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Engineering Our Climate: A Critical Review of the Geoengineering Response to Climate Change

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ABSTRACT

Various responses to greenhouse gas induced climate change have been proposed within the literature. While the most desirable response is to dramatically reduce greenhouse gas emissions, technological and financial obstacles make it difficult to realize the reductions necessary to solve the climate change problem. Several geoengineering schemes have been proposed that would compensate for increased greenhouse gas concentrations by reducing the solar energy absorbed by Earth. The most notable of these shortwave climate engineering schemes involves injection of sulfur aerosols into the stratosphere in order to disperse incoming radiation. This paper examines the geoengineering responses to climate change and demonstrates that, while the research necessary for their use should be pursued, the proposed schemes present a serious risk to the global community and their use should not be taken lightly.

INTRODUCTION

Climate Change and CO_2

It has been well documented that the earth's climate is becoming warmer. There is currently a high level of agreement among climate scientists that the warming is due to anthropogenic contributions of greenhouse gases (GHGs), with increased carbon dioxide (CO_2) concentration as the primary contributor. The atmospheric concentration of CO_2 has risen from pre-industrial levels of 280ppm to over 380ppm and is expected to continue to increase during the next century even if dramatic reductions in CO_2 emissions are enacted (Solomon et al., 2007). It is generally accepted that CO_2 emissions need to be reduced in the long-term to prevent catastrophic climate changes; however, numerous technological and social hurdles must be overcome before meaningful reductions in the global CO_2 emission rate are realized. In the short term, atmospheric CO_2 concentration will continue to rise, and the global average temperature is expected to continue climbing. The possibility of serious disruption of our climate system due to rising temperature has spurred discussion of potential actions that could be undertaken in order to stave off an imminent climate emergency.

CO_2 is a greenhouse gas because of its contribution to the so-called "greenhouse effect." Other common greenhouse gases include H_2O, N_2O (nitrous oxide), chlorofluorocarbons,

CH_4 (methane) and other molecules with a dipole moment that changes with bond length. The greenhouse effect refers to absorption by gases in the atmosphere of the outgoing, longwave (infrared) radiation; it is similar in principle to the way that the glass of a greenhouse prevents heat from escaping while allowing the energy of sunlight to enter. Greenhouse gases such as H_2O are an important component of our unpolluted atmosphere, because they prevent some of the infrared radiation emitted by the earth from escaping to space, thereby allowing the average temperature at the earth's surface to maintain a reasonably warm 15˚C rather than the predicted -19˚C (59˚F and -2˚F respectively) (Girard, 2010).

To understand the difference between the expected and actual temperature of the earth, it is necessary to examine earth's heat balance. The sun provides energy to the earth at a rate of 342 W/m^2 (watts per square meter) as measured at the top of our atmosphere. Approximately 30% of this radiation is reflected back to space by either the earth's surface or by particulates in the atmosphere; either the earth or the atmosphere absorbs the remainder. In order to maintain a constant temperature, it is necessary for the earth to emit an equivalent amount of radiation in the infrared region of the spectrum. The absorption of infrared radiation by greenhouse gases in our atmosphere upsets the balance between incoming and outgoing energy resulting in a steady state where the earth's surface temperature is elevated above the expected temperature. This is termed the greenhouse forcing because it "forces" our climate away from its expected position (-19˚C).

Radiative forcings also occur when incoming solar radiation is reflected or scattered before it can be absorbed by the earth's surface or the atmosphere. The phenomena responsible for reflecting solar input are termed albedo. Atmospheric albedo is a measure of the reflection of incoming radiation by clouds or particulates in the atmosphere; surface albedo results from the reflectivity of the earth's surface and is high for bright surfaces such as snow and ice and low for liquid water and most land surfaces. The average albedo of the earth, including both atmospheric and surface components, is around 30%. A stable climate is a steady state of energy or radiation flow, in which energy inputs are equal to energy outputs and temperature is relatively constant. This energy steady state is mathematically described by the simple relationship:

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where R_{in} is incoming radiation (solar flux, essentially constant) and R_{out} is outgoing radiation (longwave, a function of surface temperature) emitted by the earth and each term represents the energy flow in W/m^2. Thus, if the value of any one of the terms changes, there must be a concomitant and opposite change of another term in order to maintain a constant temperature (in reality many different atmospheric, terrestrial and oceanic factors contribute to the albedo and greenhouse effect terms, but this simple model shows that the overall forcings must balance in order to maintain a given temperature). In the current climate change, because the greenhouse effect is becoming stronger or larger, the earth must increase its temperature until the outgoing radiation (R_{out}) is such that the right side of the equation is again equal in magnitude to the left side, thus restoring the energy steady state.

