Global and Arctic climate engineering: numerical model studies

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We perform numerical simulations of the atmosphere, sea ice and upper ocean to examine possible effects of diminishing incoming solar radiation, insolation, on the climate system. We simulate both global and Arctic climate engineering in idealized scenarios in which insolation is diminished above the top of the atmosphere. We consider the Arctic scenarios because climate change is manifesting most strongly there. Our results indicate that, while such simple insolation modulation is unlikely to perfectly reverse the effects of greenhouse gas warming, over a broad range of measures considering both temperature and water, an engineered high CO2 climate can be made much more similar to the low CO2 climate than would be a high CO2 climate in the absence of such engineering. At high latitudes, there is less sunlight deflected per unit albedo change but climate system feedbacks operate more powerfully there. These two effects largely cancel each other, making the global mean temperature response per unit top-of-atmosphere albedo change relatively insensitive to latitude. Implementing insolation modulation appears to be feasible.

Keywords: climate engineering; geoengineering; climate; Arctic; albedo

1. Introduction

We are now, or soon will be, confronting issues of whether, when and how to engineer a climate that is more to our liking. If a decision is made to move ahead with climate engineering, those engineering the hardware of a climate engineering system seemingly would be asked to produce a system that balances the several costs of system implementation with the various benefits of achieving various distinct patterns of additional climate forcing. This requires an understanding of how the climate system would respond to different kinds and patterns of climate forcing. Here, we present results of idealized simulations using computer-based climate models as initial steps towards a broader analysis of how various changes in radiative forcing may be engineered to affect climate.

The Earth’s near-surface environment is warming rapidly (IPCC 2007). Arctic sea ice is disappearing at rates greater than previously observed or predicted (Kerr 2007) and the southern part of the Greenland ice sheet may be at risk of

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collapse (Christoffersen & Hambrey 2006). The oceans are acidifying (Caldeira & Wickett 2003) and coral reefs and other chemically sensitive marine organisms are at risk (Hoegh-Guldberg et al. 2007).

As desirable and affordable as reductions in emissions of greenhouse gases may be, they are not yet being achieved on the scale required. Emissions of CO$_2$ into the atmosphere are increasing more rapidly than foreseen in any of the IPCC marker scenarios (Raupach et al. 2007) with each release of CO$_2$ producing a warming that persists for many centuries (Matthews & Caldeira 2008). Atmospheric CO$_2$ content is increasing more rapidly than previously anticipated (Canadell et al. 2007). A continuation of historical trends in carbon dioxide emission presents, at a minimum, a risk of significant damage to human systems and/or the near-surface environment of the Earth. It has been suggested that purposeful climate engineering has the potential to diminish this downside risk (Crutzen 2006; Wigley 2006). To evaluate the potential for climate engineering schemes to diminish climate change risk, we present and analyse the results of climate model simulations.

We present results of several climate simulations designed to estimate the climate consequences of idealized patterns and degrees of insolation reduction. This work builds on earlier simulations using similar model configurations (Govindasamy & Caldeira 2000; Govindasamy et al. 2002, 2003). In those simulations, it was found that deflection of approximately 1.8 per cent of sunlight is able to offset the global mean temperature effects of a doubling of atmospheric carbon dioxide content. From a practical point of view, the Arctic is changing very rapidly so it is an obvious early target for geoengineering. From a theoretical point of view, it is interesting to explore relationships between forcing and response in different latitude bands, to get a better idea of the degree of nonlinearity of the climate system.

We do not go at any real depth into the feasibility of technical implementation or specify in detail by what means this reduction may be best accomplished (e.g. by injecting engineered insolation scattering systems into the stratosphere).

2. Climate model description and simulations

Our model simulations exercise a standard configuration of the National Center for Atmospheric Research (NCAR) Community Atmosphere Model, v. 3.1, which includes a finite-volume dynamical core, a grid that is 2° in latitude by 2.5° in longitude, 26 vertical levels, an interactive land surface and a thermodynamic sea ice model (Collins et al. 2006). The land surface model computes fluxes of energy and water based on plant type and stomatal apertures adjusted to balance carbon assimilation by photosynthesis and water loss through evaporation. The sea ice model computes the local thermodynamic balances between heat fluxes and ice formation and melting, but does not include the movement of sea ice.

