POLICY RESEARCH WORKING PAPER 4938

BACKGROUND PAPER TO THE 2010 WORLD DEVELOPMENT REPORT

# Beyond Mitigation

## Potential Options for Counter-Balancing the Climatic and Environmental Consequences of the Rising Concentrations of Greenhouse Gases

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## Abstract

Global climate change is occurring at an accelerating pace, and the global greenhouse gas (GHG) emissions that are forcing climate change continue to increase. Given the present pace of international actions, it seems unlikely that atmospheric composition can be stabilized at a level that will avoid "dangerous anthropogenic interference" with the climate system, as called for in the UN Framework Convention on Climate Change. Complicating the situation, as GHG emissions are reduced, reductions in the offsetting cooling influence of sulfate aerosols will create an additional warming influence, making an early transition to climate stabilization difficult. With significant reductions in emissions *(mitigation)* likely to take decades, and with the impacts of projected climate change—even with proactive *adaptation*—likely to be quite severe over the coming decades, additional actions to offset global warming and other impacts have been proposed as important complementary measures. Although a number of possible *geoengineering* approaches have been proposed, each has costs and side effects that must be balanced against the expected benefits of reduced climate impacts. However, substantial new research is needed before comparison of the relative benefits and risks of intervening is possible. A first step in determining whether geoengineering is likely to be a useful option is the initiation of research on four interventions to limit the increasing serious impacts: limiting ocean acidification by increasing the removal of carbon dioxide from the atmosphere and upper ocean; limiting the increasing intensity of tropical cyclones; limiting the warming of the Arctic and associated sea level rise; and sustaining or enhancing the existing sulfate cooling influence. In addition, in depth consideration is needed regarding the governance structure for an international geoengineering decision-making framework in the event that geoengineering becomes essential.

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# Beyond Mitigation: Potential Options for Counter-Balancing the Climatic and Environmental Consequences of the Rising Concentrations of Greenhouse Gases

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## Prepared as a Background Paper for the World Bank's World Development Report 2010

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## 1.0 Introduction

Although present in only trace amounts, the atmospheric concentrations of carbon dioxide ($CO_2$) and other greenhouse gases play an important role in determining the global climate. That this can happen is a result of the ability of these gases, acting in concert with water vapor, to absorb a large fraction of the infrared (heat) radiation emitted from the surface and lower atmosphere. The absorbed heat warms the layer where it is absorbed and increases both the upward and downward radiation of heat from that layer of the atmosphere. The downward directed heat is absorbed primarily at the surface, causing it to warm, which leads to greater emission from the surface, greater atmospheric absorption of the upward radiated heat and, after absorption, greater radiation of heat radiation back to the surface. Prior to the Industrial Revolution, the effect of this heat trapping feedback was to raise the global average surface temperature to ~33ºC above its preindustrial value. Popularly referred to as the *natural greenhouse effect*, it determined the preindustrial climate and sea level, which together exerted their influence on the development of preindustrial civilization, including the locations of major cities, agricultural regions, and water resource systems.

Over the past two centuries, human activities have been causing substantial increases in the concentrations of several key greenhouse gases (Forster and Ramaswamy, 2007). The atmospheric concentration of $CO_2$ is currently nearly 40% above its preindustrial level. The initial increase resulted primarily from deforestation and soil degradation, but the increase is now resulting overwhelmingly from reliance on coal, petroleum, and natural gas (collectively referred to as *fossil fuels*) to supply most of the world's energy (IPCC, 2007c). For methane ($CH_4$), human activities have raised its concentration to over 150% above its preindustrial level, although there is increasing evidence that warming in polar regions is now also causing an increase in $CH_4$ emissions. The concentrations of other greenhouse gases are also rising, primarily as a result of industrial activities, agriculture, and use of fossil fuels.

With very high confidence, scientific analyses make clear that the human-induced changes in atmospheric composition are the primary cause of the global warming of about 0.8ºC that occurred from the mid 19th century to the present (Hegerl and Zwiers, 2007). Were it not for the time lag caused by the large heat capacity of the oceans and the cooling influence of the increased loading of sulfate aerosols that results primarily from coal combustion, the global average temperature would likely be a further 1ºC warmer. Thus, the present, elevated greenhouse gas concentrations are near to committing the world to the 2ºC warming over preindustrial conditions that the Commission on European Communities (CEC, 2007) has concluded, based on its review of leading scientific studies (e.g., see Schellnhuber et al., 2006), is the level beyond which the world can expect to experience very disruptive, even "dangerous" consequences.

Although the association of fossil-fuel related emissions with global warming is now very clearly indicated, there are three reasons that taking action to stop the intensifying warming is particularly difficult:

1. *Fossil fuels provide over 80% of the world's energy*: To ensure that adequate energy is available on demand, day and night, the world has invested many tens of trillions of

2. *Time delays in the climate system lead to slow responses to changes in emissions*: While emission of greenhouse gases leads immediately to changes in atmospheric composition, and these changes lead to immediate changes in the global energy balance, the large heat capacity of the oceans and the slow responses of ice sheets and vegetation delay most of the warming response for at least several decades; a similar inertia arises as emissions are reduced. As a result, even if the emissions of all greenhouse gases could be completely halted tomorrow, about 0.5ºC of further warming would be expected over the next several decades as the oceans, vegetation, and glaciers and ice sheets catch up with the ongoing warming influences of past emissions (Wigley, 2005; Meehl and Stocker, 2007; Ramanathan and Feng, 2008). For sea level rise, the delay time is much longer, with many centuries required for glaciers and ice sheets to melt and for the deep ocean to warm, and therefore cause sea level to rise in response to the expansion of ocean waters.

3. *The long persistence time of elevated concentrations of greenhouse gases:* Although water vapor is the most important greenhouse gas, the increase in its atmospheric concentration caused directly by human activities is very small because the atmosphere adjusts over hours to days to return the excess loading of water vapor to levels in balance with the global temperature distribution. It is this dependence of the water vapor concentration on surface temperature, however, that amplifies the initial warming influence of the increasing concentrations of greenhouse gases by a factor of roughly 2 to 4 (Meehl and Stocker, 2007), creating a very strong water vapor feedback. In contrast to the short atmospheric lifetime of water vapor, the persistence times of the excess concentrations of $CO_2$, nitrous oxide ($N_2O$), and the halocarbons (CFCs, etc.) are hundreds to many thousands of years or longer (Archer, 2005; Montenegro et al., 2007). As a result, the excess warming influence due to the elevated concentrations of these gases, amplified by water vapor feedback, persists for a very long time, and so will the temperature increase that is induced (Bala et al., 2005).

   Importantly, this is not the case for aerosols and for a couple of other greenhouse gases. For example, the persistence time of the $CH_4$ excess is only a few decades, and the persistence times of the air pollutants that increase tropospheric ozone and of the sulfate and carbonaceous (sooty) aerosol particles are only days to weeks (Forster and Ramaswamy, 2007). While these short lifetimes do help to reduce the duration of their warming influence, this decrease is more than offset by the reduced cooling influence that results as the loading of sulfate aerosols declines. As a result, while a sharp decrease in the $CO_2$ emissions from combustion of coal would reduce the long-term warming influence, over the next several decades the associated reduction in the $SO_2$ emissions that are also caused mainly by coal combustion would lead to an additional warming of about 0.5ºC (Ramanathan and Feng, 2008).

## 2.0 The Reasons for Considering Geoengineering

With the pace of global warming and sea level rise increasing, with the prospects for substantial further warming even in the face of the sharp (and possibly expensive) emissions cutbacks (IPCC, 2007a), and with the very adverse projected consequences of global warming and sea level rise for ecosystems, water resources, coastlines and coastal cities and infrastructure (IPCC, 2007b), increasing attention is being paid to whether there might be any options that could assist in limiting climate change over coming decades (Crutzen, 2006[2]; Wigley, 2006; Barker and Bashmakov, 2007; Kintisch, 2007). Essentially, the question is whether, if global warming and associated changes and impacts are the inadvertent consequence of generating most of the world’s energy from fossil fuels, *are there not some well-designed, intentional interventions that could be taken that would create a global cooling influence to counter-balance, at least in part, the warming and its associated impacts*?

Actions, or interventions, taken for the primary purpose of limiting the causes[3] of global warming, the climatic changes that result, and/or the associated impacts have come to be collectively referred to as “geoengineering.” An example of such an action would involve society taking steps to exert a counteracting cooling influence directed toward limiting human-induced changes to the Earth’s climate, chemical, and environmental system. With the world having existed until recently with natural forces being dominant, and many believing that there was no way that human activities could possibly affect the global environment, resorting to geoengineering would represent a complete reversal in thinking, with humans seeking to intentionally take charge of what the future global, and perhaps regional, climate would be.

Not surprisingly, a large number of very complex and important physical, chemical, biological, and socioeconomic questions arise: Is geoengineering really possible? Can all or most adverse impacts from combustion of fossil fuels really be cancelled out? What confidence does the scientific community have in its understanding of all of this? How much would doing this cost up front and over time? Who would pay for geoengineering and actually do it? Are there any side effects of doing this? What if geoengineering is started and it does not work as we expect—what is irreversible and what is not? Are there winners and losers from undertaking geoengineering? Who would get to decide what is done? What are the optimal conditions for the Earth—and, if they exist, would they simultaneously be optimal for all peoples, for society, for

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[2] Commentaries on this article were offered by Bengtsson (2006), Cicerone (2006), Kiehl (2006), Lawrence (2006), and MacCracken (2006).

[3] Actions taken to reduce emissions at their source are generally considered mitigation rather than geoengineering.

plants and wildlife? Once geoengineering started, how long would it have to continue? How soon would decisions about geoengineering have to be made? Is it appropriate to take additional actions to modify the climate, even if the intent is to moderate what are negative impacts for at least some nations? Beyond the scientific, engineering, and economic aspects, what are the moral and ethical aspects of geoengineering, for us today and for future generations?

All of these questions (and more) are appropriate and each raises very challenging issues and trade-offs. Unfortunately, because very little research has been done, what we understand is relatively limited. Early studies suggest that there may be some approaches that might work, meaning that they might be less expensive than some approaches to mitigation (e.g., see Barrett, 2008) and that implementation would be needed in the near future to avoid ‘dangerous anthropogenic interference’ with the climate system. That very little climatic and environmental research focused on geoengineering is going on, however, means that there are important uncertainties and that accelerated research is needed in the near-term if geoengineering is going to be able to be considered in the intensifying negotiations to establish an international path forward.

This paper provides an overview of current understanding about the range of different approaches to geoengineering. From the wide range of suggested approaches, four potentially viable approaches to limiting near term impacts are identified that, in this author’s opinion, merit immediate study and consideration. Pursuing these early studies would also help to build the base of knowledge necessary for a more intensive evaluation of the viability and ramifications of global-scale interventions aimed at limiting global warming and its impacts around the world. Only with significant advances in understanding is it likely that geoengineering would become a complementary action to both mitigation and adaptation, allowing for a rebalancing among policies calling for affordable mitigation, effective proactive adaptation, and unavoidable suffering [Scientific Expert Group (SEG), 2007].

## 3.0 An Overview of Possible Geoengineering Approaches

There are three fundamental approaches to invoking geoengineering to limit the climatic, environmental, and societal consequences and impacts of human-induced changes in atmospheric composition, the climate, and the consequences of climate change [National Academy of Sciences (NAS), 1992; Leemans et al., 1995]. The approaches include (1) actions aimed at reducing the concentrations of greenhouse gases in the atmosphere; (2) actions taken to reduce the amount of absorbed solar radiation that warms the Earth; and (3) actions directed toward moderating the adverse impacts of human-induced climate change. While later sections provide more detail, the following paragraphs describe the conceptual basis for each of the three general approaches.

