On the possible use of geoengineering to moderate specific climate change impacts

Michael C MacCracken
Climate Institute, Washington, DC 20006, USA

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Abstract
With significant reductions in emissions likely to require decades and the impacts of projected climate change likely to become more and more severe, proposals for taking deliberate action to counterbalance global warming have been proposed as an important complement to reducing emissions. While a number of geoengineering approaches have been proposed, each introduces uncertainties, complications and unintended consequences that have only begun to be explored. For limiting and reversing global climate change over periods of years to decades, solar radiation management, particularly injection of sulfate aerosols into the stratosphere, has emerged as the leading approach, with mesospheric reflectors and satellite deflectors also receiving attention. For a number of reasons, tropospheric approaches to solar radiation management present greater challenges if the objective is to reduce the increase in global average temperature. However, such approaches have a number of advantages if the objective is to alleviate specific consequences of climate change expected to cause significant impacts for the environment and society. Among the most damaging aspects of the climate that might be countered are: the warming of low-latitude oceans that observations suggest contribute to more intense tropical cyclones and coral bleaching; the amplified warming of high latitudes and the associated melting of ice that has been accelerating sea level rise and altering mid-latitude weather; and the projected reduction in the loading and cooling influence of sulfate aerosols, which has the potential to augment warming sufficient to trigger methane and carbon feedbacks. For each of these impacts, suitable scientific, technological, socioeconomic, and governance research has the potential to lead to tropospheric geoengineering approaches that, with a well-funded research program, could begin playing a moderating role for some aspects of climate change within a decade.

Keywords: geoengineering, climate change, Arctic warming, hurricane intensification, aerosol cooling

1. Introduction
Global climate change is becoming more apparent and worrisome; at the same time, global emissions of the greenhouse gases that force climate change are continuing to increase (IPCC 2007a). At the present pace, there seems little likelihood that international negotiations will be able to stabilize atmospheric composition at a level that will avoid ‘dangerous anthropogenic interference’ with the climate system, as called for in the UN Framework Convention on Climate Change (IPCC 2007d, Matthews and Caldeira 2008). Complicating the situation, as emissions of carbon dioxide from coal-fired power plants are reduced, the associated decrease in sulfur dioxide emissions will lead to a reduction in the offsetting cooling influence of the resulting sulfate aerosols. Exposing the full warming influence of the increasing concentrations of greenhouse gases will further complicate the transition to climate stabilization (Crutzen 2006).

With little prospect for near-term stabilization of the climate, increasing consideration is being given to augmenting emission-reduction efforts with deliberate interventions to help limit or even reverse climate change over coming decades (Crutzen (2006) and associated commentaries by Bengtsson (2006), Cicerone (2006), Kiehl (2006), Lawrence (2006), and
MacCracken (2006); Wigley (2006), Barker et al (2007), AMS (2009), Shepherd et al (2009), Victor et al (2009)). 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, there may be well designed, intentional interventions that would create a cooling influence to counterbalance, at least in part, changes in climate and associated impacts?

Such actions or interventions, when taken for the primary purpose of changing the climate or atmospheric composition, have come to be called geoengineering. The idea is not new and first emerged with the intent of ‘improving’ the prevailing climate, changing it to the particular liking of some group or nation (Fleming 2007). In addition to updating the earlier prediction by Arrhenius (1896) that human activities were likely to ultimately cause significant changes in the climate, a prestigious panel of the President’s Science Advisory Council (PSAC 1965) suggested that geoengineering might be needed and appropriate to moderate the expected changes. Over the decades since, quite a number of reviews have been published of the strengths and weaknesses of approaches for enhancing the long-wave loss of or reducing the solar absorption by the Earth system, either of which could be used to counteract the global warming influence of emissions of carbon dioxide (CO₂) and other greenhouse gases from the atmosphere (e.g., see MacCracken 1991, 2009, NAS 1992, Leemans et al 1995, Flannery et al 1997, Keith 2000, Keith 2009, Schneider 2001, 2008, Shepherd et al 2009).

Enhancing the long-wave loss would cool the system by seeking to shift atmospheric composition back toward its preindustrial values so that emission of long-wave radiation to space would occur, on average, from a lower level in the atmosphere. In essence, this type of approach, which involves removing CO₂ or other greenhouse gases from the atmosphere, would be an augmentation of mitigation efforts that reduce emission of greenhouse gases. Approaches to removing CO₂ from the atmosphere include reforestation (see Ormstein et al 2009 for a very aggressive approach), enhancing the oceanic uptake of CO₂ by fertilizing the ocean or other means (e.g., Strong et al 2009), enhancing the geological uptake of CO₂ by accelerating the weathering of rock (e.g., Kelemen and Matter 2008), and chemically scrubbing CO₂ from the atmosphere and sequestering it in deep geological formations or in the deep ocean or in sediments (e.g., Zeman and Lackner 2004, Keith et al 2005, Keith 2008a, Strand and Benford 2009, Jones 2009).

Without significant technological advances, however, increasing uptake by more than about 1 PgC yr⁻¹ appears quite problematic. Because of their limited capacity and present high cost estimates, approaches for increasing long-wave radiation to space while global emissions of CO₂ remain high have the potential to exert only a relatively small counterbalancing effect on the accelerating pace of changes in atmospheric composition, and therefore would have little near-term influence on the increase in global average temperature (Shepherd et al 2009). On the other hand, if global CO₂ emissions can be substantially reduced, these approaches are likely to become important in pulling atmospheric composition back to earlier levels in order to moderate ocean acidification and to allow a residual level of use of fossil fuels. While testing and development of creative approaches need to go on, these approaches will not be the focus of this letter because there is little chance they could have a significant effect on climate for at least several decades.