First, we simulated a control climate using specified observed sea surface temperatures (Levitus 1982). In this mode, we can diagnose the energy fluxes into and out of the ocean as calculated by the atmosphere model, and compute the implied ocean heat transport. Then we represent the surface of the ocean as a layer of water with varying thicknesses as specified by observed ocean mixed-layer
depths. At the base of this layer, we apply the ocean heat transport computed earlier. In this way, sea surface temperatures can vary as a result of computed surface fluxes while specifying the ocean heat transport.

The only change made to the model code as distributed by NCAR was to allow for different spectrally neutral fractional reductions in incoming solar radiation in different latitude bands.

To explore the importance of nonlinearities in the climate system related to the spatial scale and the amount of reduction of solar flux incident on the Earth, seven experimental and two control simulations were conducted with this modelling tool (table 1). All simulations were run for 70 elapsed model years, with the first 40 years being discarded and the last 30 years being used to compute climate statistics.

The $1\times CO_2$ simulation is the control climate, with 280 ppm of CO$_2$ in the atmosphere and the normal amount of sunshine. The $2\times CO_2$ simulation is with doubled atmospheric CO$_2$ content climate and the normal amount of sunshine. The Global$_{1.84}$ has doubled atmospheric CO$_2$ content, but with a uniform global 1.84 per cent reduction in solar radiation at the top of the atmosphere, approximately the amount needed to offset the global mean temperature effect of a doubling of atmospheric CO$_2$ content. We then performed two more simulations focusing on the Arctic: one with a 10 per cent reduction in insolation north of 61° N (Arctic61$_{0.37}$) and the other with a 25 per cent reduction in insolation north of 71° N (Arctic71$_{0.37}$). Both of these cases deflect approximately 0.37 per cent of the global sunlight incident on the Earth. (To avoid a computational instability, the Global$_{1.84}$ simulation and a corresponding control simulation were performed using ocean heat fluxes reduced by 10% in nine (out of more than 9000) ocean grid cells, with the heat uptake redistributed zonally so as to preserve total meridional heat transport. The model represents a surface ocean layer at the base of which there is specified average ocean heat transport, based on simulations made with observed sea surface temperatures. This approach generally works well for simulations with increased radiative forcing, but for decreased radiative forcing situations can occur where the ocean

<table>
<thead>
<tr>
<th>simulation</th>
<th>atmospheric CO$_2$ concentration (ppm)</th>
<th>global mean insolation reduction (%)</th>
<th>region of insolation reduction</th>
<th>insolation reduction in engineered region (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1\times CO_2$</td>
<td>280</td>
<td>0</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>$2\times CO_2$</td>
<td>560</td>
<td>0</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Arctic61$_{0.37}$</td>
<td>560</td>
<td>0.37</td>
<td>61° N–90° N</td>
<td>10</td>
</tr>
<tr>
<td>Arctic71$_{0.37}$</td>
<td>560</td>
<td>0.37</td>
<td>71° N–90° N</td>
<td>25</td>
</tr>
<tr>
<td>Global$_{1.84}$</td>
<td>560</td>
<td>1.84</td>
<td>global</td>
<td>1.84</td>
</tr>
<tr>
<td>Global$_{0.73}$</td>
<td>560</td>
<td>0.73</td>
<td>global</td>
<td>0.73</td>
</tr>
<tr>
<td>Arctic61$_{1.84}$</td>
<td>560</td>
<td>1.84</td>
<td>61° N–90° N</td>
<td>50</td>
</tr>
<tr>
<td>Arctic71$_{0.73}$</td>
<td>560</td>
<td>0.73</td>
<td>71° N–90° N</td>
<td>50</td>
</tr>
</tbody>
</table>

Table 1. Description of simulations (Simulations include two that differ only by CO$_2$ amount ($1\times CO_2$ and $2\times CO_2$), and simulations for a world with twice the CO$_2$ in which solar insolation is decreased at various levels globally, or north of 61° N, or north of 71° N. Simulations are designed to differ from other simulations in only one respect.)

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heat transport is greater than what the atmosphere can easily supply, resulting in non-physical state with a very cold single grid cell near the Galapagos islands. A 10% weak to the implied zonal heat transport in the cells neighbouring the ‘bad’ point was enough to ‘fix’ the problem.