### 3.1 Reducing the Changes in Composition

The most effective approach to limiting changes in atmospheric composition is to reduce emissions of greenhouse gases and their precursors. This can be accomplished by both reducing demand for energy through gains in efficiency and conservation, and by switching to sources of energy that do not generate greenhouse gases (IPCC, 2007c). Actions of this type that are taken at the source of the emissions in order to limit the environmental damages that would result from generating energy are generally classified as *mitigation*. Thus, mitigation includes: deriving energy from alternative technologies such as renewables (e.g., biomass, solar, wind, geothermal, hydroelectric, etc.) or nuclear; capturing and storing or sequestering the greenhouse gases that are emitted; reducing the amount of GHGs released by increasing the efficiency of energy production and use; decreasing emissions from industrial activities; using the emitted gases to promote the use of biofuels; offsetting the emissions by enhancing efficiency or otherwise taking up greenhouse gases somewhere else (e.g., offsets in other nations); and similar such approaches (SEG, 2007).

In addition, because changing land use contributes about 15-20% to greenhouse gas emissions, efforts to limit deforestation and soil degradation and to encourage reforestation and soil improvement are also generally included within the mitigation category, although there can be reasons for taking these actions beyond seeking to limit climate change (Kauppi and Sedjo, 2001). Mitigation, encompassing both emissions limitation and offsetting, is already the focus of state, national and international policy actions, especially under the UN Framework Convention on Climate Change and the associated Kyoto Protocol.

Although the distinction is not always clear cut, there are additional types of activities beyond mitigation that can be undertaken with the primary purpose of slowing the atmospheric buildup of greenhouse cases. Examples of the type of geoengineering directed toward limiting changes in atmospheric composition will be referred to here as *composition management*. Examples of these activities include: afforestation (i.e., growing forests in regions where they have not been before and where specific actions are needed to promote tree growth); converting biomass to charcoal and mixing it into soils (which both stores carbon and increases the soil moisture holding capacity of the soils); acceleration of carbon uptake by the oceans (e.g., by fertilization of the oceans with micro- or macro-nutrients to promote biological transfer of carbon to the deep ocean); vertical stirring of the ocean to try to encourage downward carbon transport (e.g., bringing nutrients to the surface in order to enhance biological activity and carbon transport to the deep ocean); and direct removal of greenhouse gases from the atmosphere (e.g., scrubbing the atmosphere with a $CO_2$ absorbing solution and sequestering the captured carbon below the land surface or in the deep ocean; chemically dissociating atmospheric halocarbons by use of lasers to split the molecules; etc.).

Distinctions between mitigation and geoengineering are not always sharp, however, for there are also proposals that would combine an increase in the rate of carbon sequestration in the ocean or below ground with generation of energy or carbonaceous fuels (e.g., $CH_4$). For the purposes of the discussion here, actions will be included under composition management if their primary purpose is to limit the rising concentrations of greenhouse gases in order to limit climate change or ocean acidification rather than as compensation for generating emissions. For example, building a device to extract $CO_2$ out of the atmosphere would be an example of geoengineering for composition management because, given the dilute nature of the $CO_2$ in the atmosphere, doing this to support industrial processes or to accumulate $CO_2$ for use in increasing the efficiency of oil field production would not be likely to be economical compared with installing scrubbers on power plants.

### 3.2 Counter-balancing the Warming Influence

Recognizing that the increases in greenhouse gas concentrations induce their warming influence by increasing the trapping of heat, *solar radiation management* is designed to offset the warming influence by reducing the amount of solar energy absorbed by the Earth system. This category of geoengineering has received significant conceptual attention, and some authors even limit discussion of geoengineering to only this category of approach. The possible options for reducing the incidence and/or absorption of solar radiation have been reviewed, for example, by MacCracken (1991), NAS (1992), Leemans et al. (1995), Flannery et al. (1997), Keith (2000), Schneider (2001), and, most recently, Lane et al. (2007) and Schneider (2008).

Starting furthest from the surface of the Earth, the possibilities include locating and actively maintaining a solar deflector (or multiple small deflectors) in an orbit synchronous with the orbit of the Earth around the Sun, placing mirrors in near-Earth orbit, injecting aerosols into the stratosphere to reflect solar radiation from reaching the lower atmosphere and the Earth's surface (reviewed by Rasch et al., 2008b), brightening clouds in the troposphere or otherwise increasing tropospheric albedo so that less solar radiation is absorbed by the surface-troposphere system, and increasing the reflectivity of the land and/or ocean surface (e.g., painting roofs white).

### 3.3 Moderating the Response of the Climate System

Less consideration has been given to a third category of geoengineering activities, namely to moderate or counter the influences of a changing climate on the environment and society. [4] While sometimes shading toward *adaptation*, which is taken to include making society and the environment more robust to the changes in climate that are occurring (e.g., by building coastal levees), there are proposals for new types of impact management that could limit the adverse response of an environmental consequence of global warming without trying to counterbalance climate change as a whole. Examples of this type of geoengineering, which will be referred to as *impact intervention*, include proposals for: reducing the intensity of tropical cyclones; limiting the melting of snow, ice, and glaciers; limiting the rise in sea level; promoting the formation of sea ice; altering or redirecting ocean currents (e.g., by marine dams); and even reducing evaporation of water vapor from the ocean (e.g., by putting a film on the ocean).

The next section presents a number of criteria that merit consideration in evaluating the possible geoengineering approaches, including consideration of their effectiveness, consequences, and implementation. The following section provides more detail about the most developed approaches in each of the three categories, indicating the types of questions that require attention by the research community if geoengineering is to become an option along with mitigation and adaptation. Those sections are followed by a section describing the types of research that are most needed, and a section that suggests four specific geoengineering approaches that merit intense attention and early consideration.

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[4] Chapter 25 in the Working Group II contribution to IPCC's Second Assessment Report (Leemans et al., 1995) separated this category of action into two parts: altering climate feedback mechanisms, and countering harmful effects. As these two approaches are closely related, they are treated together here.

## 4.0 Considerations for Evaluating Geoengineering Possibilities

With such a wide range of possible geoengineering approaches, it is essential to develop a framework for considering those that might be most important to consider as a complement to adaptation and mitigation. A number of efforts are being made to develop possible ranking systems that could be used (e.g., see Boyd, 2008). At present, however, the possibilities are so diverse that it seems the first challenge must be to select the factors to use in comparative evaluation of the various approaches. Considerations that are likely to be of most importance are described in the following subsections.

***Design and intended effect:*** A wide range of approaches has been suggested, each seeking in different ways to offset or reverse different aspects of the changes in climate, ocean chemistry, and sea level. None of the approaches alone is capable of reversing all of the effects of increasing greenhouse gas concentrations. Most of the approaches suggested to date are focused on reducing the global increase in surface temperature, but other impacts that merit attention include limiting ocean acidification, reducing the melting of snow and ice, and moderating the rate of rise of sea level. Some approaches focus on addressing the global aspects of the problem, whereas others tend to focus on a particular region. Some of the approaches seek to counterbalance all of the human-induced changes, while others focus on, or could be used to focus on, only part of the problem, allowing some of the change to persist. Some of the approaches have been tested or have a natural analog, whereas others are new and untested, so there are varying degrees of confidence in describing how they would work. In describing each possibility, it is essential to be clear on their design and intended effect.

***Benefits and impacts:*** Each of the proposed approaches will have certain benefits, but each typically will also have adverse consequences (i.e., unintended side effects). Were human activities not already altering the climate, and indeed, threatening to cause very significant harm, the notion of taking an action to alter the global climate would, at the very least, require very significant and detailed justification to ensure that the result would be strongly positive for virtually everyone on Earth. It seems more likely, however, that taking such an action to somehow try to optimize the climate would likely be seen as trying to assume a providential responsibility. Indeed, the *UN Convention on the Prohibition of Military or Other Hostile Use of Environmental Modification Techniques*[5] was negotiated and acceded to in the 1970s in the interest of ensuring that the environment would evolve naturally and not be altered to enhance a particular objective of one or more nations at the expense of others. With respect to global warming, however, the climate and environment are already being significantly altered, and the intent of geoengineering proposals is to moderate the change, seeking, to the extent possible, to undo the human influence and return control to natural influences. Therefore, in considering the benefits and impacts, the more appropriate question is likely whether the changes experienced with geoengineering would be more or less harmful (or beneficial) than allowing global warming to proceed as projected.

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[5] The text of the treaty can be downloaded from
http://www1.umn.edu/humanrts/peace/docs/conenvironmodification.html

***Economic Cost and Phasing:*** Each of the approaches will require some investment. In that very little research has been done, information on costs is generally quite uncertain. There has been a sense, however, that the costs might well be less than the costs of switching to alternative energy technologies to reduce greenhouse gas emissions (NAS, 1992; Barrett, 2008)--how long this will be the case as the costs of renewables drop is not clear. As a general rule, however, early studies indicate that geoengineering approaches having the least significant adverse side effects would require the most investment, and vice-versa.

***Coupling to other problems and issues:*** Each of the proposed geoengineering approaches is coupled to other issues, some technological, some economic, and some cultural. A number of the approaches would basically trade one kind of pollution for another. For example, as long as coal is being used for some degree of energy generation, continuing to emit $SO_2$ into the troposphere (or choosing to augment such emissions) to increase the tropospheric aerosol loading would be relatively inexpensive and straightforward, although it would likely sustain or increase acid deposition. For both tropospheric and stratospheric injection of sulfate aerosols, increasing planetary reflectivity would also have the effect of sharply reducing the ratio of direct to diffuse solar radiation, likely leading to consequences for ecosystems and perhaps for wildlife as well as diminishing the capacity of solar technologies depending on the direct solar beam (e.g., mirror-based technologies).

***Duration and impact on future generations:*** Like the enhanced greenhouse effect that it would be addressing, geoengineering would need to extend over a prolonged period, leading to effects and obligations that would be imposed on future generations, generally without their consent. There are differences, however, among the approaches in the degree of action required over time, with some approaches requiring continued effort over time and some only needing to be implemented over a finite period. It is an open question whether different standards should apply to imposing actions over decades as opposed to imposing obligations and costs that would persist for centuries or even indefinitely. This issue is complicated by its relation to how it affects society’s efforts to reduce emissions. In particular, to the extent that the reduced impacts that are brought about by geoengineering ease the pressure and success of efforts to reduce emissions, geoengineering may rightly be seen as passing not just one problem (i.e., the obligation to continue geoengineering) to future generations, but two (i.e., an amplified extent of climate change and an even stronger obligation to continue geoengineering). This is akin to basically borrowing money to double down on a bet. With much more at risk, any failure in the system would lead to the risk being even worse than when geoengineering was begun.

***Uncertainties:*** Although suggestions that geoengineering should actively be considered as a policy option are increasing (e.g., Wigley, 2006; Ragaini, 2008), there has been very limited research on the major aspects, much less the subtleties, of most of these approaches. For those approaches on which investigations have started, the tools used have tended to be the very climate models that some of those advocating geoengineering have said introduce uncertainties in projections of the impacts of the greenhouse gases themselves. In addition, most of the studies evaluating geoengineering options have been done for very idealized cases (e.g., smoothly spread aerosols in the stratosphere) with no examination of what the consequences of treating the approaches realistically might mean to, for example, weather patterns and extremes, the natural variability and oscillations of the atmosphere-ocean system, or ecosystems and other species. For many of the approaches, there are tools to carry out better evaluations, but, lacking an adequately funded research effort, only rarely have the most advanced models been used.