By contrast, limiting the absorption of incoming solar radiation has the potential to cause a relatively rapid cooling, as has been illustrated by major volcanic eruptions, which are typically followed by a reduction in the global average temperature by several tenths of a degree for up to a few years (Soden et al 2002). Conceptually, the possibilities for sufficiently reducing the Earth’s absorption of solar radiation to counterbalance all or some of the energy trapped by the increased concentrations of greenhouse gases include:

(a) Constructing and actively maintaining a solar deflector (or multiple small deflectors) in an orbit synchronous with the orbit of the Earth around the Sun (Early 1989, Angel 2006);
(b) Placing mirrors or particles in near-Earth orbit (NAS 1992);
(c) Injecting aerosols or specially designed particles into the stratosphere or mesosphere to reflect solar radiation from reaching the lower atmosphere and the Earth’s surface (Lane et al 2007, Rasch et al 2008b, Keith 2008b);
(d) Brightening clear sky and/or cloudy regions in the troposphere so that more solar radiation is reflected back to space (Bower et al 2006, Salter and Latham 2007, Latham et al 2008);
(e) Altering the amount of reflective compounds in the troposphere, either by increasing the amount of reflecting aerosols (e.g., sulfates) or reducing the amount of absorbing material (e.g., black carbon); and
(f) Increasing the reflectivity of the land and/or ocean surface (Gaskill and Reese 2003, Seitz 2009).

Most attention in studies of geoengineering is being given to approaches intended to limit the increase in global average temperature and, by implication, all of the changes in climate associated with it (e.g., Blackstock et al 2009, Shepherd et al 2009). In these studies, geoengineering is considered to be a strategy that would be developed and then, because of the potential for significant side effects and the likelihood of complex governance issues, would be held in reserve for emergency use in the event that the pace of warming becomes particularly dangerous. While being cautious in moving toward global geoengineering is understandable, reversing dangerous situations or consequences may not be possible once thresholds are passed and the rates of warming (e.g., as a result of permafrost melting leading to greatly increased release of methane) or sea level rise (e.g., as a result of the destabilization of the Greenland or Antarctic ice sheets) become unacceptable. An additional complication is that testing proposed approaches as part of a research program would seem to ultimately require actually initiating global geoengineering in order to ensure a convincing signal-to-noise ratio could be achieved.

This letter proposes an alternative, but complementary, approach to limiting the consequences to the climate and
environment of past and ongoing greenhouse gas emissions. Recognizing that the present intensity of climate change is already dramatically altering the environment (e.g., IPCC 2007b), this letter focuses on the potential for initiating deliberate actions within ten years to counterbalance or moderate specific effects or impacts. Section 2 briefly describes geoengineering approaches that, with significantly enhanced research over the coming decade, seem potentially applicable for near-term intervention; mitigation measures such as reducing black carbon emissions, while potentially very effective, are not considered a geoengineering approach. Section 3 then considers a number of potential high-priority applications for which it may be possible to keep the unintended adverse consequences to well less than the potential benefits of limiting the climate change impacts, thus increasing the probability that appropriate decision-making bodies might approve such interventions. Section 4 summarizes what needs to be done to move forward with a program focused on developing near-term interventions that have the potential to alleviate some of the worst consequences of climate change.

2. Options for near-term intervention to limit climate change and its impacts

Integrating over the globe, fully offsetting the climatic effects of a doubling of the CO₂ concentration, or its equivalent, would require counterbalancing an increase in net downward infrared (IR) radiation at the tropopause of between 3.5 and 4.1 W m⁻² (Ramaswamy et al. 2001). Including consideration of the Earth’s albedo, this is equivalent to reducing incident solar radiation by ~1.8% (Govindasamy and Caldeira 2000) or increasing the global albedo from about 30% to about 31–31.5%.

A number of modeling studies have suggested that, although the latitudinal and seasonal patterns of the changes in IR and solar radiation are quite different, the patterns and the magnitudes of the temperature response to the two forcings are nearly equal and opposite (Manabe and Wetherald 1980, Hansen et al. 1984, Govindasamy and Caldeira 2000). This result is somewhat surprising given that the redistributions of incoming solar radiation resulting from changes in orbital elements, but that result in zero net annual forcing, drive the Earth system into climates ranging from ice ages to warm interglacials. A much more detailed study by Hansen et al. (2005) confirms that the spatial patterns of the normalized, annual average responses to globally dispersed forcings such as changes in solar irradiance, greenhouse gases, and volcanic aerosols are ‘nearly identical’. The simulations even indicated that the response patterns for spatially heterogeneous forcings like tropospheric aerosols occurring mainly in the Northern Hemisphere are ‘quite similar’. While these results would seem to confirm the IPCC presumption that the global average temperature response is largely independent of the spatial and seasonal variability of the forcing, Hansen et al. (2005) did find that the efficacy, or relative strength, of the various forcings differed, depending mainly on the vertical distribution of their influence on the Earth’s energy balance.

Although intervention to reduce absorption of solar radiation by the Earth system could occur out in space, in the mesosphere, stratosphere, or troposphere, or at the surface, the earliest suggested (Budyko 1974) and most discussed approach (Crutzen 2006, Rasch et al. 2008b) has focused on increasing the world’s stratospheric sulfate aerosol loading. Among the approaches proposed to loft the sulfur (e.g., in the form of SO₂ or other sulfate precursors) into the stratosphere have been aircraft, artillery, balloon-held hoses, and upward mixing and then stratospheric oxidation of tropospherically inert carbonyl sulfide (NAS 1992, Lane et al. 2007). A number of alternative stratospheric approaches have also been proposed, including use of microscopic corner reflectors (Canavan and Teller 1991, Teller et al. 1997) and small balloons (NAS 1992), as well as injection of self-levitating particles into the mesosphere (Keith 2008b).

One obvious advantage of lofting reflecting materials into the stratosphere or higher is that they would be expected to stay aloft for a year or longer, and much longer if lofted into the mesosphere. Another advantage is that the reflection of solar radiation takes place above the screening that would occur with clouds, ensuring the maximum effect per unit of aerosol mass. At the same time, materials lofted this high and staying in the atmosphere for extended periods tend to spread out to cover the globe. As a result, both their climatic influences and any unintended side effects (e.g., increased scattering of incoming solar radiation that diminishes the efficiency of direct-beam solar energy technologies) tend to be global in extent. While significant uncertainties remain and each of these approaches would introduce scientific and technological issues and challenges (e.g., Rasch et al. 2008b, Robock 2008a, 2008b, Robock et al. 2009, Hegerl and Solomon 2009), the cost of injection of the materials is estimated to be relatively low compared to the cost of reducing greenhouse gas emissions by enough to have a comparable radiative influence (NAS 1992, Barrett 2008).