To explore nonlinearities in the climate system, we performed additional simulations. For each of three pairs of simulations, the top-of-atmosphere solar insolation has been reduced by nearly the same amount, with the spatial distribution of this reduction differing for the two members of the pair (table 1). For example, both the Arctic61_1.84 and Global_1.84 simulations have the top-of-atmosphere insolation reduced by 1.84 per cent (i.e. by 3.2 PW), but the Arctic61_1.84 simulation applies this reduction in insolation power only north of 61°N whereas the Global_1.84 simulation reduces insolation power by this same amount through a fractional reduction in incoming sunlight over the entire Earth.

3. Results

We first compare results of the 2×CO₂ and Global_1.84 simulations, then examine the Arctic simulations, and finally address issues associated with the degree of linearity exhibited in these simulations.
A summary of results for these simulations is shown in figures 1 and 2 and in table 2. For the 2×CO₂ case, the annual mean temperature change has the expected pattern of high-latitude amplification that is statistically significant nearly everywhere. We assessed statistical significance at each model grid point using Student’s t-test (Press et al. 1992) corrected for serial correlation (Zwiers & von Storch 1995). By contrast, the case with a uniform reduction in solar intensity of 1.84 per cent resulted in statistically significant (at the 0.05 level) annual mean temperature changes over 12 per cent of the Earth’s surface. The areas with remaining statistically significant changes are predominant in polar regions (and in equatorial regions where the model exhibits low background variability). One could infer that a non-uniform reduction in solar intensity, wherein more sunlight would be deflected in the high latitudes, would eliminate most of the area with statistically significant residual annual mean temperature change in high-latitude regions.

A well-known feature of greenhouse gas climate simulations is increase in water vapour transport towards the poles leading to increased high-latitude precipitation (IPCC 2007). This increase in poleward water vapour transport is driven largely by the motions of warmer air masses that are able to carry more water vapour. By cooling the planet, climate engineering would be expected to diminish the poleward water transport seen in the 2×CO₂ case, resulting in annual mean precipitation values that are largely indistinguishable from the control case on a

Figure 2. Annual mean precipitation changes in the (a, b) 2×CO₂ and (c, d) Global_1.84 simulations. Shown are precipitation changes from the 1×CO₂ cases (a, c) and areas where the temperature change is statistically significant at the 0.05 level (b, d). This idealized climate engineering simulation indicates that relatively simple climate engineering is likely to be able to diminish precipitation changes in most of the world.

(a) Comparison of 2×CO₂ and Global_1.84 simulations

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gridpoint-by-gridpoint basis (figure 2). In the Global_1.84 simulation, annual mean precipitation changes are statistically significant at the 0.05 level over only 4 per cent of the Earth’s surface. This number is indistinguishable from zero, since we would expect 5 per cent of the Earth’s surface to appear as statistically significant at the 0.05 level by random chance alone.

Figures 1 and 2 show that a uniform 1.84 per cent reduction in total insolation restores annual mean temperature and precipitation patterns closer to the values seen in the 1×CO2 control simulations. Table 2 shows that, in the Global_1.84 simulation, temperature, precipitation and run-off over land are all more similar to the values of the 1×CO2 simulation than to those of the 2×CO2 simulation, on a global mean basis.

Clearly, it is possible that the global mean could be corrected as a result of offsetting areas with large departures from the control simulations. Another metric of climate engineering performance, which would highlight such issues, is the evaluation of the area-weighted root mean square (r.m.s.) differences of the experimental and control simulations evaluated for each model grid point. Table 2 shows that for each of these annual mean metrics (r.m.s. differences for temperature, precipitation and run-off), the Global_1.84 simulation is more similar to the 1×CO2 simulation than to that of the 2×CO2 simulation.

Similarly, it is possible that annual mean values could be improved on a gridpoint-by-gridpoint basis as a result of some months with high values and other months with offsetting low values. To obviate this possibility, we calculated r.m.s. differences for each model grid point for each month. Table 2 shows that for each of these monthly mean metrics (r.m.s. differences for temperature, precipitation and run-off), the Global_1.84 simulation is more similar to the control simulation than to that of the 2×CO2 simulation. This indicates that
the monthly mean climate of the Global_1.84 simulations is more similar than that of the 2×CO2 simulation to the climate of the 1×CO2 simulation over most model grid points.

In summary, even this extremely simple idealized climate engineering (i.e. uniform fractional reduction in sunlight) brings the 2×CO2 climate much closer to that of the 1×CO2 climate with respect to temperature, precipitation and run-off. As already noted, one could tailor the implementation of climate engineering to improve this congruence; for example, by deflecting more sunlight away from the polar regions. Of course, one could search in an *ad hoc* manner for regions and metrics wherein the 2×CO2 climate would appear to be more like the 1×CO2 climate than the Global_1.84 climate but, based on commonly applied robust metrics defined over the entire global or over all land, it would appear perverse to suggest that the 2×CO2 climate is more similar to the 1×CO2 climate than to that of the Global_1.84 climate.