***Reversibility:*** Because there are uncertainties, the natural reaction is to urge more research and to not actually do anything until there is full clarity about what should be expected from geoengineering. While this would be desirable, the world is rapidly changing, so there is some urgency to taking action. Indeed, discounting the offsetting (cooling) effects of sulfate aerosols, the loading of which would quickly be diminished if $CO_2$ emissions were cut sharply, the present anthropogenic contribution to greenhouse gas forcing is, using the 100-year Global Warming Potential (GWP) that is most appropriate for consideration of long-term climate change, roughly equivalent to a $CO_2$ concentration of 450-460 ppmv (parts per million by volume). This is the level that scientific studies (e.g., Meinshausen, 2006) suggest would have roughly a 50% likelihood of leading to warming greater than about 2ºC over preindustrial conditions, which is the amount of warming that the CEC has concluded would lead to the "dangerous anthropogenic interference with the climate system" that the nations of the world pledged to avoid in agreeing to the UN Framework Convention on Climate Change. To avoid such significant warming, it would, therefore, make sense to initiate limited geoengineering as soon as possible, even though there are uncertainties. In the face of both necessity and urgency, a prerequisite would seem to be that the approach would be at least largely reversible; that is, in case negative side effects were to arise or there were problems or higher than affordable costs of implementation, it would be desirable if stopping its implementation did not lead to significant or permanent adverse consequences.

***Research and development needs and prospects:*** Recognizing the potential need for early invocation of geoengineering, especially if the sensitivity of the climate to greenhouse gases is near the high end of current estimates, it is important to have a sense of the research and development needed to gain the understanding that would make geoengineering a viable option. Thus, what needs to be done, at what cost, and how long might it take? The types of questions that arise include: What sorts of efforts would be needed and what can be carried out on a computer and what would best be carried out by actually undertaking the effort at a small and inconsequential scale? What new technologies would be needed to implement the approach cost effectively, and what are the prospects for such developments? To date, the elements of a comprehensive, international research plan have not been assembled.

***Governance and international responsibility:*** Even if one or more of the suggested approaches is found to be workable and likely to be beneficial, there is the overarching question of how might geoengineering be undertaken. How would the decision be made, or even considered? What body, if any, has the authority to take on overall management of the Earth's climate? What set of information would they need and how would this be developed? How would a decision be made? What level of confidence in the results would be required? How would nations that might be adversely impacted be compensated, and how would this be judged—relative to the impacts of geoengineering alone, or in combination with the greenhouse-induced changes?

Based on the enumeration of the possible approaches and issues contained in the following sections, the final section of the report attempts an integration and synthesis, including identification of those approaches that, with modest research and development, might, separately or in combination with other approaches, be considered for further research and then implementation over the coming decade. In addition, the approaches are identified that, with lengthier research and development, might be considered for longer-term implementation because they appear to have less significant side effects, are easier to implement, or are able to treat aspects of climate change that would not otherwise be addressed. If geoengineering is indeed to be further considered as a policy alternative, much work needs to be done to clarify the possibilities and practicalities (technological, economic, and political) of suggested approaches—and to further encourage the development of new ideas, which, although arising with astonishing frequency, seem to often suffer from serious shortcomings.

## 5.0 Consideration of the Most Mentioned Geoengineering Approaches

Proposals to geoengineer the global climate go back to at least the 1960s, and only slightly less ambitious ideas go back even further (Fleming, 2004). Over this period, reviews and preliminary examinations have thinned the ranks, eliminating approaches that seem least viable. A number of approaches, however, have withstood the early examinations, and some are starting to receive more detailed examination and even initial experimental testing. In the subsections below, a number of the most mentioned approaches are described and analyzed.

### 5.1 Lowering the Atmospheric Concentrations of Greenhouse Gases

The present atmospheric loading of carbon is roughly 770 PgC (1 PgC equals 1 petagram of carbon, or a billion metric tons of carbon). Human-caused emissions of carbon in 2007 totaled ~10 PgC, of which ~8.5 PgC (equivalent to roughly 31,000 MMTCO$_2$e in the units used in the energy policy community) were from combustion of fossil fuel and the rest were from changes in land cover (Canadell et al., 2007). Interestingly, assuming that the amplitude of the seasonal cycle in the CO$_2$ concentration at Mauna Loa is representative for the Northern Hemisphere, the net hemispheric cycle of net biospheric uptake (i.e., growth minus decay from spring until fall) and release (decay minus growth from fall to spring) totals about 8 PgC, so annual fossil fuel emissions are now exceeding the seasonal greening of the Northern Hemisphere biosphere.

The annual increment in the atmospheric concentration is now over 2 ppmv per year, equivalent to an increase in the atmospheric burden of over 4 PgC/yr, indicating that about half of the annual fossil fuel emissions are persisting in the atmosphere for an extended period, with the rest being taken up by the terrestrial biosphere and the ocean. Proposals to limit the annual increase in the CO$_2$ concentration by geoengineering seek to increase terrestrial and/or marine uptake or to scrub CO$_2$ from the atmosphere (e.g., Martin and Kubic, 2007; Keith, 2008a) and to sequester it underground or in the depths of the ocean or in ocean sediments (e.g., IPCC, 2005; Caldeira et al., 2005; Goldberg et al., 2008), or even to increase uptake by accelerating chemical reaction of CO$_2$ with unweathered rock (Kelemen and Matter, 2008).

The terrestrial biosphere includes about 500 PgC in above ground biomass and about three times that amount in the soils (Prentice, 2001). The annual net primary productivity is about 10% of the aboveground biomass (giving an average lifetime for living biomass of just under 10 years). About 20% of the soil carbon (the detritus component) has a lifetime of less than 10 years but ~10% has a lifetime of over 1000 years. If fossil fuel emissions continue at their present rate through the century, storing all of the carbon emitted during the 21st century in the terrestrial reservoir would require storing an amount of carbon roughly equal to all of the carbon now present in the world's aboveground biomass and short-lived detritus, or roughly doubling the 30% of the Earth's land area covered by forests (Fischlin and Midgley, 2007). As a result, early ideas about planting more trees along highways or other limited corridors would not accomplish much. Indeed, given the demand for land for food and fiber products and for communities, fully offsetting $CO_2$ emissions by expanding terrestrial carbon uptake is just not possible. While every effort should be made to increase land storage of carbon (IPCC, 2000a; Lovejoy et al., 2008), it is likely to be a challenge just to keep the net amount of terrestrial carbon constant.

Given the difficulty of accumulating and storing sufficient carbon in the terrestrial biosphere, consideration is being given to limiting emissions by capturing the $CO_2$ at power plants and then transporting it to the deep ocean by pipeline. While this would be categorized as mitigation based on the definitions used in this report, gathering the carbon after it has been emitted into the atmosphere and dispersed, and then sequestering it in the ocean is generally categorized as geoengineering. An early approach proposed for capturing dispersed carbon involved growing trees on land, harvesting them, and then sinking them to the bottom of the ocean (Marchetti, 1975). To counterbalance fossil fuel emissions, this would require harvesting and sinking to the ocean bottom roughly 1% of the existing vegetation per year as well as replanting and likely having to fertilize those areas to encourage regrowth of the trees. Assuming the average time to maturity of a tree is 50 years, this approach would require including about 50% of the world's forested area in a sequential process of harvesting trees, sinking them in the ocean, and then regrowing trees on the cleared land. This level of sequestration seems far more than would be possible, and, in addition, it would be a terrible waste of the solar energy that has been captured in the wood over such an extended time. If indeed the economic costs of climate change impacts justified a harvest/sink/regrow process of this magnitude, it would seem to make far more sense, and likely be far more economical, to be transforming the biomass to biofuels and not mining and combusting the fossil fuels at all. Indeed, pursuing a combined biomass-fossil fuel process that generated energy while also sequestering carbon underground appears to be a quite promising technology (Kreutz et al., 2008).

At the present rate of $CO_2$ emissions, the net uptake of $CO_2$ by the oceans is ~2.3 PgC/yr, split between the extra amount transmitted to the deep ocean by the overturning circulation (actually a reduction in the net upward transport) and by the sinking of biomass (fecal pellets, skeletons, etc.). Warming of the ocean is projected to reduce the overturning component, and warmer ocean waters (like carbonated beverages) hold less $CO_2$, so climate change is likely to affect the natural carbon cycle in a way that makes the situation worse, not better. However, because there are some indications that biological activity could be increased in some regions of the ocean by the addition of apparently missing micro- or macro-nutrients, there is considerable interest in determining if fertilizing the ocean could be used to increase ocean uptake and downward transport of carbon. Basically, powered by solar energy, the notion would be to make an investment of micronutrients to drive additional uptake of carbon by the marine biosphere while perhaps also increasing fish stocks to help feed the world.

A number of small-scale tests of ocean fertilization have been conducted and more have been proposed, some funded by venture capitalists hoping that success might provide carbon credits that could be sold to those needing to offset emissions in the international cap-and-trade system that seems likely to be negotiated. Results to date are not nearly definitive, and the scientific community has raised a number of concerns about the effectiveness and safety of iron fertilization (e.g., see http://www.scor-int.org/SCOR-GESAMP.pdf). Questions meriting investigation include: whether adding micronutrients in one location to utilize apparently unused macronutrients is just displacing growth of marine life that would have occurred further along the water's path; whether the carbon that sinks is really kept away from the atmosphere for centuries or is only dissolved a bit deeper in the ocean and so would be released back to the atmosphere within a few decades; and how all of the accounting is being done, because drawing $CO_2$ into the ocean in one location will just lead, by adjustment of the chemical equilibrium between the atmosphere and upper ocean, to out-gassing elsewhere of at least a fraction of the $CO_2$ that is being taken up? In addition, the long-term problems with this approach are that: (a) the higher the ocean carbon content, the more acidic the ocean waters are, thereby adversely affecting the ability of many marine organisms to form carbonate shells; and (b) the warmer the ocean gets, the less the ocean overturns, and so the less nutrient-rich waters are brought to the surface, diminishing the level of natural ocean biological activity and the pumping of carbon to the deep ocean.

There have also been proposals to basically farm the ocean for biomass. Such proposals are at the interface of mitigation and geoengineering in that they are, basically, biologically harvesting the solar energy that falls on the ocean surface. The American Methanol Institute a number of years ago proposed growing algae out in the equatorial Pacific, and augmenting the available ocean nutrients by using a fraction of the resulting biofuel (in their case, methanol) to bring up deeper, nutrient-rich waters. The rest of the resulting methanol was to be used to displace use of fossil fuels, so this ocean-based approach was intended mainly as a way to mitigate fossil fuel emissions. Although not now so focused on sequestration, the present range of activities in this area is quite broad (e.g., see http://www.algaebiofuelsummit.com/), and might well be combined with efforts to enhance fish production, so helping to increase global food stocks.