It is increasingly being recognized that the rapidly changing climate and the possibility of approaching thresholds provide a strong rationale for undertaking a significant research program on the potential for geoengineering approaches to slow or reverse climate change (e.g., Shepherd et al. 2009). While most such studies have focused on reducing global average temperature as the metric, the focus of this letter will be on approaches that have the potential to be targeted toward specific regions or consequences of global climate change, seeking to moderate the worst outcomes as global energy and economic systems are transformed to be climate neutral. As described in section 3, among the particularly severe consequences of climate change and emissions mitigation that geoengineering might be able to beneficially moderate are the rapid warming of the Arctic, the intensification of tropical cyclones and drought, and the loss of the cooling offset presently provided by sulfate aerosols.

That human interventions can lead to large changes in forcing and climate in particular regions has been made clear in several studies (e.g., Hansen et al. 2005). As an example from geoengineering studies, Caldeira and Wood (2008) demonstrate that limiting solar radiation absorbed in the
Arctic would have the strongest influence in that region. For tropical cyclones, the temperatures of ocean waters that they pass over have an important influence on their intensity (e.g., Santer et al 2006, Emanuel 2008), suggesting that reducing sea surface temperature in particular regions has the potential to moderate the projected increase in the likelihood that such storms would grow into the most intense categories.

Going back at least to studies by Namias (1977, 1978), it also appears that storm tracks, at least across the Pacific Ocean, are affected by patterns of ocean temperature anomalies. Changes in equatorial Pacific sea surface temperatures as part of the El Niño/Southern Oscillation are also known to redirect storm tracks (Latif et al 1998). Although all of the responses and relationships governing the hydrologic cycle response are not intuitively obvious and uncertainties remain (e.g., Held and Soden 2006), intervening to alter seasonal average sea surface temperatures in particular regions by up to a few degrees, thereby creating gradients over the ocean or with adjacent land areas, merits investigation to determine, for example, if prolonged drought (or flooding) could be moderated.

Geoengineering approaches affecting the stratosphere, troposphere, and surface each have the potential to cause significant changes in solar absorption over limited regions. Robock et al (2008) considered the case of aerosol injection into the polar regions and found, for example, strong cooling in that region, but also a diminished monsoon intensity as a result of land surface cooling in lower latitudes. In a related study, Tilmes et al (2008) found that augmenting the aerosol burden in the Arctic stratosphere led to springtime ozone reduction, introducing another potential side effect of considerable importance.

A limitation of both studies, however, was their presumption that the aerosol loading in the polar stratosphere would be increased on a year-round basis. From a geoengineering perspective, injecting aerosol precursors year-round fails to take advantage of the fact that the aerosols can only affect solar radiation when the Sun is significantly above the horizon (which is also after the time of year when the ozone layer could be significantly affected). To generate a global aerosol loading, year-round injection is important because the aerosols are spreading and the aerosol lifetime is roughly a year (Robock et al 2008). For the case of an Arctic injection into the lower polar stratosphere, however, Robock et al (2008) determined the aerosol lifetime to be only two months. If this is the case, and the time could likely be adjusted up or down by altering the height or exact location of the injection, injection only during the sunlit months should be adequate to build up the needed summertime aerosol layer. The effect could even be fine-tuned, building up and phasing down the injection in conjunction with the changing solar zenith angle to generate a time-dependent radiative effect over the sunlit period (e.g., it might be desirable to have a low loading in the spring when the snow albedo is high and a larger loading in the summer after the surface albedo has been reduced by surface melting).

Although there are potentially important uncertainties relating to the particle size and radiative influence for injections of various types and at various rates (Rasch et al 2008a, 2008b), limiting the injection to the months when there is sufficient sunlight would seem to suggest that essentially the same reduction in heat uptake in the Arctic could be achieved with roughly a third as much aerosol as was used in the 3 Mt SO$_2$ yr$^{-1}$ injection examined by Robock et al (2008). Cutting the injection by a factor of three would likely reduce dispersion of the SO$_2$ to mid-latitudes and possibly make at least some side effects less likely. A wider range of unintended consequences of such injections, however, do need to be investigated, including changes in the higher moments of atmospheric behavior (i.e., the weather and its variability) and how humans and ecosystems might be affected, as Kravitz et al (2009) have started to do. In addition to focused modeling studies, significant information can likely also be gained through cases studies of high-latitude volcanic eruptions (e.g., Oman et al 2005, Izrael 2008), field experiments involving injection of relatively small amounts of tracers, natural (anti) analogs such as the decrease in SO$_2$ emissions in Europe and North America, and even significant injections of SO$_2$ or other aerosol precursors for a few weeks from a few locations during Arctic spring and summer.

While there are important uncertainties regarding the magnitude of the aerosol influence (e.g., Forster et al 2007), both direct (i.e., aerosol scattering) and indirect (i.e., cloud brightening) processes contribute to reducing absorption of solar radiation. As a result, the cooling influence of sulfate aerosols is effective under a wide variety of weather conditions. Indeed, the central estimate is that the present loading of sulfate aerosols exerts a cooling influence that offsets ~40% of the present warming influence of the human-induced increase in the concentrations of greenhouse gases (Forster et al 2007). Because the SO$_2$ emissions are primarily in the Northern Hemisphere, the cooling influence is also; indeed, detection–attribution studies suggest that it was the cooling influence of sulfate aerosols during the mid- to late-20th century that was enough to counterbalance the warming influence of the rising CO$_2$ concentration in the Northern Hemisphere until the 1970s (Hegerl et al 2007).

Bower et al (2006) and Salter and Latham (2007) have proposed an alternative approach for reducing absorption 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 cloud droplets. Injection of cloud condensation nuclei would be from a fleet of uniquely designed, wind-propelled vessels that would sail beneath marine stratus cloud decks spraying a mist of seawater out the top of their masts (Salter et al 2008). Natural convection would be used to carry a substantial fraction of the mist (or at least the cloud condensation nuclei (CCN) that are critical to cloud brightening) up into the low-level clouds. This approach builds upon observations 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.