(b) Comparison of Arctic simulations

We performed a number of simulations in which insolation was diminished north of 61° N and 71° N. Annual mean temperature results can be seen in figure 3 and selected statistics appear in table 3. The goal of these simulations was to estimate the amount of insolation reduction needed to bring the Arctic climate in a high CO2 world climate closer to that of the pre-industrial state. We recognize that these simulations are highly idealized and that real climate engineering is unlikely to produce step function changes in radiative forcing at a defined latitude.

As noted earlier, the sea ice model used here is a thermodynamic one, so the results from that model should be interpreted as being suggestive and not conclusive. Nevertheless, results obtained using this model indicate that minimum sea ice area may be arbitrarily adjusted by varying insolation to various extents over different areas (figure 4). A linear regression on the results obtained here suggests that restoring September sea ice extent to its pre-industrial value in a 2×CO2 atmosphere would require reduction of insolation by approximately 21 per cent over the 2.7 per cent of the Earth that lies north of 71° N.

Model simulations with increased greenhouse gas concentrations typically result in increased water vapour transport into the polar regions. Reducing the amount of sunlight incident over the northern polar region only modestly reduces this water vapour transport (table 3). Because the reduction in sunlight cools the Arctic region, a greater fraction of the precipitation occurs there as snow instead of rain, resulting in marked increases in snow depth. This suggests that if a main goal of climate engineering is to reduce poleward water vapour transport to prevent a shutdown of the North Atlantic meridional overturning circulation, insolation would need to be diminished at lower latitudes. On the other hand, if a primary goal of climate engineering were to prevent loss of the Greenland ice sheet, then increased snowfall may be considered an asset and it may be more effective to engineer insolation reduction at high northern latitudes.

(c) Overview of all simulations

For each of three pairs of simulations, we have reduced top-of-atmosphere solar insolation by nearly the same amount, with the spatial distribution of this reduction differing for the two members of the pair. For example, the
Arctic61_1.84 and Global_1.84 simulations each have total top-of-atmosphere insolation reduced by 3.2 PW, but in the Arctic61_1.84 simulation this insolation reduction is applied only north of 61° N, whereas in the Global_1.84 simulation, the insolation is reduced by the same 3.2 PW but this reduction is spread over the entire Earth. Figure 5 demonstrates the approximate linearity of global mean temperature response to insolation reduction in our simulations. This apparent
linearity is the result of a near cancellation of two opposing effects. On average, high-latitude albedo is greater than low-latitude albedo at baseline, so a change in the high-latitude top-of-atmosphere insolation leads to a relatively smaller change in solar radiation absorbed at the Earth’s surface (table 2). However, the high latitudes have feedback processes involving snow and ice albedo that make their temperature response more sensitive to changes in radiative forcing; this greater climate sensitivity results in a global mean temperature change from high-latitude insolation changes that is close to that of the global mean. As a concatenated result of these countervailing considerations,

**Figure 4.** September sea ice fraction. Depending on the amount of insolation reduction and where it is reduced, simulated sea ice extent at the annual minimum can be adjusted at will. (a) $1 \times \text{CO}_2$, (b) $2 \times \text{CO}_2$, (c) Arctic61_0.37, (d) Arctic71_0.37, (e) Arctic61_1.84, (f) Arctic71_0.73, (g) Global_1.84, (h) Global_0.73.
Table 3. Results for $2 \times CO_2$ and climate engineering simulations relative to control simulations. (All simulations have 560 ppm CO$_2$ and are compared against simulations with 280 ppm CO$_2$.)