Proposed Solutions to Climate Change

The best long term solution for GHG-induced climate change is to dramatically reduce anthropogenic greenhouse gas emissions. Because the most important anthropogenic greenhouse gas is CO_2, the debate about the appropriate response to climate change tends to focus on reduction of CO_2 emissions by either utilizing renewable fuels that do not contribute to a net increase in atmospheric CO_2 concentration, sequestering CO_2 prior to emission, or increasing the efficiency with which we generate and utilize energy from fossil fuels. The technologies necessary to effect a significant change in global CO_2 emissions are currently in a development stage and, while capabilities are continually improving, annual CO_2 emissions are likely to continue to increase in the near future. The inertia of the upward global CO_2 emission trend has led to discussion of methods to compensate for the high levels of atmospheric greenhouse gases.

The large-scale responses to climate change fall under the category of geoengineering. These methods aim to affect the earth's climate by manipulating natural processes on a global scale. Geoengineering schemes can be categorized in two groups: those aimed at reducing the greenhouse effect, and those aimed at reducing the net solar input (R_{in} – Albedo).The first category would do so by removing CO_2 from the atmosphere; the most notable proposal under this category is fertilization of the open oceans in order to stimulate rapid growth of phytoplankton that soon die and drift to the bottom of the ocean, taking with them atmospheric carbon dioxide that is taken up by phytoplankton production (Barker, 2007). This idea continues to be researched with limited success. However, such removal of CO_2 from the atmosphere usually involves slow processes. Therefore, reducing the greenhouse effect via CO_2 removal should bring about long term cooling of the earth, but is not expected to produce immediate results. Since most of the discussion of geoengineering revolves around the solar input reducing methods, CO_2 reduction methods will not be further considered in the paper.

Other geoengineering proposals involve interrupting the radiative energy balance of the earth by reducing the net absorbed amount of shortwave solar radiation. These methods are termed "shortwave climate engineering" by Blackstock et al. (2009); this description accurately portrays both the mechanism and intended effect of these schemes and will be - referred to - throughout this paper. Shortwave climate engineering methods are expected to produce an immediate (less than one year) effect on the earth's climate; similarly, the effects are expected to be short-lived, so that no lasting impact will be result, should it be necessary to stop using the method. Moreover, we have a fairly good understanding of the short-term effects of altering the earth's solar input due to "natural experiments" such as volcanic eruptions. The immediacy of shortwave climate engineering makes it attractive as a means of responding to increased warming of the earth due to increased CO_2 concentration in our atmosphere, particularly if that warming were to take place more quickly than expected. The application of this climate engineering, or geoengineering, approach-, is seriously - debated among scientists -primarily due to a lack of reliable modeling to predict what unwanted effects may result from such action.

A number of mechanisms have been proposed for reducing solar input to the earth's surface, some more viable than others. Among the more prominent examples include placing a screen or spacecraft between the earth and the sun (Angel, 2006), and introducing aerosol materials into the atmosphere; these include aerosolizing seawater in the troposphere in order to increase cloud cover (i.e., atmospheric albedo) over our oceans (Latham, 2008) or sulfate in the stratosphere (Crutzen, 2006) in order to scatter incoming light globally. Of the proposed mechanisms, injection of sulfate into the stratosphere has received the most attention in recent years and the bulk of this paper will focus on principles and developments as they pertain to sulfate injection, accompanied by discussion of some of the advantages and disadvantages of the other two schemes mentioned above.

Volcanic Eruptions and Shortwave Climate Engineering via Albedo/Aerosol Enhancement

Sulfate (SO_4^{2-}) is a naturally occurring aerosol component of our atmosphere. Sulfate in the troposphere originates from natural sources such as gaseous sulfur compounds (H_2S) from anaerobic decomposition of organic matter and sulfur dioxide (SO_2) from volcanic eruptions and from burning of coal. In the troposphere, sulfur gases are quickly (2-3 days) converted to H_2SO_4 in clouds and fall with precipitation, resulting in acid rain. The picture for the stratosphere is rather different. Stratospheric sulfate primarily results from SO_2 contributed by very large and explosive volcanic eruptions, such as the 1991 eruption of Mt. Pinatubo in the Philippines. Just as in the troposphere, stratospheric SO_2 is converted to H_2SO_4, however, clouds do not exist in the stratosphere, and sulfate therefore agglomerates into aerosol particles that remain suspended for 1-2 years on average (Crutzen, 2006). These stratospheric aerosol particles scatter incoming solar radiation and thus cause less energy to be absorbed by the earth's surface. This effect can be seen from temperature data in the years following the eruption of Mt. Pinatubo (or any other very large volcanic eruption).