Although marine stratus clouds are the most common cloud type over the oceans, this approach is potentially only effective under particular weather conditions. A modeling study by Latham et al (2008) suggests that, with global implementation, a significant global cooling influence could be created. For regionally focused applications, the advantages
the surface albedo. Several suggestions have been made about how best to accomplish this. For land areas, covering the surface with a more reflective material is conceptually possible. The problems, however, include that the open areas tend to be quite arid and already have a relatively high albedo, making it necessary to cover very large areas (e.g., Gaskill and Reese 2003), and that darker areas like forests and urban areas are both intensely utilized and not readily made more reflective. In addition, imposing a large change in the energy balance in particular locations would likely affect regional weather, creating more important side effects than for the much smaller changes in albedo over much larger areas than would result from tropospheric and stratospheric aerosol injections or cloud brightening. As a result, except for special situations, approaches based on increasing land surface albedo seem likely to be either modest (Akbari et al 2009) or unacceptable.

For ocean areas, a continental-sized area would need to be covered by floating reflectors to have a large enough influence to offset global climate change. Such an approach would, as a result, be likely to impose significant ecological and meteorological impacts (Leemans et al 1995). Mimicking the processes that make ship wakes more reflective than undisturbed ocean waters, Seitz (2009) has proposed increasing ocean albedo by having a fleet of ships inject very large numbers of very small bubbles over very large areas. Like the CCN injection approach for clouds, the effect would be expected to last a few days. In that this approach is only applicable in clear sky areas, it would complement the cloudy sky approach of Salter and Latham (2007), such that one might imagine a ship that lofted spray upwards under cloudy conditions and injected bubbles downward under clear sky conditions. Both approaches are being tested by different groups in the laboratory and, based on these results, are likely to be tested in limited field experiments.

There are a few additional surface-based approaches that might be used to bring about changes in particular regions. Lovelock and Rapley (2007) propose an array of wave-powered pipes to vertically mix surface and deeper waters over large areas, while Bowers et al (2009) have recently filed for a patent on a related approach to mix warm surface waters with cooler waters only up to a few hundred meters below the surface. Bowers et al (2009) envision, for example, deploying enough of these devices to cool an area roughly the size of the Gulf of Mexico in order to moderate hurricane intensification. A problem with these approaches, however, is that the cooling is not generated by reducing the amount of absorbed solar radiation, but rather by mixing energy down into the ocean, which would tend to sustain and even enhance both global warming and sea level rise.

Other even more specific approaches proposed over the past several decades include damming rivers or narrow straits in order to alter ocean currents and river flows in ways that would alter ocean temperature, salinity, and/or stability. These approaches are not, however, considered in this discussion as they are generally only applicable in very fixed and limited areas.

3. Impact intervention: focused application of geoengineering approaches

With the changes in climate already causing significant impacts and with reductions in global emissions of greenhouse gases and black carbon sufficient to stabilize the climate very likely to take many decades, this section focuses on the potential for geoengineering to address three particular aspects of the climate change challenge. Each could lead to impacts that are so severe that their alleviation likely has the potential to be of greater importance to society than the cost and intergenerational burden of researching, implementing, and sustaining the proposed intervention. Each of the three objectives, if they could be accomplished without inducing significant side effects, would moderate particularly severe outcomes:

1. Limit the likelihood of extreme conditions in the sub tropics: specifically, consider the potential for limiting:
   (a) the projected increase in the likelihood that tropical cyclones will intensify to the highest categories; and
   (b) that wintertime storm tracks in the eastern Pacific will lock into patterns that contribute to sustained drought.

2. Offset the amplified changes in climate occurring in high latitudes: specifically, consider the potential for limiting:
   (a) warming of the Arctic and the associated loss of sea ice and melting of mountain glaciers; and (b) deterioration of the Greenland and Antarctic Ice Sheets and their potentially inundating contribution to sea level rise.

3. Offset the significant global warming that will be associated with the reduction in SO2 emissions and sulfate aerosol loading resulting from sharply reducing CO2 emissions from coal-fired power plants.

Although the areas listed are not the only choices that could be made, they do encompass activities focused on the disruption being caused by climate change in a particular region, by a particular type of event, and inadvertently as a result of shifting to alternative sources of energy. Because these choices do have the potential to moderate very negative impacts (e.g., reducing water resources, reducing biodiversity, and increasing the pace of sea level rise and global warming) affecting both the immediate region and the global community, consideration of the important and complex ethical, legal, and social issues may be more straightforward to address than would be the case for global geoengineering, which would seem more likely to have winners and losers. Whether this relative weighting will actually be the case and be sufficiently convincing to be able to move toward implementation needs to be carefully evaluated through an international research and analysis effort.

While meeting any of the particular objectives would very likely be beneficial to society and the environment, even achieving all of the objectives would not be a substitute for
aggressive mitigation. First, none of these strategies would deal with the very important issue of ocean acidification that will occur as a result of the rising CO$_2$ concentration itself (Caldeira and Wickett 2003). While not considered in this letter, geoengineering approaches focused on limiting the rise in the atmospheric CO$_2$ concentration merit separate and independent research and development. Second, the actions proposed in this letter only have the potential to slow the onset of some of the irreversible consequences of global climate change; mitigation is required to truly reduce their ultimate likelihood. Third, each of the strategies would impose an obligation on future generations to continue the proposed interventions. There are, therefore, impelling moral and ethical arguments for reducing emissions as rapidly as possible in order to avoid having to continue geoengineering far into the future. Although geoengineering is not an ultimate or independent solution to the challenge of global climate change, its potential to moderate, or at least delay, some of the worst outcomes would seem, however, to merit consideration.

3.1. Moderating the intensity of subtropical extremes

The additional energy trapped by the rising concentrations of greenhouse gases tends to increase evaporation and the onset of drought, increase the amount of water vapor held in the atmosphere, and increase the fraction of rainfall occurring from intense convective storms (Meehl et al 2007). On the global scale, there is a poleward extension of the subtropical regions where descending air tends to suppress precipitation, except generally during intense storm or monsoonal conditions. Even though the critical temperature increases with global warming and the increasing CO$_2$ concentration tends to stabilize the atmosphere, warming of subtropical ocean waters appears to increase the likelihood of intense tropical cyclones (e.g., Knutson et al 2009). Warming-induced changes in atmospheric circulation and variability are also projected to leave subtropical regions such as the southwestern United States excessively dry (Christensen et al 2007), contributing in turn to significant reductions in water resources and a greater likelihood of wildfire.