<table>
<thead>
<tr>
<th></th>
<th>$2 \times CO_2$</th>
<th>Arctic71_0.37</th>
<th>Arctic61_0.37</th>
<th>Global_1.84</th>
<th>Arctic61_1.84</th>
<th>Global_0.73</th>
<th>Arctic71_0.73</th>
</tr>
</thead>
<tbody>
<tr>
<td>southernmost latitude with insolation reduction</td>
<td>—</td>
<td>71° N</td>
<td>61° N</td>
<td>90° S</td>
<td>61° N</td>
<td>90° S</td>
<td>71° N</td>
</tr>
<tr>
<td>insolation reduction in engineered region (%)</td>
<td>0</td>
<td>25</td>
<td>10</td>
<td>1.84</td>
<td>25</td>
<td>0.73</td>
<td>50</td>
</tr>
<tr>
<td>global mean insolation reduction (%)</td>
<td>0</td>
<td>0.37</td>
<td>0.37</td>
<td>1.84</td>
<td>1.84</td>
<td>0.73</td>
<td>0.73</td>
</tr>
<tr>
<td>temperature change (K)</td>
<td>3.46</td>
<td>-0.28</td>
<td>0.68</td>
<td>0.83</td>
<td>-11.18</td>
<td>2.39</td>
<td>-3.18</td>
</tr>
<tr>
<td>change in sea ice fraction (%)</td>
<td>-8.6</td>
<td>3.5</td>
<td>0.5</td>
<td>-1.3</td>
<td>29.0</td>
<td>-5.2</td>
<td>12.5</td>
</tr>
<tr>
<td>change in snow depth (%)</td>
<td>-15.3</td>
<td>54.2</td>
<td>17.3</td>
<td>-5.8</td>
<td>366.4</td>
<td>-12.1</td>
<td>149.7</td>
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<td>change in precipitation (%)</td>
<td>15.5</td>
<td>14.9</td>
<td>10.7</td>
<td>0.8</td>
<td>-10.7</td>
<td>9.9</td>
<td>12.7</td>
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<tr>
<td>change in evaporation (%)</td>
<td>13.1</td>
<td>-12.4</td>
<td>-8.5</td>
<td>3.0</td>
<td>-61.2</td>
<td>10.6</td>
<td>-28.7</td>
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<tr>
<td>change in atm water vapour transport to Arctic (%)</td>
<td>17.2</td>
<td>35.2</td>
<td>25.1</td>
<td>-0.8</td>
<td>27.0</td>
<td>9.4</td>
<td>43.6</td>
</tr>
<tr>
<td>change in atm heat transport to Arctic (PW)</td>
<td>0.0</td>
<td>0.3</td>
<td>0.2</td>
<td>0.0</td>
<td>0.6</td>
<td>0.0</td>
<td>0.4</td>
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<tr>
<td>percentage of change in surface albedo</td>
<td>-7.2</td>
<td>6.3</td>
<td>4.4</td>
<td>-1.6</td>
<td>37.8</td>
<td>-5.3</td>
<td>9.9</td>
</tr>
<tr>
<td>percentage of change in TOA albedo</td>
<td>-1.1</td>
<td>2.4</td>
<td>2.1</td>
<td>-0.6</td>
<td>11.7</td>
<td>-1.2</td>
<td>2.9</td>
</tr>
<tr>
<td>change in September sea ice fraction (%)</td>
<td>-44.3</td>
<td>29.2</td>
<td>7.0</td>
<td>-4.3</td>
<td>135.9</td>
<td>-25.6</td>
<td>76.8</td>
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<td>results averaged over entire planet</td>
<td></td>
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<tr>
<td>temperature change (K)</td>
<td>2.13</td>
<td>1.83</td>
<td>1.75</td>
<td>0.11</td>
<td>0.15</td>
<td>1.34</td>
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<td>change in ice fraction (%)</td>
<td>-29.76</td>
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<td>-4.32</td>
<td>0.85</td>
<td>-20.47</td>
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<tr>
<td>change in precipitation (%)</td>
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<td>3.82</td>
<td>3.50</td>
<td>-1.13</td>
<td>0.92</td>
<td>2.12</td>
<td>3.35</td>
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<td>change in absorbed shortwave radiation (PW)</td>
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<td>0.08</td>
<td>0.00</td>
<td>-1.81</td>
<td>-1.29</td>
<td>-0.51</td>
<td>-0.20</td>
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global mean temperature changes in this model appear to be closely tied to the percentage reduction in the global top-of-atmosphere insolation and are less sensitive to the geographical pattern of this reduction (figure 4).