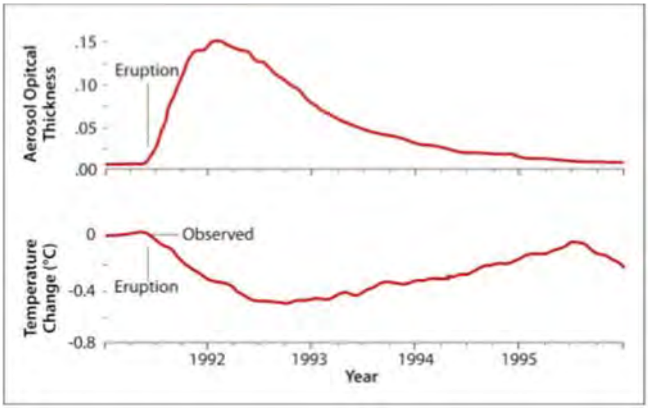

Figure 1. Optical and temperature effects in the years following the eruption of Mt. Pinatubo. (From Blackstock et al., 2009)

Since geoengineering through sulfate injection is similar to climate change caused by volcanic aerosols, it is important and helpful for us to study and understand how current and past volcanic eruptions have impacted climate. To do this, high quality data are needed concerning eruption magnitudes and the atmospheric aftermath of the eruptions. In addition to data from modern volcanic eruptions, reliable ice core data, particularly those for the last 1000 years, are being increasingly developed through the measurement of sulfate concentration in ice cores. The ice core data have the advantages that they are quantitative, can be linked to paleoclimate records and can potentially differentiate between large stratospheric eruptions and short-lived tropospheric eruptions based on isotope fractionation (Cole-Dai, 2010). Ice core data also help to develop reliable climate models based on volcanic forcings. Climate models allow us to explore long term climate effects of large eruptions or the effect of multiple eruptions over a relatively short time period. Climate data from ice cores also corroborate the increasing greenhouse effect during the twentieth century and the apparent climate impact of several large eruptions in the latter half of the century.

DISCUSSION

The shortwave climate engineering scheme discussed by Crutzen (2006) is designed to counter the greenhouse warming by emulating the global cooling seen after the eruption of Mt. Pinatubo by deliberately injecting sulfate (or a precursor) into the stratosphere. The amount of sulfate to be injected depends on the magnitude of cooling deemed necessary. It is estimated that the Mt. Pinatubo eruption injected approximately 10 Tg (1 Teragram=10^{12}g=1 million tons) of sulfur into the stratosphere. While this amount of sulfur sounds (and is) huge, it is only about 20% of current annual anthropogenic sulfur emissions (Blackstock et al., 2009). The amount of sulfur required for climate cooling on a continuous basis would be much less than that, with estimated values ranging from 1-5 Tg per year at a cost on the order of $30 billion per Tg.

Wigley (2006) proposed that sulfate injection could be used in conjunction with CO_2 emission reduction in order to stabilize the climate in the short-term by the former while developing technology and infrastructure to achieve the latter for the long-term solution. Wigley's proposition would use shortwave climate engineering as a means to cover the time period between now and when substantial reductions in CO_2 emissions, which the scientific community generally argues are necessary to avoid catastrophic climate disruptions, can be achieved. While his proposed scheme has certain advantages (particularly in delaying the need for immediate CO_2 reductions and thus reducing associated costs and possible economic disruptions), the feasibility of the method is based on two assumptions about environmental effects: firstly, "the Mt. Pinatubo eruption caused detectible short term cooling but did not seriously disrupt the climate system" and adding sulfate to the stratosphere "should therefore present minimal climate risks;" secondly, adding sulfate to the stratosphere "would delay recovery of stratospheric ozone slightly but only until anthropogenic chlorine loadings returned to the levels of the 1980s" (Wigley, 2006).

Since 2006, when this scheme was initially proposed, evidence has emerged raising serious questions about these assumptions. First of all, Blackstock et al. (2009) argue that the lack of disruption of the climate system by the aerosols of a brief volcanic eruption is probably due to the fact that "thermal inertia due to the oceans' large heat capacity smoothes and delays the climate response to a change in radiative forcing". Were these stratospheric sulfate loadings sustained over a longer period of time, temperature change would have likely been much greater, and other components of the climate system, precipitation in particular, might also be severely affected. Tilmes et al. (2008) address the second assumption by demonstrating that recent modeling indicates that addition of an aerosol component such as sulfate into the stratosphere will have significant negative effects on ozone depletion. This is because chlorine activation reactions that destroy ozone molecules take place on the surface of solid particles. Under normal stratospheric conditions, formation of significant solid particles only occurs under extremely cold conditions, i.e., in polar stratospheric clouds (PSCs). As a result, ozone depletion is more pronounced over the Antarctic than in the warmer Arctic. Sulfate aerosols would provide additional surface areas for chlorine activation, with the result that enhanced ozone depletion can be expected, particularly in the northern hemisphere. The expected recovery of the "ozone hole" over the Antarctic would be delayed by 15-30 years and possibly longer, pushing the expected date when pre-1980s conditions would be restored to 2090 or into the next century (Tilmes et al., 2008).