While most attention has gone to removal of atmospheric $CO_2$, removing other greenhouse gases, especially those that have a high global warming potential (GWP) as compared to $CO_2$, also merits consideration as a geoengineering approach. One proposal, which arose in thinking about the challenge of meeting the goal of the Montreal Protocol to limit depletion of stratospheric ozone, was to use lasers to dissociate, and thus destroy, chlorofluorocarbons before they can contribute to ozone depletion. Such an approach may merit further consideration as a means of limiting the long-acting warming influence of many of the long-lived halocarbons and perfluorocarbons. To make up for their low concentration, the notion was to bounce a laser signal many times between mirrors on nearby mountaintops such that the pathlength was extended and an energetic photon was more likely to actually strike a halocarbon molecule. Finding a way to destroy methane ($CH_4$) in this manner might be particularly useful, given that its 20-year GWP is ~3 times its 100-year value (Forster and Ramaswamy, 2007), meaning that reducing the concentration of methane to well below its present concentration, whether by mitigation or geoengineering, would have an early and significant limiting effect on the warming influence of greenhouse gases.

With nearly 100 PgC tied up in arctic soils (Ping et al., 2008), much of it likely as $CH_4$, another class of productive geoengineering actions could well involve finding ways to keep the ground frozen and/or, because of its high GWP, converting the $CH_4$ to $CO_2$ before release. With observations indicating that the $CH_4$ concentration is again starting to rise, possibly as a result of increased natural emissions from thawing permafrost and/or from the ocean floor, successful research could have a very large payoff.

### 5.2 Reducing the Incidence and Absorption of Solar Radiation

Geoengineering the climate via solar radiation management refers to efforts to reduce the amount of solar radiation absorbed by the Earth system by the amount required to offset the increased trapping of infrared (IR) radiation by the rising concentrations of greenhouse gases. Considerations of the Earth's energy balance indicate that fully offsetting the equivalent of a $CO_2$ doubling, which is often calculated to lead to an increase in net downward IR at the tropopause of between 3.5 and 4.1 $W/m^2$ (Ramaswamy, 2001), would require reducing the amount of incident solar radiation by ~1.8%.[6] Although the latitudinal and seasonal patterns of the changes in IR and solar radiative forcings are quite different, model simulations indicate that the latitude-season temperature responses to the two forcings are nearly equal and opposite (Manabe and Wetherald, 1980; Hansen et al., 1984; Govindasamy and Caldeira, 2000). The results of these modeling studies seem to confirm the IPCC presumption that the global average temperature response is largely independent of the spatial and seasonal variability of the forcing (i.e., that the climate sensitivity is essentially independent of the type and spatial distribution of the forcing).

While these results appear to ease the challenge of geoengineering, such a conclusion is also somewhat surprising, given that changes in the Earth's orbital elements,[7] which simply redistribute solar energy by latitude and season, but cause virtually no change in global annual forcing, are the driver of ice age cycling. What is apparently happening is that the oceans are providing an important buffering effect to the seasonal variation of solar radiation. Considerably more research is needed, however, to understand the potential long-term consequences of geoengineering, especially because the offsetting effect of geoengineering is not nearly as strong for the seasonal and latitudinal distribution of precipitation as it is for temperature.

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[6] Based on a solar irradiance of about 1368 $W/m^2$, the global average incident flux of solar radiation at the top of the atmosphere is about 342 $W/m^2$ when spread around the Earth. About 30% is reflected away, primarily by clouds but also by the Earth's surface, so 1.8% of the absorbed radiation is ~4.3 $W/m^2$. This is necessarily larger than the often cited figure for the radiative forcing from a $CO_2$ doubling because that figure has been reduced as a result of the rapid thermal adjustment of the stratosphere to the $CO_2$ doubling.

[7] Three aspects of the Earth's orbit around the Sun vary in time, leading to cyclic variations in the seasonal and latitudinal distributions of solar energy. The three elements are: (i) the ellipticity of the Earth's orbit, which varies between near circularity and slight ellipticity with a frequency of ~100,000 years; (ii) the tilt of the Earth's axis, which varies between about 22 and 25 degrees with a period of ~41,000 years; and (iii) precession, which cycles the time of year of closest approach to the Sun through the seasons with a period of ~26,000 years. When the major and minor contributions of these cycles, which are a result of the time-varying pull of the Sun and planets, are combined, the periodicities that emerge, particularly for the amount of solar radiation reaching high latitudes, match well with the periodicities for glacial cycling determined from variations in isotopic ratios and other variables observed in ice cores.

For purposes of comparison of suggested approaches in the following discussion, the actions required to reduce solar radiation by 1% are described. Such an effort would be roughly enough to offset half (in a logarithmic sense) of a doubling of the $CO_2$ concentration. Based on current emissions scenarios, this would be about the level of effort required to offset the radiative forcing for the emissions projected for the 21st century, assuming one of the moderate IPCC SRES scenarios (IPCC, 2000b). The proposed geoengineering approaches are considered starting from highest above the surface of the Earth.

***Geostationary orbit***: Early (1989) proposed placing a solar deflector at the first Sun-Earth Lagrange point (~1.5 million kilometers toward the Sun, referred to as the L1 point), where the gravitational pull of the two bodies would be about equal so that maintaining the deflector in place would require minimal energy. To reduce solar radiation by ~1%, a disk having a diameter of ~1400 km would be required. Viewed from Earth, the deflector would appear to be smaller than the Sun (so would not be visible without special telescopes) and its effect would be to reduce the intensity of the solar beam by about 1%, which is likely too small to have significant ecological or other detrimental consequences. However, Early suggested that pursuing this approach in the most cost-effective manner would require setting up a manufacturing plant on the Moon; as a result, the cost of construction would be in the trillions of dollars. While the rate of onset of the effect could be controlled by angling the deflector and easily stopped if unforeseen, but adverse, environmental consequences arose, the resources would need to be essentially fully committed up front before there could be any diminution of solar radiation. Because these costs would likely be greater than the diminishing difference in costs between fossil fuel and renewable or other energy sources, and, in that the shift away from $CO_2$ emitting energy technologies would be needed in any case to limit ocean acidification, augmenting funding for renewable energy technologies from the start might well be a less expensive and risky path and would not require sustaining the offsetting effort for many generations.

To overcome the large initial costs for building a manufacturing plant on the Moon, Angel (2006) proposed creating a sunshade at the L1 point by lofting a very large number of small deflectors directly from the Earth's surface. When fully deployed, Angel's proposed sunshade (or parasol) would consist of roughly 10 trillion autonomous flyers, each being very thin, having a diameter of 0.5 to 1 meter, and including an onboard control mechanism that would use the solar wind to "sail" the flyer in a way that would maintain orientation and separation. Angel proposed that the flyers be launched from the Earth's surface to the L1 point using an electronic launcher that would be fired 20 million times over coming decades, each launch carrying 800,000 flyers in a stack weighing 1000 kg. While the overall cost would be substantial, the offsetting effect could be incrementally increased to the level needed. Further analysis of this approach is underway, with the most important issue relating to engineering and technological aspects of the proposal.

***Near-Earth orbit***: Solar shielding could also be lofted into near-Earth orbit, although the effects of rocket exhaust on the stratospheric ozone layer might well be problematic. Offsetting roughly 1% of the incoming solar radiation would require about 55,000 orbiting solar mirrors (e.g., spread out Mylar sheets), each roughly 10 km by 10 km in size (NAS, 1992). While this approach could be undertaken incrementally, the control problem would be overwhelming, not to mention that in passing between the Sun and Earth's surface, each of the orbiting mirrors would eclipse the Sun, causing sunlight at the surface to flicker. To avoid the flickering problem, Kahle and Deirmendjian (1973), expanding on an idea appearing in Hoyle (1957), had much earlier proposed creation of an orbiting cloud of particles, although this would be difficult to maintain given the effects of the solar wind, which would tend to push the particles out of orbit. Given the relatively significant problems of tackling global warming from near-Earth orbit, such approaches have received little attention and are not discussed further in this article.

***Stratosphere and above:*** Enhancing the global loading of sulfate aerosol particles in the stratosphere, as proposed several decades ago by Budyko (1974) and more recently by Crutzen (2006), has received considerable attention. An important advantage in evaluating this approach is that the diminution in solar radiation would be roughly equivalent to the influence of an annual to biennial series of major volcanic eruptions similar to what has been experienced in the past, although the geoengineering activity would need to persist indefinitely. One advantage of stratospheric aerosols, as compared to augmenting the sulfate aerosol loading of the troposphere that presently offsets a substantial fraction of the radiative forcing from increased greenhouse gas concentrations, is that the lifetime of stratospheric sulfate particles is typically a few years as opposed to a few days. Another advantage of the sulfate-injection approach is that it can be tried in an incremental manner and, in the event of adverse consequences, be quickly halted.

Although enhancing stratospheric aerosol loading would lead to very colorful sunrises and sunsets, an important disadvantage of sulfate aerosol particles is that they forward scatter roughly five to ten times as much radiation as they reflect, whitening the skies and seriously diminishing the direct solar beam (Izrael, 2008). Such scattering would reduce the effectiveness of the technologies that generate energy using the direct component of the solar beam, such as the solar power tower.[8] In addition, the biosphere would be affected; for example, following the Pinatubo eruption, Gu et al. (2003) found that the greater amount of diffuse radiation was able to better penetrate the vegetation canopy, enhancing primary productivity and carbon uptake.

In addition, because the aerosols reduce the amount of solar radiation reaching the surface, they tend to reduce the amount of energy available to drive the hydrologic cycle. Model simulations by Bala et al. (2008) indicate that, for similar changes in the net change in the energy balance at the tropopause, stratospheric aerosols and greenhouse gases have similar effects on surface temperature, but that the aerosols result in a larger proportional reduction in the hydrologic cycle than would a decrease in the greenhouse gas concentration.

Another important side effect is that the injected sulfate aerosols, like volcanic aerosols, have the potential to exacerbate loss of stratospheric ozone or, at the very least, slow recovery from the depletion caused by injections of chlorofluorocarbons and other halocarbons. With the increasing concentration of $CO_2$ tending to cool the lower stratosphere, having a large permanent loading of

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[8] Following the El Chichón eruption in 1982, engineers from the Sandia National Laboratory in Livermore CA asked atmospheric scientist at the nearby Lawrence Livermore National Laboratory how their observations at the Barstow, California prototype solar power tower installation, which was roughly in the same latitudinal band as the early volcanic cloud, could be showing that total solar radiation dropped ~2% whereas power production had dropped ~25%. They were encouraged to upgrade their instrumentation to measure the reduction in the direct beam radiation, and found that it had, like their power production, dropped about 25%. Once the volcanic aerosol loading decreased, the system worked as designed.

additional aerosols might, in particular, cause significant depletion in polar regions to persist for decades (Tilmes et al., 2008).

Rasch et al. (2008a) summarize the results of the newest model calculations that have been carried out to evaluate the use of sulfate aerosols for solar radiation management. They find that there are many details that will need to be investigated, ranging from considerations of the effects on particle size distribution of injecting the particles using a million 4-hour aircraft flights per year to issues of the seasonal effects of the aerosols and their lifetimes and distribution in the stratosphere. Calculations by Robock et al. (2008) also indicate that, while the temperature change from the rising concentrations of greenhouse gases can largely be offset, this may not be the case for precipitation.

Much more analysis is needed to clarify these issues, however, not only of the physics governing a relatively uniform aerosol distribution (as covered in Rasch et al., 2008a), but also for other particle distributions (e.g., having latitudinal and/or longitudinal gradients) and time (e.g., seasonal differences) and for greater or lesser offsets than the changing radiative forcing from greenhouse gases. In addition, analyses of the impacts of aerosol injections need to look at more than the average responses of temperature and precipitation, looking, in particular, at changes in the higher moments of atmospheric behavior (i.e., the weather and its variability) and how humans and ecosystems might be affected (Kravitz et al., 2008; Robock, 2008a).