4. Comments on technical implementation

(a) Scattering light

All matter scatters electromagnetic radiation. Small particles appear to be the most effective form for climate engineering. The goal is to maximize matter–radiation interaction favouring forms of the greatest electromagnetic cross section for sunlight. Thus, the particles of greatest interest would be those with dimensions of the order of the wavelength of the optical radiation to be scattered, as such particles tend to scatter radiation with the highest specific efficiency and minimal mass usage. The characteristics of the scattering are specified by the microscopic physics that determines the (complex) polarizability of the material for the wave frequency of interest, and by the material’s geometry that deploys this augmented polarizability over that of the underlying vacuum over some portion of three space (Landau & Lifshitz 1984). The choice of particle parameters, primarily size, shape and composition, and the location of their emplacement would likely be based on environmental, economic and aesthetic considerations. Emplacement of (sub-)microscopic particles in the stratosphere, for example in the polar stratosphere, has the practical advantage of residence times exceeding a year—long enough to allow economically efficient climate engineering while short enough to provide some reversibility should unintended consequences prove greater than anticipated.
In terms of mass, quasi-resonant scattering materials are markedly superior to metals, which in turn are greatly advantaged over dielectrics as substrates for engineered scatterers (Teller et al. 1997). However, the relative (photo) chemical inertness of selected dielectric materials, repeatedly demonstrated at scale in major volcanic eruptions involving extensive particulate mass insertion into the stratosphere, motivates their initial selection in order to minimize first-time risks of unwanted side effects (Teller et al. 1997, 1999, 2004; Hyde et al. 2003), including significant interactions with stratospheric ozone. The use of materials with large ratios of real to imaginary components of complex polarizability over pertinent spectral bands to constitute engineered scatterers is generally preferable, as scattering of light by the engineered particulates is usually preferred to photon absorption (and consequent local stratospheric heating).

(b) Scattering ultraviolet and infrared

The near-ultraviolet and near-infrared spectral bands contain roughly half of the total insolation in energetic terms. These wavelengths may be largely superfluous (or actually deleterious, in the case of the shorter wavelength ultraviolet) for biospheric purposes, and thus portions of these spectra may be attractive candidates for being scattered back into space by an engineered scattering system (which can be designed to have considerable spectral selectivity). For example, the use of Rayleigh scattering to preferentially scatter back into space an appropriate fraction of the deeper ultraviolet portion of insolation appears to be a relatively appealing approach, since a usefully large portion of total insolation is available for attenuation and this solar spectral band’s radiation appears to be net damaging to the biosphere: single photons of UV-B and UV-C insolation are deleterious to both plants and animals, primarily due to photodamage of their DNA. Indeed, the World Health Organization estimates approximately 60 000 human deaths occur annually due to sunlight-engendered skin cancer, which is generally believed to be due rather exclusively to the UV-B spectral component of insolation (WHO press statement of 26 July 2006 issued by Dr Maria Neira, WHO Public Health and Environment Director; http://www.who.int/uv). Associated direct economic losses may significantly exceed $10 thousand million per year, and economic impacts of crop damage may be of comparable scale. Thus, there is potential for geoengineering to diminish risks to both climate and cancer, as well as to avoid substantial direct economic costs in sectors ranging from agriculture to public health. The sky may become discernibly bluer.

(c) Particle composition

A baseline scattering system for climate engineering purposes may be implemented with approximately 100 nm diameter spherules comprising at least one (possibly hydrated or carboxylated) oxide of the magnesium-through-titanium group of metals-and-metalloids; Mg, Al, Si, S, Ca and Ti all appear to be apt prospects. There is little basis in radiative physics for selecting any particular one due to their similar dielectric properties in the UV spectral band; thus convenience and estimated differential side effects constitute the present choice criteria. Metals per se, though of much greater potential scattering efficiency, may raise concerns related to their ozone interactions and respiratory
impacts, even when coated, e.g. with a thin durable oxide layer. The use of resonant scatterers, though eminently appealing in terms of mass efficiency, is handicapped by contemporary ‘packaging’ and deployment technology considerations (Teller et al. 1997).

Among dielectrics, many alternatives have been proposed (e.g. NAS 1992) and all appear to be fundamentally workable. Liquid SO$_2$ (or perhaps SO$_3$) appears to be optimized for mass efficiency, transport convenience and relative non-interference with all known processes of substantial biospheric significance, although fluidized forms of MgO, Al$_2$O$_3$ or SiO$_2$ (e.g. as hydroxides in water) seem competitive in most pertinent respects. Amounts presently considered for stratospheric injection are of the order of 1 per cent of the SO$_2$ annual mass injection into the troposphere by all processes, which are roughly half each of natural and anthropogenic origin, so that the eventual descent of stratospheric sulphate particulates into the troposphere will add negligibly to the globally averaged levels, although somewhat greater fractional increases may be expected at high latitudes. With respect to prospective impact on the ozone layer, Crutzen (2006) estimates the probable effect magnitude of geoengineering-contemplated stratospheric injections of sulphate particulate to be less than that of the Mt. Pinatubo eruption. Any scheme would need to take into consideration particle aggregation and interaction with water and other compounds found in the stratosphere.

