radiation for terrestrial ecosystem productivity." J. Geophys. Res. **107**: 4050.
Gu, L., D. Baldocchi, et al. (2003). "Response of a deciduous forest to the Mount Pinatubo eruption: Enhanced photosynthesis, ." Science **299**: 2035-2038.
Gu, L., J. D. Fuentes, et al. (1999). "Responses of net ecosystem exchanges of carbon dioxide to changes in cloudiness: Results from two North American deciduous forests.", J. Geophys. Res. **104**: 31,421–431,434.
Kelfkens, G., F. R. de Gruijl, et al. (1990). "Ozone Depletion and Increase in Annual Carcinogenic Ultraviolet Dose. ." Photochemistry and Photobiology **52**: 819-823.
Kravitz, B., A. Robock, et al. (2009). " Sulfuric acid deposition from stratospheric geoengineering with sulfate aerosols." J. Geophys. Res. **114**: D14109.
Kunzig, R. (2008). "A Sunshade for Planet Earth." Scientific American(November).
Lenton, T. M. and N. E. Vaughan (2009). "The radiative forcing potential of different climate geoengineering options." Atmos. Chem. Phys. **9**: 5539-5561.
Liepert, B., J. Feichter, et al. (2004). "Can aerosols spin down the water cycle in a warmer and moister world?" Geophys. Res. Lett. **31**: L06207.
Matthews, H. D. and K. Caldeira (2007). "Transient climate–carbon simulations of planetary geoengineering." Proc. Nat. Acad. Sci. **104**: 9949–9954.
Mercado, L. M. and e. al. (2009). "Impact of changes in diffuse radiation on the global land carbon sink." Nature **458**: 1014-1018.
Murphy, D. M. (2009). "Effect of stratospheric aerosols on direct sunlight and implications for concentrating solar power " Environ. Sci. Technol. **43**: 2784-2786.
National Academy of Sciences (1992). Policy Implications of Greenhouse Warming: Mitigation, Adaptation, and the Science Base. Washington, D.C.
Nel, A. (2005). "Air pollution-related illness: Effects of particles." Science **308**: 804.
Ramanathan, V., P. J. Crutzen, et al. (2001). "Aerosols, climate and the hydrological cycle." Science **294**: 2119-2124.
Ranjan, P., S. Kazama, et al. (2006). "Effects of climate change on coastal fresh groundwater resources." Global Environmental Change **16**: 388-399.
Rasch, P. J., P. J. Crutzen, et al. (2008). "Exploring the geoengineering of climate using stratospheric sulphate aerosols: The role of particle size." Geophys. Res. Lett. **35**: L02809.
Rasch, P. J., S. Tilmes, et al. (2008). "An overview of geoengineering of climate using stratospheric sulphate aerosols." Phil. Trans. R. Soc. A. **A366**: 4007-4037.
Robock, A., L. Oman, et al. (2008). "Regional climate responses to geoengineering with tropical and Arctic SO2 injections." J. Geophys. Res. Atmos. **113**: D16101.
Roderick, M. L., G. D. Farquhar, et al. (2001). "On the direct effect of clouds and atmospheric particles on the productivity and structure of vegetation." Oecologia **129**: 21-30.

Rose, A., Y. Cao, et al. (2000). "Simulating the economic impacts of climate change in the Mid-Atlantic region." Climate Research **14**: 175-183.
Rosenfeld, D. (2000). "Suppression of rain and snow by urban and industrial air pollution." Science **287**: 1793-1796.
Sedjo, R. A. (2010). Adaptation of forests to climate change, Resources for the Future. **DP 10-06**.
Stanhill, G. and S. Cohen (2001). "Global dimming: a review of the evidence for a widespread and significant reduction in global radiation with discussion of its probable causes and possible agricultural consequences." Agricultural and Forest Meteorology **107**: 255-278.
Stern, D. I. (2005). "Global sulfur emissions from 1850 to 2000." Chemosphere **58**: 163-175.
Tilmes, S., R. Muller, et al. (2008). "The Sensitivity of Polar Ozone Depletion to Proposed Geoengineering Schemes." Science **320**: 1201-1204.
Ting-Fang Shih, S. R. Carter, et al. (2009). "Economic evaluation of skin cancer prevention in Australia." Preventative Medicine **49**: 449-453.
Trenberth, K. E. and A. Dai (2007). "Effects of Mount Pinatubo volcanic eruption on the hydrological cycle as an analog of geoengineering." Geophys. Res. Lett. **34**: L15702.
Ward, P. L. (2009). "Sulfur dioxide initiates global climate change in four ways " Thin Solid Films **517**: 3188-3203.
Zachos, J., M. Pagani, et al. (2001). "Trends, rhythms, and aberrations in global climate 65 Ma to present." Science **292**: 686-693.

DISTRIBUTION

1	MS0735	John A. Merson	6730
1	MS0736	Marianne C. Walck	6760
5	MS0754	Patrick V. Brady	6730
5	MS0750	Peter H. Kobos	6732
2	MS0754	Barry Goldstein	6734
2	MS0750	Mark J. Rigali	6736
1	MS 0899	Technical Library (electronic copy)	9536

Sandia National Laboratories