In addition to contributing to storm intensification, ocean warming can also lengthen the period during which sea surface temperatures are sufficiently warm for this to occur. That climate change is leading to warmer ocean waters and increasingly destructive storms is becoming increasingly apparent. Santer et al (2006) found that human-induced climate change is the likely cause of rising ocean temperatures in the regions where hurricanes in the North Atlantic basin tend to intensify. Associated with these changes, a larger fraction of tropical cyclones is developing into the more intense storms (Trenberth and Jones 2007), and the total destructive power of these storms is rising (Emanuel 2005).

Damage and inundation along coasts and in inland river valleys is also rising (Swiss Re 2009, Munich Re 2004), especially, but not solely, to the higher populations and more expensive development in coastal areas (Pielke et al 2008, Anthes et al 2006). With sea level also rising, intensification of tropical cyclones is likely to lead to even higher wind speeds and storm surges in the future, resulting in greater coastal inundation and damage, including to areas not previously considered vulnerable. Combined with the greater likelihood of very intense rains inland, especially in hilly and mountainous regions, climate change is very likely to increase the potential for tropical cyclones to inflict significant death and destruction on many low-lying islands, vulnerable coastlines, and inland valleys.

Initial attempts to moderate hurricane development focused on reducing the strength of such storms after they had formed and developed (Fleming 2004). Experiments conducted roughly 50 years ago sought to determine if seeding near-eyewall clouds in hurricanes would modify their track or intensity so that major urban centers could be protected. These experiments were generally unsuccessful, both as a result of observational and theoretical limitations. However, with the recent availability of new, very high-resolution hurricane models, theoretical studies are beginning to provide greater insight into the factors controlling storm development, track, and intensification.

Rather than modify the atmosphere, Bowers et al (2009) propose to cool the surface ocean ahead of specific storms. The challenges to responding in this way, however, are that predicted storm paths can cover large areas, the predictability of storm intensification is limited, there is a relatively short time window to act, and the storms have so much energy that altering them requires large interventions over short times. Narrowing the goal to preventing the most intense storms from striking major cities would limit the size of the area where temperatures would need to be reduced, but would also leave coastal areas outside the protected areas still exposed.

As an alternative to moderating the strength of a particular storm, redirecting a storm’s path has been proposed in order to moderate destruction and damage. Although being able to do this is still only a theoretical possibility, modifying an approaching weather system in a modest way (perhaps by cloud seeding) might be able to increase the likelihood that a particular tropical cyclone could be pushed out to sea, or at least away from a major population center (e.g., see Fleming 2007). A key problem with relying on such an approach, however, would be its dependence on having a high degree of predictability of both the particular storm and surrounding weather systems out to several days, and this is quite problematic given limitations in observations, theory, and models.

A more practical, although still challenging, approach to limiting storm intensification would seem to be to limit the annual accumulation of energy stored in the upper ocean (e.g., in the Caribbean Sea, Gulf of Mexico, Bay of Bengal, Philippine Sea, etc). Basically, the idea would be to modestly reduce the rate of solar absorption and energy storage over a large area for many months rather than try to exert a large influence on a particular storm over its short lifetime. In principle, such interventions could be accomplished by:

1. Reducing the amount of solar energy reaching the ocean surface by brightening marine stratus clouds using the approach of Salter and Latham (2007) and Latham et al (2008);
are leading to increased release of CO2 and methane, thus warming soils and local infrastructure. Impacts in the Arctic are also amplified high-latitude warming (ACIA 2004). For example, The Arctic is already experiencing adverse impacts from sea level rise

3.2. Limiting high-latitude warming and its contribution to sea level rise

The Arctic is already experiencing adverse impacts from amplified high-latitude warming (ACIA 2004). For example, sea ice retreat is threatening the life cycles of key species and allowing wave erosion of long-inhabited barrier islands, and permafrost warming and thawing are disrupting ecosystems and local infrastructure. Impacts in the Arctic are also contributing to larger scale impacts. Of particular long-term significance for the global community, warming soils are leading to increased release of CO2 and methane, thus intensifying the global greenhouse effect, while melting glaciers and ice sheets are contributing to both additional warming and sea level rise. For Northern Hemisphere mid-latitudes, reduced Arctic Ocean sea ice cover, particularly through the fall and early winter, limits deep chilling of the overlying air to such an extent that, as it spreads to mid-latitudes, the location and intensity of its collision with moist, subtropical air, particularly over central North America, are changing. In that it these air mass interactions that generate, for example, the weather of eastern North America, the warmer Arctic is leading to milder autumn weather and delayed onset of winter over much of the region (ACIA 2004, MacCracken 2008, GCCCIUS 2009).

Global warming is also increasing loss of ice from the Greenland and Antarctic ice sheets (Lemke et al 2007). Although the best estimates of model simulations calculating the effects of climate change on the surface moisture budgets of the ice suggest that they should suffer no net loss through the 21st century (Meehl et al 2007), satellite observations suggest that both ice sheets are currently losing mass (Rignot et al 2008a, 2008b).

As a consequence of the anomalously cold 1960s in taking actions that would warm the Arctic by melting sea ice (e.g., see Weart 2004), the approaches for preserving and even restoring sea ice extent and thickness will necessarily be quite different. That a relatively modest reduction in solar radiation could have a useful restoring influence is suggested by how rapidly sea ice extent has been changing over the past few decades when the increases in greenhouse gas concentrations have led to an increase in the radiative flux of only a few tenths of a W m−2 (Forster et al 2007). That there has been an even greater reduction in sea ice extent than calculated in model simulations may be a result of the decrease in Arctic haze that has occurred due to reductions over the past few decades in sulfate loading as a result of the decrease in SO2 emissions from power plants in Europe and the former Soviet Union (Quinn et al 2007). Modeling of the contributions of individual forcings to warming done by Shindell and Faluvegi (2009) suggest that increased forcing due to increasing deposition of black carbon has also likely been playing a role, although data from Alert and some other Arctic observing stations suggest that black carbon deposition has actually been decreasing over the period that sea ice retreat has been accelerating (Quinn et al 2007).