(d) Placement in the stratosphere

Many different schemes and mechanisms have been proposed for inserting scatterers into the stratosphere, and these generally fall into two basic categories: batch-mode insertion and continuous injection. The 1992 National Academy study surveyed many of the batch-type processes, of which ground-to-stratosphere transport by high-altitude-capable aircraft (Teller et al. 1997) is emblematic. For example, it appears that of the order of a half-dozen B747-class aircraft operated intensively can lift above the tropopause at higher latitudes and there deploy-as-nanometric aerosol the MT/year mass flows of dielectric material sufficient to offset via global albedo modulation a doubling of atmospheric CO$_2$ (Wood et al. 1998). Few-fold more modest transport and deployment mass flows similarly deployed at polar latitudes apparently would suffice to reverse the Arctic warming widely expected to result from a doubling of atmospheric CO$_2$ (Wood et al. 2006). An annual rate of 1 million tonnes of SO$_{2,3}$ is equivalent to a time-average rate of approximately 20 litres per second of liquid SO$_{2,3}$, which when dispersed into 0.1 $\mu$m diameter droplets results in approximately $4 \times 10^{19}$ such droplets per second, having an aggregate geometric cross section of approximately 0.3 km$^2$; over a 30 million second interval, i.e. a year, of the order of 10 million km$^2$ of geometric cross section is thus deployed, which is of the order of a few per cent of the Earth’s surface area, as desired. (Interestingly, the areal rate swept out by the wings of the deployment aircraft is a few per cent of a km$^2$ s$^{-1}$, so that the optical depth of the as-initially deployed swath of aerosol droplets is only of the order of 10, and the as-deployed swath of particles needs disperse by only an order of magnitude in integrated vertical column density in order to become fully effective as a stratospheric insolation scattering system; a modest degree of electrostatically driven aerosol dispersion is expected to be sufficient to ensure this, should eddy diffusion itself not do so.)

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However, more *ad hoc* approaches seem to be capable of operating with considerably more modest hardware and personnel endowments, and thus at lower system-level cost; these tend to rely on continuous, rather than batch, transport of material to be engineered into a stratospheric insolation scatterer. Piping up a liquid in a well-engineered hose is exemplary (Wood 2005; Wood *et al.* 2006). For instance, such a hose composed of high-tensility material could be suspended from a buoyant structure such as the US Department of Defense’s prospective High-Altitude Airship down to ground level. At the pipe top, the stream of liquid $\text{SO}_2$ sourced by the ground station may be aerosolized into the ambient stratosphere by any of the variety of means contemplated for doing likewise from heavy-lift transports.

It seems feasible, in principle, to emplace enough particles to engender an optical depth of engineered scattering material, sized to preferentially scatter near-UV insolation and geographically positioned over the Arctic. Given an estimated residence time of the order of a year, we estimate a required time-averaged injection rate of roughly $300,000\ \text{tonnes yr}^{-1}$ of $\text{SO}_2$, which amounts to approximately $10\ \text{kg s}^{-1}$. The corresponding ground-level pumping power against the approximately $2.5\ \text{kbars}$ gravitational ‘head’ between ground level and 16 km release altitude amounts to approximately $2\ \text{MW}$, to which some pipe frictional losses and comparatively modest aerosolization ‘overhead’ must be added, so that a total of perhaps $4\ \text{MW}$ would be required. System optimization of hose mass and the mass of $\text{SO}_2$ which fills it over its approximately $25\ \text{km}$ slant length indicates that each will amount to approximately $2\ \text{tonnes}$. To achieve the approximately $3\ \text{PW}$ insolation reduction needed to offset a doubling of atmospheric $\text{CO}_2$ would require about three times the mass at the optimum approximately $25\ \text{km}$ altitude in the mid-tropic stratospheric reservoir. Several-fold larger mass estimates are indicated for near-equatorial injection in order to attain whole-planet climate engineering (Wood 2005; Wood *et al.* 2006). In either case, a single ground-level station—perhaps even a ship-borne one—might suffice to perform the entire geoengineering task from a technical standpoint.