In addition to analyses of the offsets and their impacts, research, analysis, and even prototype demonstrations are needed of the various proposed approaches for augmenting the stratospheric loading of sulfate aerosols. Among the approaches proposed have been aircraft, artillery, balloon-held hoses, and upward mixing and then stratospheric oxidation of tropospherically inert carbonyl sulfide (COS), each of which would introduce scientific and technological aspects meriting research and development.

There have been several suggestions for how to overcome the negative impacts on stratospheric ozone and sky color. For example, Crutzen (2006), presumably recalling the “nuclear winter” studies of the 1980s (Pittock et al., 1986), suggested injecting soot instead of sulfates, which not only would reduce scattering but would warm the stratosphere and help to offset $CO_2$-induced stratospheric cooling and the consequent reduction in ozone. The history of alternative suggestions goes back considerably further, however. Chang and Shih (1991) not only proposed the use of “Welsbach materials and other oxides of metals which have high emissivity (and thus low reflectivities) in the visible and 8-12 micron infrared wavelength regions,” but also patented the idea.

As an alternative approach, Canavan and Teller (1991) and Teller et al. (1997) proposed injecting microscopic particles that were actually small corner reflectors.[9] Such reflectors would efficiently bounce the solar radiation back toward its source without scattering significant radiation. Because most ultraviolet (UV) radiation is absorbed by the ozone in the stratosphere, having the corner reflectors sized to optimally reflect such radiation, which was the wavelength

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[9] Corner reflectors are created by three intersecting, orthogonal planes, just as are the corners in a room. Assuming each of the planes are coated with a reflective material, light incident on a corner reflector strikes the three planes in succession and comes out in exactly the opposite direction, much like a handball hit into a corner.

initially proposed, would actually have relatively little effect on the amount of energy reaching the surface-troposphere system (and thus would not offset the warming influence of the increasing concentrations of greenhouse gases). In addition, reducing the amount of UV radiation reaching the troposphere might well adversely affect tropospheric chemistry and reduce the chemical cleansing capacity of the atmosphere; on the other hand, reducing the down-coming UV radiation would increase the time it takes to become sunburned and so perhaps reduce incidence of skin cancer.

As another alternative in its analysis, NAS (1992) considered an approach involving lofting of millions to trillions of larger, reflective, high-altitude balloons. Maintaining enough aloft would likely make this approach costly due to the need to provide lift and to limit deterioration due to high-energy UV radiation. Such balloons could be configured like corner reflectors or especially coated on their upper side to increase reflectivity. Whether so many balloons might interfere with communications would need to be considered.

The most recent proposal (Keith, 2008b) is to inject small particles into the mesosphere. By clever design and choice of materials, the injected particles could be self-levitating, taking advantage of the electrostatic and magnetic fields present at high altitudes. Except to the extent that the particles would age and be damaged in the harsh high-altitude stream of solar radiation, these particles could have a lifetime of several years or more, thereby balancing the greater cost for their production and injection. Theoretically, at least, the particles could also be designed to primarily reflect wavelengths that are not in the visible part of the spectrum (so, for example, being in the near-infrared range), thus reducing side effects (except perhaps for species making use of a wider spectral band than humans). While the approach appears viable, developing an optimal design and checking for as yet unrecognized side effects remain to be done.

***Troposphere:*** The present global tropospheric sulfate loading, which results primarily from $SO_2$ emissions from elevated stacks of coal-fired power plants,[10] creates the whitish haze that extends over and often far downwind from major industrialized areas. Because there are both direct and indirect (i.e., cloud-brightening) components of the global cooling influence, the strength of the cooling influence is only roughly known. IPCC’s best estimate is that aerosol cooling offsets ~40% of the overall warming influence of the human-induced increase in the concentrations of greenhouse gases, an amount equivalent to the warming influences of the increases in concentration of all of the non-$CO_2$ greenhouse gases (Forster and Ramaswamy, 2007).[11] Because the $SO_2$ emissions are primarily in the Northern Hemisphere, the cooling influence is also, and it was likely the increase in $SO_2$ emissions from elevated sources in the mid-20th century that led to a sharp increase in the Northern Hemisphere’s sulfate loading and inhibited

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[10] Surface-level emissions of $SO_2$ have an atmospheric lifetime of only a day or two before being removed by dry or wet deposition, so only a small fraction of the emitted $SO_2$ is typically converted to sulfate. Emissions from tall stacks, by contrast, have lifetimes of a week or more, allowing a significant fraction of the $SO_2$ to be converted to sulfate aerosols.

[11] An inadvertent consequence of this near-perfect offsetting has been to largely limit many of the discussions of policy actions to limiting emissions of $CO_2$, thereby sometimes hiding the important and cost-effective opportunities that exist for control of the non-$CO_2$ greenhouse gases. That the offset is so close is purely fortuitous and is very unlikely to persist as emissions and control measures change.

warming by the rising greenhouse gas concentrations until the greenhouse gas influences on radiative forcing began to prevail in the early 1970s.

Given the cooling effect of tropospheric sulfates, augmenting (or managing) their tropospheric loading is thus an alternative to augmenting their stratospheric loading. There are, however, several potentially important adverse consequences. First, because the lifetime of sulfates in the troposphere is roughly a week, the emission of $SO_2$ into the troposphere must be ~100 times larger than would be required for stratospheric injections, where particle lifetimes average ~2 years. As a result, to generate global coverage and to minimize the disturbance of the atmospheric circulation that would result from sharp spatial inhomogeneities, geoengineering based on management of the tropospheric sulfate loading would require substantial emission of $SO_2$ and a worldwide array of source locations (or construction of special $SO_2$ emitting towers to burn and inject sulfur previously removed from power plant exhaust streams). The resulting sulfates would also be likely to have adverse health consequences, reduce visibility, and increase acidic deposition ("acid rain") that would need to be considered in comparison to the impacts of the warming that is averted. The advantage of this approach, of course, is that injecting $SO_2$ into the troposphere is straightforward and the effects are reasonably well understood in that coal-fired power plants presently emit large amounts of $SO_2$. If emission of $SO_2$ can be done intermittently, however, doing so only when trajectory forecasts indicate a relatively long atmospheric lifetime, could reduce the amount needed and the subsequent deposition and damage.

While the health, visibility, and ecological impacts of sulfates have led to extensive efforts in the developed world to reduce $SO_2$ emissions, the emission levels in China, India, and other nations where coal combustion are very likely increasing. That most of these emissions are likely occurring near the surface is one factor contributing to the visibility impairment in these regions. Primarily low-level emission is also suggested by satellite observations of optical depth, which do not show the emissions creating long plumes extending far downwind (see Figures 2.11 and 2.12 in Forster and Ramaswamy, 2007). If developing nations follow the path of the developed nations in cleaning up their air pollution, their initial step will be to build tall stacks that loft the $SO_2$ emissions, thereby reducing near-surface deposition and visibility impairment, but allowing more sulfate formation and creating whitish haze layers that extend far downwind. The more time that the haze is over the dark ocean surface, the greater will be the cooling influence. It is not inconceivable that if the sulfate levels are increased in this way, the Northern Hemisphere could experience a pause in global warming as it did during the mid-20th century.

Because the advanced combustion technologies that are being used in many regions tend to capture the $SO_2$ (selling it for other purposes), it may be that the global sulfate loading is likely to decline over coming decades. Assuming that high sulfur coal continues to be burned, however, it would likely be relatively straightforward to bypass this capture, thereby creating a cooling influence by intentionally increasing the tropospheric sulfate loading, thereby directly reducing incoming solar radiation and brightening clouds. To the extent that the sulfate remains over the oceans and is scavenged there, the associated environmental consequences seem likely to be quite low; on the other hand, an increase in sulfate particle loading over land would increase health impacts, and, if the sulfate is removed by precipitation in concentrated areas (e.g., in precipitation onto the mountainous areas of Japan and California), there could be important ecological effects. While there are a number of investigators modeling the global tropospheric aerosol budget, there has not been, to my knowledge, any analysis of optimal designs for a release strategy. To evaluate this approach, research is needed on the implications of emissions being from limited areas, the consequences for weather and the environment, the consequences for health, and the long-term consequences of persisting in the effort for perhaps many decades or longer.

Bower et al. (2006) and Salter and Latham (2007) have proposed an alternative approach for increasing tropospheric reflection of solar radiation. Rather than create a sulfate haze, they propose to brighten existing marine stratus cloud decks by decreasing the size and increasing the number of droplets in the clouds. These authors have suggested that this could be accomplished by deploying fleets of uniquely designed, wind-propelled vessels that would spray a mist of seawater out the top of their masts (Salter et al., 2008). Alternatively, although their routing is more limited, the existing commercial fleet of vessels might be equipped with a shipping container containing the required spraying devices. The suggestion is that the mist would then be carried aloft into the low-level clouds by naturally generated convective motions. This approach is intended to mimic and expand upon the observation that the exhaust plumes from ships sailing under marine stratus clouds appear to create bright contrail-like streaks that have been clearly visible from satellites. The authors suggest that deploying on order of a dozen, clipper-ship size craft each year could offset each year’s emissions.

Latham et al. (2008) have analyzed the potential effects of implementing this approach and find that full implementation could significantly increase the global albedo, thereby creating a cooling influence that would offset at least some of the radiative forcing contributed by higher greenhouse gas concentrations. Given the likelihood that cloud brightening would have a positive impact, the next step would be to proceed to a field test, which, in comparison to many of the other approaches, should be doable at modest cost (i.e., a few tens of millions of dollars), especially because the effect is directly measurable and reversible (the enhancement would likely last only a few days). The short lifetime of the influence, however, would mean that creating a global effect would require many ships simultaneously and continuously emitting a mist of seawater in order to sustain the albedo increase. Another disadvantage would be that only certain regions have the right set of conditions for this approach to work, and regional implementation might well perturb regional weather patterns. On the other hand, this approach might be particularly suitable for counterbalancing local to regional-scale impacts, such as reducing the warming of ocean waters in regions where hurricanes and typhoons form and intensify, where bleaching of corals is expected, or where melting of Arctic sea ice is occurring.

***Land surface:*** While extensive snow and ice cover represent natural examples of the cooling influence of bright surfaces, the potential for geoengineered approaches to counter greenhouse gas induced warming by increasing surface reflectivity is quite limited. Not only do clouds and atmospheric absorption reduce the amount of solar radiation that reaches the surface by ~50% compared to the top of the atmosphere, but only ~30-40% of that amount falls onto land areas. In addition, the amount of available land with a low albedo that could be significantly enhanced is generally committed to purposes such as agriculture or forests.

To avoid covering land needed for other purposes, Gaskill and Reece (2003) proposed increasing the reflectivity of large areas of desert. They estimated that it would require covering ~70,000 $km^2$ of land each year with a Mylar film to counter the effects of each year's addition of greenhouse gases. Although covering a bright desert area would limit the increase in the albedo per unit area that could be achieved, choosing such regions would, assuming the weather remains unchanged, benefit from having clear skies. A critical research question is whether such large-scale modification of the surface albedo would alter the regional weather and climate, and, if so, the environmental and societal consequences of such changes. In addition, there would be the practical problem of maintaining the effectiveness of the reflective surface over time.