When the potential risks of stratospheric sulfate injection are elucidated, it becomes increasingly apparent that under most circumstances, this geoengineering approach to counter global climate warming is undesirable. Hegerl and Solomon (2009) argue that one problem with our current approach to assessing risks associated with the proposed geoengineering schemes is the single focus on temperature to the exclusion of other (potentially more critical) factors, such as precipitation. Hegerl and Solomon also note that current models do a good job of predicting temperature changes based on changes in radiative forcings because temperature response is "quite straightforward"; however, the evaporation of water in the hydrologic cycle is more dependent on net absorption of solar radiation than on the surface temperature of the earth (Figure 2). Additionally, Blackstock et al. (2009) point to drought in the Sahel region of Africa, from the 1950s to the 1980s, as a lesson in the potential risk of mixing increased greenhouse warming with aerosol-induced solar input reduction. Decreased tropical sea surface temperatures have been implicated as the primary cause, and there is general agreement that increased greenhouse effect alone cannot explain the conditions, but when paired with aerosol inputs into the troposphere by industry, the effect is adequately explained. Thus, "[shortwave climate engineering] intervention (such as stratospheric aerosol loading) could amplify climate change impacts already being generated by increasing CO_2 concentrations" (Blackstock et al., 2009).

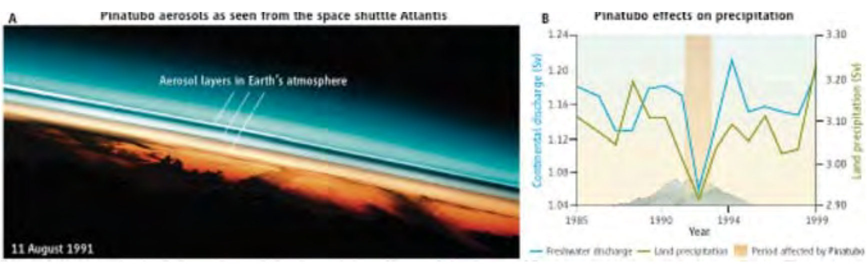

Figure 2: Atmospheric (left) and precipitation (right) effects of the June, 1991 eruption of Mt. Pinatubo. From Hegerl and Solomon (2009).

Two other shortwave climate engineering schemes mentioned previously are: enhancement of maritime clouds and the use of spacecraft to shade the earth. Each of these plans has advantages and disadvantages when compared to sulfate injection. Maritime cloud enhancement (Latham, 2008) would involve generating fine aerosols of seawater in the ocean to increase cloud cover and therefore reflection albedo. The most significant advantages of this scheme are that only seawater aerosols, a natural component of the troposphere, are involved and that it is highly adaptive to real-time needs. Floating vessels would be used to produce the aerosol particles, and thus, actual cooling effects could be adapted so that they have the smallest possible impact on people by simply changing the positions of the vessels. In comparison, stratospheric sulfate injection would affect the entire globe, with very limited ability to control its effects once the sulfate is introduced to the atmosphere. A disadvantage of Latham's proposal (2008) is that no natural experiments have been found to predict the effectiveness or feasibility of the method; the proposal is based exclusively on modeling and experience with weather systems.

The use of spacecraft to effect cooling of the earth is a proposition that is somewhat futuristic in that many technologies would need to be developed in order to make it possible. Development of the required space technologies would make it very costly financially; it would take many years to deploy the technologies; constant maintenance would be needed in order to sustain the effectiveness over the long term. On the positive side, gaining the technical knowledge as outlined by Angel (2006) would certainly enhance our capabilities for space travel. The biggest problem, in addition to not knowing if the technical abilities required could possibly be developed in the required timeframe, is that the same resources could used to develop technologies to solve CO_2-related issues such as reducing our dependence on fossil fuels, or improving energy efficiency. The latter are the real issues at hand in the broad climate debate.