Reducing incoming solar radiation seems likely to be the most practical approach for reversing the loss of sea ice. The proposed reduction in solar radiation could potentially be accomplished by increasing the aerosol loading of the stratosphere or troposphere. Increasing the reflectivity of marine stratus in or near the Arctic (Salter and Latham 2007) or using bubbles or other approaches to increase the surface albedo of the open water areas in the region (Seitz 2009) might also be approaches to cooling the Arctic.

For stratospheric injections (Rasch et al 2008a), the altitude and timing of injection could be chosen to ensure that most of the aerosols would be aloft only during the sunlit months, thereby limiting their potential contribution to intensification of springtime ozone depletion. Calculations by Caldeira and Wood (2008) indicate that reducing radiation north of about 60°N by about 10% or north of 70°N by 25% would offset the greenhouse-gas-induced warming of a full CO2 doubling. Studies by Robock et al (2008) that actually injected SO2 to form sulfate aerosols generated similarly strong cooling for a loading of 3 Mt yr−1 of SO2, although essentially the same effect could, as indicated earlier, likely be created with an injection of a third of this amount concentrated during the sunlit season. To offset only the warming and ice melt of the last few decades, an injection of several tenths of a Mt of SO2 per year might well be sufficient. That Kravitz et al (2009) found that injections of megaton-level amounts of SO2 per year would lead to loadings and deposition significantly below present rates, suggests that the tropospheric injections proposed here would also not create significant ecological impacts.
Augmenting tropospheric aerosol loading could also be used to reduce solar absorption in the region, basically acting to deliberately restore the most reflective components of the Arctic haze that have been removed over the last several decades as a result of clean-up of air pollutant emissions (Quinn et al 2007). The primary advantages cited for augmenting the stratospheric rather than tropospheric sulfate loading have been that the lifetime of stratospheric aerosols average about two orders of magnitude longer (i.e., roughly 500 days versus 5 days), and that this more than offsets the increased cost of lofting aerosol precursors into the stratosphere. However, for a polar rather than a global application, the advantage of stratospheric over tropospheric injection is greatly reduced or even reversed. One factor of 10 is erased because the lifetime of aerosols in the lower polar stratosphere is roughly two months (Robock et al 2008). Another factor of several can be made to go away by extending the average lifetime of aerosols injected into the troposphere by limiting injection to weather situations and locations where rainout and dry deposition are minimized. Another factor of a few in cost could be overcome by releasing the SO$_2$ or sulfate precursors from either low mountains or through hoses that extend up to about a kilometer. In addition, limiting injection to months of the year when the Sun is above the horizon would increase the relative effectiveness of the amount injected, although likely differences in the rate of conversion of aerosol precursors to sulfate need to be considered.

The shorter lifetime of tropospheric aerosols would also allow closer matching of the injection to the desired change in forcing. In situations where the surface and troposphere are convectively coupled, injection of aerosols that are darker than the surface would be expected to generate warming. However, in stratified conditions, this is not strictly the case. Calculations to estimate the optimal timing and quantity of tropospheric injections (e.g., not injecting when surface albedo is high) have yet to be done, but the objectives would be to promote later surface melting in the spring, less uptake of solar radiation in the summer, and earlier and more extensive formation of sea ice in the fall. Delaying the start of the melt season and generally increasing the presence of sea ice would activate snow and ice albedo feedback mechanisms, thus taking advantage of a natural process to further limit absorption of solar radiation.

Given that the injection would be done during only about a third of the year and only for wind trajectories heading into the Arctic, the amount injected would very likely be a small fraction of recent emissions from coal-fired power plants in the Eurasian region, so well within recent experience. If snow and ice albedo feedbacks are activated, strong aerosol injection every few years might adequately promote Arctic cooling so that the additional sea ice would persist for several years, thus alleviating the need for aerosol injections every year. In addition, the longer duration of sea ice would extend the time during which the overlying air would be significantly cooled, thus sustaining the Arctic ‘air conditioner’ (ACIA 2004) and tending to restore traditional weather patterns, especially over North America (MacCracken 2008).

From the global perspective, the most critical impact resulting from warming in the Arctic is very likely going to be the increase in sea level resulting from, initially, the melting of mountain glaciers and, over the long-term, from the loss of ice mass from Greenland. Interestingly, Caldeira and Wood (2008) found that, while solar radiation management could be used to return the region’s temperature and sea ice cover to preindustrial or mid-20th century conditions, the regional increase in precipitation projected by models to result from global warming would persist because cooling the Arctic would not substantially reduce the warming of mid- and low-latitude ocean waters where most evaporation reaching the Arctic takes place. As a result, greater than baseline amounts of precipitation would be expected. With polar temperatures decreased, the increased precipitation would be more likely to fall as snow, possibly reversing the region’s loss of ice from the melting of mountain glaciers and the Greenland Ice sheet.

For the Greenland and Antarctic ice sheets, however, the most important loss term in the future is expected to result from acceleration of ice stream movement, particularly for ice streams terminating in ocean waters. For these ice streams, warming ocean waters appear to be the primary factor affecting their movement (Bindschadler 2009). This is the case, for example, for the Jakobshavn Glacier on the west coast of Greenland, which is retreating back up a fjord that connects Baffin Bay to the interior of Greenland. This connection is important because interior Greenland is below sea level because of the enormous weight of the ice sheet. It is the potential access of ocean waters to a bottom- resting ice sheet at several locations for both the Greenland and Antarctic ice sheets that recently led Bindschadler (2009) to give a best estimate for the two ice sheets to contribute 1.0 ± 0.5 m to global sea level by 2100 due to dynamical processes alone. This amount would be in addition to the 0.2–0.6 m estimated by IPCC as likely to result from thermal expansion, melting mountain glaciers, and the surface mass budget of the ice sheets.

To significantly slow the rate of sea level rise and reduce the likelihood of ice sheet collapse, a critical research question is whether geoengineering approaches could be used to cool the ocean waters that are contributing to the destabilization of the ice streams? The bubble injection approach suggested by Seitz (2009), for example, might be able to be used to increase the summertime albedo of nearby ocean waters that are expected to come in contact with the ice streams, so in the fjord areas and beyond. Alternatively or in addition, the cloud brightening approach of Salter and Latham (2007), which can be quite locally applied, could be used to reduce penetration of sunlight to the ocean surface in these regions. By breaking up sea ice, icebreakers could also be used to reduce the insulating effect of sea ice, increasing heat loss from underlying ocean waters. Given the potential impacts if significant mass is lost from the ice sheets, an aggressive effort to investigate possibilities seems clearly merited.