Rather than increase the albedo of large, unused areas, another alternative would be to increase the albedo of existing uses of the land by, for example, whitening the roofs of structures and transportation corridors (Akbari et al., 2008). Although the fraction of the Earth's surface that could be affected is relatively small unless a means (e.g., genetic engineering) is developed to increase the average reflectivity of trees and grasslands (see Morton, 2009), the basic problem with geoengineering the land surface as a means of achieving a global result is getting enough of a change over a large enough area. An additional problem is that regional changes in the weather seem likely to result, as has been evident in studies that, for example, investigate the potential effects of deforesting the Amazon (e.g., Dickinson and Kennedy, 1992). Smaller scale efforts would, however, seem likely to have a favorable result in the local area as well as reducing the heat load on particular structures or communities, and if such changes were done worldwide, there might well even be a noticeable large-scale effect (Akbari et al., 2008).

***Ocean surface:*** Because the ocean's albedo is low, raising it could lead to a very large change in surface reflectivity. Were this to be done by floating a reflective structure, its size would need to be roughly the size of a continent in order to raise the global albedo by 1%. Such an extensive covering would have significant impacts, particularly by reducing both the amount of energy absorbed and the evaporation. In addition, there would be impacts on the weather and ocean currents, perhaps reducing the overall effectiveness of the approach. Russell Seitz (2008, personal communication) has proposed an interesting alternative to covering the ocean surface with a reflector. His approach would augment the formation of tiny bubbles by the natural wave-breaking processes. Injected a few meters below the surface, for example by existing ships as part of a process to reduce their drag (Graham-Rowe, 2008) or by the type of special ships proposed by Salter et al. (2008), the lifetime of very small bubbles might be as long as a few days, and, over this time, the albedo of the ship wake would be increased by several percent.

Finally, efforts to maintain or increase the formation of sea ice might be possible. If a way could be found to transfer heat from the water below sea ice to the surface so that it could be radiated upward during the polar night when the insulating effect of sea ice limits upward flow of heat from the ocean, sea ice could be made thicker and therefore longer lasting, thus making it more capable of reflecting solar radiation away during the polar summer. With the Arctic being the source of the very cold air that spreads south into mid-latitudes, creating violent weather when the air mass undercuts warm, moist air, increasing the extent and persistence of sea ice could exert an important cooling influence on the climate that would become manifest through its effects on the weather.

When the sea ice is thin, an approach to thickening the ice that has been suggested is to break up the new ice using icebreakers, which would allow heat to escape more easily in the disrupted regions; the disadvantage, of course, is that doing so would likely be quite expensive. An alternative approach would be to construct a fleet of floating devices that would augment wintertime heat flow through the sea ice while enhancing surface albedo in the summer. Possible approaches would include floats that provide a high thermal conductivity path from below to above the sea ice, and distributed snow-making machines that would shoot sea water up from below the sea ice, perhaps powered by the thermal gradient that exists from below to atop the ice. While theoretically imaginable, engineering such devices and assuring an adequate capability seem likely to be problematic in the wintertime environment.

### 5.3 Counter-acting Specific Impacts or Effects in Specific Regions

Using geoengineering to counterbalance specific consequences of global warming or effects in specific regions has also been proposed. While adaptation and increasing resilience to impacts are approaches to moderate the adverse consequences of climate change, they focus on how human activities might be adjusted to avoid or limit the specific adverse consequences. By contrast, geoengineering approaches would seek to reduce the intensity of the factor or process leading to a particular impact or set of impacts. Several proposals likely merit more detailed consideration than has been given to date.

***Moderating the intensity of hurricanes and typhoons:*** The projected increase in the intensity and rain production of tropical cyclones (i.e., typhoons, hurricanes, etc.) threatens to cause greatly increased damage to the increasing number of people living in potentially vulnerable coastal regions. Initial studies to seed near-eyewall clouds in hurricanes in order to modify their track started roughly 50 years ago, but were generally unsuccessful for both observational and theoretical reasons. With the new, very high-resolution models, theoretical studies are starting to receive a bit more attention, but problems remain in determining ways to alter such large and intense weather systems. What would be most useful is some sort of environmentally friendly, easily dispersed, inexpensive, and controllable surfactant that would slow evaporation of the seawater that ultimately powers these storms, but none has yet been developed (Kerry Emanuel, personal communication, 2001).

Alternatively, finding a way to limit solar absorption or to increase ocean mixing might be used to cool ocean waters in areas where tropical cyclones intensify, thus limiting the energy available to power these storms. For example, increasing the reflectivity of low-level marine stratus clouds as proposed by Salter and Latham (2007) could be used to limit ocean warming in the regions where tropical cyclones tend to form or intensify (e.g., in the Caribbean Sea, Gulf of Mexico, Bay of Bengal, Philippine Sea, etc.). There are even proposals more akin to weather modification for modifying the atmosphere in order to promote development of the large-scale weather patterns such that they tend, a few days hence, to push advancing tropical storms out to sea (e.g., see Fleming, 2007). Although research on such ideas is in its very earliest stages, the newest models are becoming capable of analyzing the potential effectiveness of such proposals, something that was not possible when hurricane modification was first attempted.

***Preserving the ocean's meridional overturning circulation:*** Johnson (1997) argues that, to reduce the likelihood of a reduction in the Meridional Overturning Circulation and consequent cooling of the North Atlantic, damming the Strait of Gibraltar might be useful. Taking this action would tend to keep Europe and the North Atlantic region warm by cutting off the cooling influence of the high salinity waters that form in the Mediterranean. Other, less developed, ideas have also been proposed. The very high-resolution ocean models that are becoming available provide a useful tool for evaluating such ideas.

***Preserving Arctic sea ice:*** Although there was interest during the anomalously cold 1960s in the possibility of taking actions to melt Arctic sea ice (e.g., see Weart, 2004), recent attention has focused on ways to preserve it. Several authors have suggested that damming the Bering Strait or Siberian rivers flowing into the Arctic, which could be done to alter the salinity, stabilization, and or heat transport, might be useful in controlling what happens in the Arctic Ocean. Ocean circulation models are finally becoming adequate to undertake such investigations.

Rather than altering ocean currents, sharply reducing incoming solar radiation coming in over the Arctic[12] seems likely to offer a number of the benefits of stratospheric aerosol injection while avoiding the global consequences of sharply modifying the ratio of diffuse and direct solar radiation. Reductions in the radiation could, theoretically, be accomplished by lofting of sulfate aerosols or other reflectors (e.g., corner reflecting balloons or particles) in large amounts over the high latitudes where natural ecosystems are used to dealing with low light levels. The injection altitude could be chosen to ensure that the aerosols would stay aloft only during the sunlit months, thereby limiting their contribution to intensification of springtime ozone depletion. The diminution in solar radiation would be made sufficient to promote earlier and more extensive formation of Arctic sea ice. Augmenting the sea ice cover, with its high albedo, would in turn reduce absorption of solar radiation and induce further cooling. The longer duration of a cold sea-ice surface would extend the time during which the overlying air that later spreads to mid-latitudes would be cooled, thus tending to restore traditional weather patterns.

Calculations by Caldeira and Wood (2008) indicate that sufficiently reducing solar radiation in the Arctic could indeed offset greenhouse-gas-induced warming in that region and that limitations would extend southward through the northern mid-latitudes. While a substantial aerosol loading or lofting of balloons would be needed to fully counteract a $CO_2$ doubling (e.g., enough to reduce radiation north of about 60ºN by about 10% or north of 70ºN by 25%, or about half this amount for 50% of this effect), it might be possible that, rather than darkening the skies every year, a heavier injection every few years might promote sufficient Arctic cooling that the additional sea ice with its higher albedo would persist for several years.

An interesting result learned from the model simulations is that, while the region's temperature and sea ice cover could theoretically be returned to preindustrial conditions, the increase in precipitation caused by global warming would persist. This persistence would occur because most global evaporation occurs over the mid and lower latitude oceans. As a result, cooling the Arctic would not substantially reduce the warming, and so the evaporation, in those regions that feeds moisture to the Arctic. Because the existing and additional precipitation would occur

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[12] Proposed initially by the author of this article at the Department of Energy's 2001 workshop (E. Khan, unpublished manuscript).

mainly as snow, the loss of mass by mountain glaciers and the Greenland Ice Sheet might well be reversed, thereby benefiting nations around the world by slowing the rate of sea level rise (and perhaps also helping to sustain the Meridional Overturning Circulation). An additional benefit would be that the colder Arctic would likely lead to recovery of the region's unique ecosystems and species (e.g., polar bears, seals, etc.).

***Sustaining mountain glaciers and ice sheets:*** Another significant adverse impact of global warming is the melting back of mountain glaciers and other large masses of ice in mid- and low-latitudes. Not only would slowing their melting limit sea level rise, but the annual release of meltwater is also an important source of water for rivers and communities. In that deposition of dark particles on the surface of ice sheets significantly enhances glacial melting, the most straightforward approach would be to sharply reduce their emission. Because that will take time, in part because there are so many distributed sources (e.g., from cooking stoves, inefficient vehicles, etc.), attempts are beginning over very limited areas to determine if reflective insulation can be used to cover the glaciers through the period of summer warmth, thus reducing the solar load and keeping air warmer than freezing from direct contact with the glacier's surface. Expanding such efforts to the large-scale is likely to be problematic because the insulating material that would limit melting during the warm part of the year would need to be removed in order to allow essential cooling during the cold part of the year.

***Limiting sea level rise:*** The rate of sea level rise over the past decade has been about twice that observed over the 20th century and much larger than the average rate over the past few thousand years when many major cities developed in low lying, and now vulnerable, coastal areas. Sea level rise is resulting mainly from the melting of glaciers and ice sheets, and thermal expansion of warming ocean waters, although other terms, including depletion of groundwater and slowing down in the global Meridional Overturning Circulation could be contributing. Increasing the storage of water in reservoirs, groundwater, and reforested areas would help to limit sea level rise, although this will likely prove to be difficult as rain systems shift and warmer temperatures increase the rate of evaporation from reservoirs. Actively spraying seawater atop the East Antarctic Ice Sheet would be helpful, but the energy would need to be derived from local renewable sources (e.g., temperature gradients) and engineering of the large system that would be needed would be difficult, particularly in the very cold climate of Antarctica.

One other approach that might provide limited help would be to pipe water into various of the depressed land areas that exist (e.g., Qattara Depression in Egypt). A more important benefit of doing this would actually be deriving hydroelectric power from the process, which could be done continuously if the flow of water was limited to the rate of evaporation that would occur over such an area.

***Limiting ocean acidification:*** The rising concentration of $CO_2$, while beneficial to many land plants up to a somewhat higher $CO_2$ concentration than at present assuming water and nutrients are not limiting, causes acidification of ocean waters. Acidification could be reduced by limiting emissions of $CO_2$, by increasing $CO_2$ removal from the atmosphere through augmentation of natural removal processes, or by altering oceanic chemistry to limit acidification. A range of proposals has been put forward. For example, Rau and Caldeira (2002), House et al. (2007), and Rau et al. (2007) have proposed approaches, in effect, to accelerate the long-term natural buffering process that occurs as a result of the weathering of rocks. Such an enhancement of natural weathering processes—equivalent to giving a bromide to the ocean—would likely pose a very large logistical challenge as the mass of material required for buffering is typically several times as large as the mass of $CO_2$ to be sequestered.