COMMENTARY

Because of the possibility of a climate emergency in our future, research on pertinent factors surrounding geoengineering in response to climate change should begin immediately, with the understanding that it will likely never be desirable to implement such a response; however, the technology and an understanding of its risks should be in place to provide an option, should that be deemed necessary.

At this point, the risks of climate engineering with the proposed methods clearly outweigh the benefits that we might receive. Wigley's (2006) combined climate-engineering/CO_2-reduction approach most likely would affect the temperature of the earth as expected, but climate is much more than temperature, and other parts of our climate system would almost certainly be affected. There remain questions on what and how other components of the system will be affected. It would hardly be of benefit to society if we cool the earth through geoengineering, only to find ourselves with widespread drought in critically important regions of the earth. Furthermore, sulfate injection would be continuous, for the aerosols are removed from the atmosphere in a year or so. We would need to replenish the stratosphere with sulfur every one or two years in order to maintain efficacy of cooling. How long do we want to commit ourselves to such an action that alters the atmospheric environment?

Another primary assumption with any of the proposed schemes is that, should severe consequences arise from climate engineering, we should be able to stop using the method and things will return to baseline within a few years. What if this is not true? For instance, after oceanic currents are altered by reduced solar radiation inputs, would they return to their normal patterns? All of this is to say that it is not in our best interest, as a global community, to apply any of the proposed techniques unless it is deemed necessary as a last resort to prevent certain catastrophe.

The expected impact of both global warming and climate engineering will vary by region. Some areas are expected to get warmer and dryer; others will likely get wetter and cooler. This means that shortwave climate engineering will likely produce “winners and losers” and could lead to serious international conflicts over water resources (Hegerl and Solomon, 2009). There are also serious concerns regarding deliberate alteration of the earth’s climate. Firstly, who will decide what geoengineering scheme will be used, when we should use it and how much cooling is necessary? What about the potential of using shortwave climate engineering as a political tool or as a weapon? What if severely negative impacts are felt by a certain region while other regions are less affected? How do we decide whose existence is more important? What about ecological impacts? Ocean acidification is already occurring and changes in precipitation patterns would almost certainly impact sensitive ecosystems.

It is apparent that the application of short wave climate engineering should not be undertaken lightly. There is a need for more research on both our natural climate system and on shortwave climate engineering (Blackstock et al., 2009; Crutzen, 2006). Cicerone (2006) argues that “refereed papers are to be encouraged in this field; they will permit poor or dangerous ideas to be seen as such and meritorious ones to develop further”. Both Cicerone and Blackstock et al. demonstrate that research should be broken into distinct phases, and that a moratorium should be placed on experiments that will affect the actual climate until more data is gathered and agreement is in place on risks involved and the acceptance of those risks. Our current understanding of the earth’s systems would be greatly expanded by such a research effort.

CONCLUSION

It should be apparent that shortwave climate engineering as a stand-alone solution to the problem of greenhouse warming is not an option. The methods that have been proposed and examined so far do not account for non-temperature effects of rising atmospheric CO_2 concentration such as ocean acidification. As a society, we need to reduce our emission of CO_2 into the atmosphere. Given the current resistance to reduction efforts in international governing bodies, the prospects of quickly reducing CO_2 emissions appear less than encouraging. Therefore, we can expect CO_2 levels to increase into the future, with predictable warming and maybe unexpected effects on the earth’s climate. Given the possibility of catastrophic climate disruptions, it is prudent to examine shortwave climate engineering options as a means to combat such events and to allow for the development of a permanent and sustainable solution. Therefore, we must invest in climate and earth systems research, with a focus on development of models to accurately predict the effects associated with proposed shortwave climate engineering schemes. Currently, the risks associated with deployment of such a scheme are very high. Much more information is needed before prudent use of such measures becomes likely.

In closing, shortwave climate engineering should not be deployed except in the case of utmost emergency; even then, it should not be considered unless we have adequate knowledge of the unintended effects (both short- and long-term). Beyond the technical obstacles, important human factors must be considered; moral and ethical issues surrounding climate engineering must be evaluated in a thorough manner. Thus, we must expand research of the proposed climate engineering schemes, of alternative energy and of the climate system in general. The payback will be likely be substantial. The only acceptable solution to climate change in the long term lies in reducing our emission of greenhouse gases. Myriad advantages will come along with reduced dependence on fossil fuels to power our lifestyle; these may include cleaner air and water due to reduced pollution by emissions and mining operations. Crutzen (2006) closes his geoengineering proposal by stating “Finally, I repeat: the very best would be if emissions of the greenhouse gases could be reduced so much that the stratospheric sulfur release experiment would not need to take place. Currently, this looks like a pious wish”.

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