While intentionally modifying the climate is inherently controversial (Robock 2008a, 2008b; Hegerl and Solomon 2009), Arctic geoengineering has the potential to offer significant benefits to those both within and outside the region. In that the Arctic Ocean’s biological activity depends on cold temperatures, returning the Arctic to a colder state
would likely be beneficial for existing species (e.g., polar bears, seals, etc), although the environmental impacts of reductions in solar radiation do merit investigation (e.g., by evaluating the response of the region’s species and ecosystems to high-latitude volcanic eruptions). Keeping the Arctic cold would also help to sustain Indigenous cultures (ACIA 2004) and the region’s unique appeal to those who have chosen to live there. The main foregone benefit of warming would likely be reduced economic development based on the region’s mineral resources, although the associated thawing of the permafrost greatly complicates their transport across the terrestrial landscape.

For the international community, the most important benefits would likely include a reduced rate of sea level rise, reduced release of CO2 and CH4 from permafrost and ocean sediments, sustaining of the cooling effect of the Arctic on mid-latitude weather, and the preservation of northern habitats for many migrating species (ACIA 2004), whereas forgone benefits include shorter shipping routes and easier access to resources beneath and ashore from the Arctic Ocean.

To further investigate potential interventions, more detailed modeling experiments are needed, working toward protocols for initial field experiments. Among the questions to be investigated is how the cooling of one polar region rather than both might affect the global atmospheric circulation, including the positioning of the inter-tropical convergence zone (although such an effect might be compensated by reducing uptake of solar radiation in the high latitudes of the Southern Hemisphere). Additional research is also needed on the most practical, effective, and economic approaches for reducing absorption of solar radiation, on the comparative use of sulfate aerosol precursors and of alternative materials that might lead to less scattering of the incoming solar beam, on the regional pattern and timing of interventions that would be most effective for the particular objective, and on associated effects on the weather, ecosystems, and accumulations of ice and snow.

Complementing the Arctic studies, consideration is also needed of what could be accomplished by applying similar approaches in the high latitudes of the Southern Hemisphere, focusing especially on how best to sustain the Antarctic Ice sheet. Given the difference in the geographic setting, with the Southern Ocean surrounding a polar land mass and supplying moisture to it, interventions are likely going to be different, although cooling ocean waters near ice shelves is likely an approach deserving early attention.

3.3. Sustaining the global aerosol cooling offset

At present, the emission of SO2 from coal combustion is leading to a global sulfate burden that is exerting a cooling influence of about 1.1 W m⁻², reducing the net warming influence from the combination of greenhouse gases and land cover change from about 2.8 to about 1.7 W m⁻² (Forster et al 2007). Were the climate at equilibrium with the current human-induced forcings, the sulfate aerosol loading would be masking about 1 °C of warming. As a result, if mitigation efforts ended all CO2 emissions (at least from coal-fired power plants), the associated SO2 emissions would also be expected to go to zero. Because the lifetime of sulfate aerosols in the atmosphere is roughly a week, whereas the lifetimes of the CO2, N2O and halocarbon perturbations tend to be many centuries, the cooling offset of the present sulfate loading would be lost relatively quickly once emissions ended. A calculation done with the MAGICC code of Wigley (2008) indicates that eliminating the sulfate loading would be roughly equivalent to an instantaneous increase in the global CO2 concentration of about 100 ppm. Exposed to the full warming influence of the elevated greenhouse gas concentrations, it would be virtually impossible for emissions control measures to limit global warming to 2 °C.

Geoengineering may offer the opportunity to sustain the aerosol cooling influence, but with much lower emissions and, therefore, considerably reduced side effects. In that most of the cooling influence of sulfate aerosols has been in the Northern Hemisphere, exerting a similar latitudinal effect could be accomplished by injection of stratospheric or tropospheric aerosols, perhaps increasing the Northern Hemisphere loading more than the loading of the Southern Hemisphere¹. The increased aerosol loading, particularly in the case of the globally spread stratospheric aerosols, would tend to whiten the sky worldwide, adversely impacting the performance of solar technologies relying on the direct solar beam and affecting the biosphere in ways not fully understood, though possibly leading to additional forest uptake of carbon and changes in the mix of species because sunlight would reach lower into the forest canopy (Mercado et al 2009). While sulfate aerosols injected into the troposphere would have a shorter lifetime than those injected into the troposphere, the cost of lofting aerosols (or aerosol precursors) would be significantly less for 1 km injections as opposed to 15–20 km injections. In addition, there would be a reduced presence of the aerosols over populated continental areas and the increase in the albedo resulting from tropospheric aerosols would likely be greater than for stratospheric aerosols because of their cloud brightening effect.

An important consideration would be choosing the locations for the emission of aerosols (or aerosol precursors) for maximum effect. For much of the 20th century, the SO2 emissions were emitted mainly in the countries bounding the North Atlantic; more recently, most of the emissions are coming from China and southeastern Asia. In each of these regions, having the emissions concentrated in small regions has caused significant health problems, acid deposition, and visibility impairment. There is no reason to conclude that the present or past locations, patterns, and amounts of SO2 emissions have been optimal for exerting a cooling influence on the climate—indeed, the pattern of emissions has likely exerted a near maximum negative impact on health.

By augmenting sulfate aerosols (or their precursors) in remote regions of the troposphere, the goal would be to

¹ An as yet unexplored possibility might be to inject aerosols into particular locations for a few weeks during particular seasons, creating a latitudinal band or pattern of high aerosol loading that would create a temperature gradient and thus affect atmospheric circulation. That doing something like this might work is suggested by the studies indicating that changes in solar UV radiation can affect stratospheric circulation in ways that affect the weather, excite or diminish particular oscillations, and even alter the climate of the troposphere (Balachandran et al 1999, Rind et al 2005).
optimally maintain, or even enhance, the cooling influence that offsets at least some of the warming influence of the growing concentrations of greenhouse gases. Augmenting sulfate loading over the mid-Pacific and Indian Oceans could increase the efficiency of the aerosol layer due to the elevated sun angle and low surface albedo, while creating only a small increment to acid deposition. Whether the associated increased scattering of the solar beam would affect marine life and upper ocean conditions merits investigation, perhaps initially by evaluating the effect of changes in light scattering as SO₂ emission sources have shifted from the North Atlantic region to southeastern Asia.