## 6.0 Creating a Decision Process for Geoengineering

Research on the scientific aspects of geoengineering, including the cost of actually carrying it out, is one aspect of determining whether such approaches merit consideration as a policy option that could be considered along with mitigation, adaptation, and suffering through the impacts of climate change. A traditional approach for evaluating the merits of a course of action is comparison of costs and benefits of such efforts. Comparing the direct costs of the geoengineering itself relative to the costs of reducing emissions by an equivalent amount is the most straightforward (e.g., see NAS, 1992), but this leaves out the potential benefits of the avoided impacts of climate change, which seem likely to be important.

As made clear in analyses by Stern (2007) and Nordhaus (2007), evaluating the benefits of limiting the pace of future climate change can lead to quite different results as a result of differing assumptions about the appropriate manner in which to weigh the present importance of future impacts. In addition, reductions in impacts are necessarily estimated based on the results of extended term simulations of very complex climatic, ecological and socioeconomic models, which leads to outcomes that are at least as uncertain as the projections of climatic impacts without mitigation or geoengineering. For example, in evaluating approaches for solar radiation management, in addition to all the climate-related impacts, an analysis would have to weigh the direct effects of the further rise in the $CO_2$ concentration, including the negative consequences of allowing ongoing acidification of the ocean and the positive effects of enhanced water use efficiency and productivity of some crops. That many analyses (e.g., IPCC, 2007b) comparing fossil versus renewable sources of energy are so limited in their analysis of the consequences of the changes in $CO_2$ and climate makes clear that considerable further research and analysis will be needed, including considering the results in both cost-benefit and risk-based frameworks.

One important complication of any such analysis involves the time dimension, because, assuming that one or more viable and cost-effective approaches to geoengineering can be found (e.g., injection of aerosols into the stratosphere), the commitment to the approach must match the lifetime of the $CO_2$ increment that is supposedly being offset. To first order, this means that continued emission of $CO_2$ would need to be offset by roughly a 200-year commitment to the stratospheric injection because, were the geoengineering effort to be halted for any reason, the radiative forcing of the remaining $CO_2$ would no longer be offset and the atmospheric temperatures would likely jump up toward a higher equilibrium temperature relatively rapidly (Brovkin et al., 2008; Robock et al., 2008). In that each of the approaches requires some maintenance or renewal (e.g., additional launching of mirrors, lofting of particles or reflecting balloons, or augmenting the number of mist-dispersing ships) the commitment to the offset will, without the approval of future generations, impose responsibility and costs on them.

Coming to an understanding of what creating a multi-generational commitment might mean is likely to be very difficult. While there have been national, and even international commitments to creating infrastructure (e.g., road, rail, and air transportation) over multiple generations, most of these commitments have been associated with an increase in some tangible or visible benefit—indeed, profit has likely been the most powerful motivating force. By contrast, there are only a few examples of multi-century commitments to protective efforts (e.g., the Great Wall of China and the dikes constructed by The Netherlands), and these were generally constructed in response to actual calamities or threats. For geoengineering, however, the prospective benefit is avoiding a projected, but not experienced, calamity. Because a number of the impacts are likely irreversible, taking action before the most adverse consequences are actually apparent is important; indeed, because waiting to invoke geoengineering until after the emergence of such damaging changes as the loss of critical biodiversity or the initiation of the melting of much of the Greenland Ice Sheet would forego most of the potential benefits.

Maintaining nuclear deterrence offers another example of a societal commitment that lasted over several decades. Examples over longer periods with only projected threats include, perhaps, ideologically driven decisions such as countries isolating themselves from foreign contact, or religiously driven undertakings such as the building of cathedrals. Most of the examples, however, were regional in scope or involved only one or a few countries and lasted only a few centuries, providing only very limited insight into whether a global coalition of nations could be kept together to sustain the necessary diversion of resources for many centuries.

That implementation of some of the geoengineering approaches might not require an international effort has introduced a new twist to the issue. Indeed, solar radiation management using stratospheric aerosols might well be within the capabilities of one nation, with insertion of aerosols doable over the land area of that nation and from over the open ocean. Wanting to sustain its use of fossil fuel derived energy to raise the living standards of its people, for example, might China act unilaterally if it became convinced that global warming was leading to sharp disruption of the life-sustaining monsoons on which it depends? If the US became convinced that global warming was leading to more and more powerful hurricanes that were devastating its Southeast, might it choose to act unilaterally? Scott Barrett (2007) has begun to examine such issues, and there are many additional questions (not further elaborated here) that will need to be addressed if geoengineering is going to be seriously considered.

In addition to the political, ethical, and economic issues that such a long-term commitment would raise, there is also a potential legal hurdle. In reaction to US attempts at weather modification during the Vietnam War, the nations of the world agreed in 1978 to the *UN Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques*[13] (Fleming, 2004), which essentially prohibits weather modification that any nation experiencing the impacts would consider hostile or environmentally damaging. In that "climate" is really a mathematical construct created by averaging over the weather, it would not be far-fetched to argue that this treaty might well not permit geoengineering schemes to be used for the purpose of climate change, or counterbalancing it (indeed, not changing climate patterns is specifically mentioned as being covered in one of the understandings of the treaty). The notion of one or a few countries proceeding to undertake some geoengineering action without the permission of all countries would almost certainly be considered hostile by some

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[13] The text of the treaty can be downloaded from http://www1.umn.edu/humanrts/peace/docs/conenvironmodification.html

nation. While there is an exception in the Convention relating to peaceful purposes, a treaty modification might need to be negotiated regarding how much change would be undertaken and who would decide the conditions to be aimed for.

There has already been some experience with political consideration of geoengineering, and in this case additional considerations arose. In its initial formulation in mid-2001, President Bush's Climate Change Technology Initiative included consideration of geoengineering as one of the possible categories for consideration, leading to a workshop in the fall of 2001 and preparation of a draft report (Ehsan Khan, personal communication). However, a powerful argument against proceeding emerged as the analysis continued, namely that if a viable and low cost geoengineering alternative really were available, economic analysis would then seem to argue against continuing to try to reduce $CO_2$ emissions. As such, geoengineering would really be, in essence, an enabler for ongoing addiction to fossil fuels, roughly equivalent to foregoing fire insurance based on an assurance that the fire department was right next-door and could quickly put out any blaze.

If finding and implementing an effective approach to geoengineering were to weaken the resolve for reducing emissions, then the benefit of limiting climate change would come at the cost of imposing an even longer and greater responsibility for future generations to continue the geoengineering offset, especially because the consequences of failure would be increased due to the extra emissions that would be allowed. Recognition of this unintended response chain led to a change in the argument that DOE staff were using to justify research on geoengineering (Ehsan Khan, personal communication), namely to viewing geoengineering as a backstop strategy to (or insurance policy for) mitigation and adaptation, to be called upon only in the event of unexpectedly rapid or extremely damaging impacts.

Crutzen (2006), however, argues that climate change has nearly or already reached the point where dangerous consequences seem likely to result, and Hansen et al. (2008) point out that important tipping points are near or have already been passed, so this qualification is becoming moot. Indeed, Crutzen (2006) argues that societal addiction to fossil fuels is so severe that society needs to move ahead with research and even testing of viable approaches, especially in that the costs of research are likely to be small compared to, for example, the recent US budget expenditures for energy-technology research of roughly $3B per year (which amounts to an investment of only about 3 cents per US citizen per day).

Quite clearly, wider discussion and exploration of views are needed (Wigley, 2006; Ragaini, 2008; Robock, 2008a, 2008b; Robock and discussants, 2008), both at international scientific and intergovernmental levels.

## 7.0 Requirements for Enhancing the Scientific Basis for Proceeding

In addition to the need for further research on the scientific aspects of each specific approach and further consideration of how the value-based and governance issues might be addressed, there is also a need for a much closer understanding of the fundamental approximation underpinning all of the geoengineering approaches. Basically, each of the approaches relies on a finding that emerged over the past few decades that forcings with different latitudinal and seasonal patterns will nonetheless have the same latitudinal and seasonal response of surface temperature. For example, Crutzen (2006) cites the results of Govindasamy and Caldeira (2000), whose model results indicate that, at least for the surface temperature response, roughly a 1.8% decrease in the solar constant would quite closely offset the latitudinal and seasonal temperature response to a doubling of the $CO_2$ concentration, even though there are significant differences in the seasonal and spatial patterns of forcing. Indeed, this assumption is implicit in the global-scale summation of forcings made by the IPCC (2007a), which, although the regional patterns of response can somewhat vary, treat as equivalent, at least in a policy planning sense, the forcings caused by increasing concentrations of greenhouse gases, sulfates and other aerosols, tropospheric ozone, contrails, and land cover change.

That this may well not be the case would seem to be demonstrated by the correlation of the waxing and waning of ice ages with the cycling of orbital elements. Essentially, all that the orbital element changes do in terms of radiative forcing is to alter the seasonal and latitudinal pattern of incoming solar radiation; they do not significantly change the integrated annual solar flux to the Earth system. As a result, orbital forcing would be assigned a near zero value on the IPCC forcing diagram (attempts to explain ice age forcing typically do so by counting the albedo influence of the ice sheets as a forcing, but this seems to be confusing a forcing with a feedback). Factors (such as changes in solar irradiance) that are given small values on the IPCC chart of forcings typically have small effects on global average temperature, yet orbital variations appear to be the drivers of the ice age cycling that the Earth has experienced over the past million years and more, causing changes in global average temperature of 5-6ºC. If geoengineering is going to have to be used over several centuries, it is going to be necessary to go beyond the few decade simulations by climate models that have suggested the offset can be calculated on a global basis.

The point to be made is that the IPCC chart is a simplification—the actual model simulations show the situation is a good deal more complex. For example, the cooling influence of the greater loading of sulfate in the Northern than in the Southern Hemisphere in the mid-20th century allowed a slightly larger warming in the Southern Hemisphere, and regional modification of sea surface temperatures during an El Niño, can affect the atmospheric circulation around much of the world. Thus, before proposing that geoengineering might be able to really counterbalance the climatic response from increasing greenhouse gas and aerosol concentrations, a much clearer explanation and much more simulation is going to be needed to investigate the long-term effects on climate of differences in the latitudinal and seasonal patterns of the forcing, and how changes in the oceans and in snow and ice cover might affect the response.

While analysis has begun for some of the geoengineering approaches (Caldeira and Wood, 2008; Latham et al., 2008; Robock et al., 2008), much more consideration is needed regarding how the approaches might be implemented over time and in association with other types of changes in the climate and environment. There is already some indication that volcanic aerosols can, by altering the atmospheric circulation, produce winter warming over Northern Hemisphere continents (e.g., see Robock, 2002), making it likely that stratospheric aerosols intended to cool the climate could warm the climate in some regions and at some times of the year, adding to the warming from the higher concentrations of greenhouse gases. However, much more effort will be needed, not only seeking to understand the consequences of geoengineering, but also to better understand the causes of glacial-interglacial cycling and how both the increasing concentrations of greenhouse gases and geoengineering offsets might connect to the longer term natural cycles of the Earth's climate.

## 8.0 A Near-term Agenda for Impact Intervention

With so many possibilities and so much scientific research needed, all while there is also significant controversy about the moral, ethical, and environmental aspects of even considering geoengineering, it seems appropriate to identify some initial steps that would seek to determine if some of the worst and most inevitable consequences of human interference with the global climate can be limited. From what is understood at present, I would urge initiating meaningful research on the following four approaches that are focused on intervening with climate system behavior in order to limit or moderate the adverse impacts associated with human-induce increases in greenhouse gas concentrations.