Although not ideal because darker aerosols also tend to be emitted, the SO₂ could be emitted from the elevated stacks of coastal power plants, for example in China and India. A more effective approach, however, would likely be to emit the SO₂ or other aerosol precursors from mountains or through elevated hoses that are located on remote islands in the central Indian and Pacific Oceans where there are relatively few people and the average zenith angle is high. Emissions would be significantly less than associated with current fossil fuel emissions and deposition would be spread over a much larger area, so ecological impacts would likely be less than at present. The advantages of using the approach based on tropospheric injection of sulfate aerosols (and/or precursors) rather than the Salter and Latham (2007) cloud brightening approach would be that the former would exert an influence in both clear and cloudy skies and that dispersal would be easier because of the longer atmospheric lifetime of sulfate as compared to CCN. The advantages of the Salter and Latham (2007) approach would be that there would be no injection, and therefore deposition, of sulfur compounds, and that, if the ships could be constructed to emit microbubbles during clear sky conditions, the ships could create a larger effect for roughly the same investment.

Focused modeling and enhanced observation programs could provide significant insights. Associated research should also be initiated to evaluate 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). In addition, consideration should also be given to any alternative approaches for reducing solar absorption.

4. Concluding thoughts

The increasing pace of human-induced climate change has created a serious predicament for the world. Drastically reducing the world’s use of fossil fuels seems likely to take time and, although promising long-term savings (e.g., Stern 2007), may raise near-term energy costs. As a result, global warming is likely to press up against or even exceed the 2°C level that the Commission of European Communities (CEC 2007), for example, has concluded is likely to lead to dangerous and unacceptable consequences.

With technology having set climate change in motion, proposals to undertake geoengineering as a counterbalance to human-induced global warming naturally raise a number of important and complex questions (Robock 2008a, 2008b, Victor 2008, Blackstock et al 2009, Shepherd et al 2009, Hegerl and Solomon 2009). Is geoengineering really possible? Can all or most adverse impacts from combustion of fossil fuels really be offset? What confidence does the scientific community have in its understanding of geoengineering and its impacts? How much would geoengineering cost up front and over time? Are there beneficial or problematic side effects? What if geoengineering is started and it does not work as expected—what is irreversible and what is not? Does geoengineering lead to winners and losers? What are the optimal conditions for the Earth—and, if they exist, would they simultaneously be optimal for all peoples, for society, and for plants and wildlife? Who would get to decide? Once geoengineering started, how long would it have to continue? How soon do decisions about geoengineering have to be made? Who would pay for and carry out the geoengineering efforts?

Is it appropriate to take additional actions to modify the climate, even if the intent is to moderate the negative impacts of greenhouse-gas-induced climate change? And beyond the scientific, engineering, economic, and legal aspects, moral and ethical aspects of geoengineering, for us today and for future generations, need to be considered.

With little geoengineering research going on, important uncertainties exist and understanding of potential risks and possibilities is relatively limited. Early studies suggest that some approaches have the potential for limiting warming, but also suggest the potential for important side effects. Initiating a significant long-term research program is essential. Drawing from the range of possible geoengineering approaches, this letter suggests three specific focuses for the initial phase of this effort, choosing objectives that can be expected to be viewed as generally beneficial, if they can be accomplished without substantial adverse side effects. Insights gained from such research would not only build the knowledge base for their possible implementation, but also provide a more-informed basis for considering the viability and ramifications of global-scale geoengineering, especially if global climate change reaches the emergency level mentioned in recent reviews (Shepherd et al 2009).

What is most clear from review of the various geoengineering options is that returning the climate to its undisturbed state would be very difficult, if possible at all. Therefore, especially in light of the close coupling of society and the environment to the present climate (IPCC 2007b, Stern 2007) and the increasing seriousness and imminence of potentially catastrophic impacts, sharply reducing the increasing emissions of greenhouse gases is essential, even presuming geoengineering approaches might offer some help in limiting the most adverse outcomes. What geoengineering has the potential to contribute is to expand the set of possible tools for pursuing, even if only temporarily, the UNFCCC’s objective of preventing ‘dangerous anthropogenic interference’ with the climate system. That is, geoengineering may actually be able to keep the increase in temperature below a specified
level and have adverse side effects less severe than would be the case without intervening. Because of its many implications for society, transforming geoengineering into a plausible policy option will also require a strong research effort encompassing studies on socioeconomic and political governance and ethical and legal concerns (e.g., Wigley 2006, Barrett 2007, Victor 2008, AMS 2009).

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 shelve the peak change in climate and increase the likelihood that the most adverse and irreversible environmental and societal consequences will not be triggered. Continued delay in sharply cutting emissions, however, will lead not only to more severe impacts, but likely also to the need to implement global-scale geoengineering for a number of centuries. Despite its potential, the risks and necessary long-term commitment associated with geoengineering would seem to strengthen the case for seriously addressing the climate change issue with a much more aggressive energy research and emissions control effort by all nations (e.g., see Hoffert et al 2002, IPCC 2007c).

Rather than being considered a complement to mitigation that would allow a slower pace for emissions reductions, geoengineering is more appropriately a complement to adaptation and the building of resilience. While perhaps having the potential to serve as an insurance policy against truly catastrophic impacts (DOE 2001, Blackstock et al 2009), waiting until such impacts have begun would likely mean that the geoengineering intervention would need to be very intrusive, probably making the likelihood of adverse and disruptive side effects higher than if geoengineering were begun earlier and successful in moderating the most extreme impacts.

Through focusing consideration of geoengineering on specific objectives and carefully matching geoengineering approaches to the desired outcomes, the proposals in this letter are intended to provide a framework for moving forward with a strong research program directed at near-term implementation. By proposing to use emerging capabilities to deal directly with the most adverse consequences of climate change as opposed to simply surrendering to them, this approach may offer the potential of more easily facing and reconciling the many perspectives raised regarding the need for and appropriateness of geoengineering as an option for dealing with climate change. While serious questions and uncertainties remain, might focused geoengineering possibly be a middle ground in a world of increasing extremes?

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