### 8.1 Limiting Ocean Acidification and Carbon Build-up in the Atmosphere

While dramatically cutting $CO_2$ emissions from fossil-fuel combustion must be the primary action to limit ocean acidification and its threats to marine life and coral atolls and islands,[14] finding effective ways to increase the sequestration of carbon in ocean sediments and in the very deep ocean could play a significant role in limiting both acidification and climate change. Iron fertilization of nutrient rich, but biologically depleted waters is the most widely touted possibility, although there are serious questions about how much of the carbon taken up in new growth really makes it to the ocean sediments. Given the time it takes for the micronutrient addition to promote growth, larger and longer-lasting field experiments are needed. An alternative fertilization approach is to add urea to increase the macronutrient loading. Considerable research is needed to determine potential impacts on ocean ecosystems, and in that both of these approaches change ocean color, the vertical profile of ocean heat uptake is altered, which has the potential to affect the intensity of storms drawing heat from the ocean.

A more aggressive and geographically expandable approach would be to bring cool, nutrient rich waters to the surface (e.g., Lovelock and Rapley, 2007), which would not only stimulate regional marine life over areas with virtually no fishlife, but also cool ocean areas that are warm (e.g., hurricane intensification regions or coral reefs). Harvesting the increased marine life could provide fish-protein (and the skeletons should then be sequestered below ground) and biomass for food and to create biofuels (thus reducing the need for fossil fuels). The skeletons and fecal matter of the marine life that are not harvested would add to the downward flux of carbon to the sediments. In that this approach would not be using nutrients already likely being used by existing marine life, the ecological effects of such efforts are likely to be less than would result from iron fertilization. Initial research on aspects of a wave-powered pump suggests that the approach might work (see http://www.atmocean.com/), but much more research and investigation is needed. Even if not implementable on a large enough scale to significantly limit climate change and ocean acidification, success would likely be beneficial because of the likely

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[14] That the threat is real and imminent is clear from the observed shoaling (shallowing) of the saturation horizon—the depth at which the calcium carbonate that makes up fish skeletons and coral atolls is made (Bindoff and Willebrand, 2007).

increase in harvestable marine biomass and the consequent reduction in utilization (and release) of carbon by terrestrial biomass.

### 8.2 Limiting Ocean Warming in Critical Areas

The accumulation of heat in the ocean due to the higher greenhouse gas concentrations increases evaporation and warms surface waters, both of which contribute to the intensification of tropical cyclones and other storms. Already, there are indications that a larger percentage of nascent tropical cyclones are developing into more powerful hurricanes and typhoons (IPCC, 2007a), increasing the damage and inundation occurring along coasts and inland. In addition, warmer than typical ocean temperatures have been increasing the frequency of coral bleaching episodes. Reducing, or at least limiting the rise, in the temperatures of waters in tropical-cyclone formation and intensification regions could be very beneficial.

Approaches for doing this include at least the Latham et al. (2008) suggestion for increasing cloudiness, ocean pipes to cool specific ocean areas (Lovelock and Rapley, 2007), and an emerging approach to increasing ocean surface albedo by injecting small bubbles (Russell Seitz, personal communication). While these approaches have the potential for exerting a global influence if fully deployed, a much more limited and feasible deployment in specific areas could be very beneficial and would also allow testing of the global concept. Even were the climate not changing, exploring the potential for these approaches to limit storm intensification and coral bleaching could be beneficial, especially considering the situations being faced by the increasing numbers of people living in coastal regions and on vulnerable islands.

### 8.3 Limiting High-Latitude Warming and Its Contribution to Sea Level Rise

The Arctic is already experiencing adverse impacts from the amplified onset of global warming that occurs in high latitudes—and then spreads its effects to lower latitudes. Sea ice retreat is threatening both key species and coastal communities, while melting of glaciers and ice sheets is contributing to sea level rise. These changes have been caused by a relatively small increase in the warming influence in the area, suggesting that a relatively modest reduction in solar radiation into the region could be beneficial. If enhancing the tropospheric or lower stratospheric aerosol loading in the region could be used to exert a cooling influence, the change would also benefit mid-latitudes because the Arctic serves, in effect, as the "air conditioner" for the Northern Hemisphere, creating the cold air that is necessary to sustain mid-latitude weather patterns and storm tracks.

Initial model studies indicate that reduced solar radiation into the region would limit regional and Northern Hemisphere warming while also promoting increased snowfall and building up glaciers and ice sheets, thereby helping to limit sea level rise. In that the stratosphere is at comparatively low altitude in the region and the aerosols only need to be present during the Arctic summer, injection should be relatively inexpensive. Because the Arctic summer troposphere is quite stable and rarely experiences convection, an alternative approach to lower stratospheric injection might be tropospheric injection. This could be achieved, for example, by releasing $SO_2$ from power plant stacks in Europe and North America when meteorological conditions are forecast to carry the air mass into the summertime Arctic. While tropospheric aerosols would have a shorter lifetime, injection would likely be less costly than for stratospheric injection and the lower altitude might be beneficial in limiting the spread of the injected aerosols to lower latitudes.

In that the Arctic Ocean's biological activity depends on cold temperatures, returning the Arctic towards a colder state would likely be beneficial to existing species, and the reduction in solar radiation seems unlikely to have significant side effects. Evaluating the region's response to previous volcanic eruptions would provide one way of evaluating potential adverse impacts, and, in any case, given that the stratospheric aerosols would naturally be removed from the atmosphere each year (and tropospheric aerosols even more rapidly), it would be unlikely that pursuing this approach would do any long-term harm. However, much more detailed modeling experiments are needed to investigate the issue and to design the optimal protocol for an initial experiment. While sulfate aerosols can be used, and research is needed on the best and most practical injection techniques, investigation should also be carried out on alternative materials that might lead to less scattering of the incoming solar beam so that the stratospheric aerosol approach might be considered over more of the Earth if warming accelerates.

### 8.4 Sustaining the Global Aerosol Offset

At present, the emission of $SO_2$ from coal combustion is leading to a global sulfate burden that is offsetting about 0.5ºC of global warming. Were the world to be able to cut its $CO_2$ emissions to zero, human-induced $SO_2$ emissions would also approach zero. Because the lifetime of sulfate aerosols in the atmosphere is roughly a week whereas the lifetimes of the $CO_2$, $N_2O$ and halocarbon perturbations tend to be centuries (or more), the cooling offset of sulfates would be lost relatively quickly, leading to a strong warming influence despite the reduction in emissions of long-lived greenhouse gases. While one of the most frequently suggested geoengineering steps is $SO_2$ injection into the global stratosphere, that would likely require a very significant effort and lead to a significant worldwide reduction in the direct solar beam that is needed by solar thermal and other technologies that use mirrors to concentrate the energy or depend on the intensity of the solar beam.

A viable alternative to stratospheric injection might well be to manage the emission of $SO_2$ to the troposphere from existing and planned coal-fired power plants, seeking to maintain or even increase the overall cooling influence of these aerosols, especially by building up their concentrations in remote regions (such as over the ocean) where problems of acidifying precipitation and scattering of the direct beam would not be likely to cause serious impacts. While the developed nations have been reducing their $SO_2$ emissions in order to reduce acid precipitation onto sensitive regions (generally in the upper mid-latitudes), with China and India building coal-fired power plants (and perhaps building tall stacks in order to disperse the emitted products from the region of the emission—just the strategy the developed nations pursued 50-80 years ago), there is likely to be an increase in lower latitude sulfate loading, especially over ocean areas. Energetically, such an effect would be especially beneficial in clear air because ocean albedo is low and solar intensity is high. In addition, for cloudy areas, the increase in aerosol loading might well increase the albedo of low-level clouds, achieving the increase in cloud albedo of the Salter-Latham approach, but without having to have a fleet of ships emitting a spray of sea water.

A focused modeling and enhanced observation program could evaluate the potential for seeking to manage the global sulfate burden in ways that would provide a maximum offset to greenhouse gas accumulation, helping to limit warming. Associated with this research effort should also be an evaluation of the effects of all types of aerosols on precipitation and precipitation systems in the lower latitudes, especially in terms of effects on the monsoons, for which there is some evidence that current aerosol emissions and changes in land cover may be having a detrimental effect (Levin and Cotton, 2009).

## 9.0 Concluding Thoughts

The rate of increase of climate change, along with the continuing increase in emissions of greenhouse gases, has created a very serious predicament for the world. Drastically reducing the world's use of fossil fuels will take time and may raise near-term costs for energy, even after the effort gets seriously started and production costs for new energy technologies drop. As a result, global warming is likely to press up against or even exceed the level that the Commission of European Communities, for example, has concluded is likely to lead to dangerous and unacceptable consequences. For this reason, it seems prudent for the nations of the world to initiate an effort in geoengineering, with the first, ten-year phase devoted to: (a) addressing whether selective geoengineering (i.e., impact intervention) can be used to moderate some of the most severe impacts that are emerging, and (b) exploring what next steps might be possible if reducing global emissions and adapting to the consequent impacts of climate change prove difficult.

A comprehensive socioeconomic and political governance research effort needs to be undertaken in coordination with the research activities on the physical, chemical, and biological aspects and complications of various geoengineering approaches. Although it may be possible for geoengineering to be undertaken by one nation, every nation would be affected by any action that is taken. For this reason, it is essential that discussions begin on governance issues relating to geoengineering. Already, investor-funded experiments in support of iron fertilization have raised questions over what international entity or institution has jurisdiction. Questions about using geoengineering to limit the intensity of tropical cyclones or Arctic warming would be much more complicated, and questions about even further efforts to limit overall global warming would be even more complex. Thus, in addition to scientific research on possible approaches and their impacts, social, ethical, legal, and economic research should be supported to explore what geoengineering is and is not within bounds of international acceptance.

What is most clear from review of the various geoengineering options is that, were this the objective, returning the climate to its undisturbed state would be very difficult, if possible at all. Therefore, especially in light of the increasing seriousness and imminence of potentially catastrophic impacts, sharply reducing the increasing emissions of greenhouse gases merits strong near-term action, even if geoengineering approaches might offer some help in limiting the most adverse outcomes. In that some moderation of impacts likely can be achieved, research into geoengineering that has the potential of benefiting the world community of nations would seem to be a prudent step to begin in the near-term in order to expand the set of policy choices available for meeting the UNFCCC's objective of preventing "dangerous anthropogenic interference" with the climate system. An optimal outcome would seem to be that mitigation can be accomplished relatively rapidly and relatively easily, such that geoengineering might need to be implemented for only several decades in order to shave off the peak change in climate, thereby increasing the likelihood that the most adverse environmental and societal consequences would not be triggered.

Continued delay in sharply cutting emissions, however, will not only lead to more adverse impacts, but would be likely to create the need for implementing a high level of geoengineering that would need to be carried on for centuries, even though the benefit to the typical citizen would be based on possibilities rather than realities (i.e., similar to the case that must be made for sustaining a nuclear deterrent). Indeed, the risks and the necessary long-term commitment involved in geoengineering would seem to favor making an even stronger case for recognizing the seriousness of the climate change issue and encouraging a much more aggressive energy research and emissions control effort by all nations (e.g., see Hoffert et al., 2002).

Geoengineering, therefore, should not be seen so much as a complement to mitigation that would allow a slower pace for emissions reductions, but more as a complement to adaptation and the building of resilience in that it might prevent the worst impacts, and, if warming really takes off, act as an insurance policy against the very worst impacts. For this to be the case, however, a structured approach with a broad-based research and assessment program is sorely needed.

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