In the absence of at least detailed engineering design—preferably supplemented with at least sub-scale experimentation—all such mass estimates must be considered to be quite provisional; similarly, cost estimates in the absence of detailed engineering and prototype evaluation must be deemed rather tentative. Nevertheless, it is not clear that either deployment or sustained operations of such systems would cost as much as billions of dollars per year, i.e. they might be several orders of magnitude less expensive than the authoritatively estimated costs of global carbon rationing a few decades hence (Stern 2006) and even of net negative direct cost when offsetting direct economic savings of avoided UV-B photodamage are considered.

5. Discussion

(a) *Comments on the model simulations*

We have presented highly idealized numerical simulations of extremely simple climate engineering involving spatially uniform reductions of incoming sunlight at the top of the atmosphere over specified northern polar regions and the entire Earth. Commonly discussed schemes, such as the release of sunlight scattering
particles into the stratosphere (i.e. above the tropopause, where rain-out does not limit the residence time of such particles) might be expected to produce similar climate responses, but this expectation has not yet been carefully evaluated.

We start by asking what sort of climate one might like to achieve and then investigate what sorts of radiative forcing change might be needed to produce that climate. Thus, our simulations consider idealized patterns of radiative forcing change. This is in contrast to complementary approaches (e.g. Rasch et al. 2008) in which one simulates a release of sunlight scattering particles and then investigates what patterns of radiative forcing and climate are thereby produced.

We have used similarity to the simulated pre-industrial climate as a basic metric of performance of a climate engineering system. The pre-industrial climate may not be ‘optimal’ (in one or more senses) and one could imagine evaluating performance of climate engineering systems based on a variety of cost functions that do not involve reference to either present or past climates, but instead to some other conception of what would constitute a desirable climate.

(b) Comments on climate engineering in a broader context

Regardless of what we might consider to be prudent or imprudent with respect to CO₂ emissions into the atmosphere, these emissions continue to increase and as a result atmospheric CO₂ concentrations also continue to increase. In the absence of countervailing measures, continuing increases in atmospheric CO₂ concentrations can be expected to lead to warmer near-surface temperatures. No one can be certain of the consequences of these changes for human or natural systems. If we were faced with an imminent climate catastrophe where further warming would push us over some critical ‘tipping point’, and we chose to address this situation via CO₂ emissions reductions, a near-complete cessation of CO₂ emissions would be required to prevent further warming (Matthews & Caldeira 2008), one whose abruptness might make the likelihood of its attainability appear remote.

However, the idealized model results shown here indicate that there may be considerable opportunity to diminish some adverse consequences of CO₂ emissions to the atmosphere through intentional climate modification. Nobody claims that such climate engineering would be perfect or is devoid of risks. Furthermore, it is clear that such climate engineering will not reverse all adverse effects of carbon dioxide emission; for example, climate engineering will not reverse the acidifying effect of carbon dioxide on the oceans (Caldeira & Wickett 2003). Furthermore, plant growth may be augmented in a high CO₂ world with relatively low temperatures, due to CO₂ fertilization of photosynthesis without corresponding increases in transpiration and respiration rates (Bala et al. 2006). This may affect natural ecosystems, but is likely to be advantageous for crop yields.

Let us consider the counterfactual situation in which we already had zero CO₂ emissions energy economy. For example, assume that we were already using some combination of nuclear fission, renewables, carbon with capture and storage, electric vehicles, etc. Nobody knows what such total emission abatement would really cost, but let us assume for the present discussion that, with reasonably optimized research, development and deployment, a CO₂ neutral energy system would cost all of us an additional 2 per cent of our income, worldwide and forever. Now, let us assume that somebody proposed that we
could increase our income by 2 per cent, but that we would thereby heat up the planet’s surface, acidify the ocean, risk melting major ice sheets, shift precipitation patterns and so on. Would we trade that added environmental damage and risk of damage for 2 per cent more income globally and forever? If we would not want to ‘sell out’ such a carbon-neutral energy system if we already had one, then the basic issue is the difficulty of creating the system, not the additional cost of ‘operating’ it \textit{per se}.

There are several major challenges in obtaining deep reductions in CO$_2$ emissions. For the world to cut CO$_2$ emissions deeply, nearly all actors would need to nearly totally eliminate their CO$_2$ emissions. However, the burning of fossil fuel produces immediate benefits to the user of the energy thereby attained. By contrast, the climate costs of that fossil fuel burning will be borne broadly throughout the world and primarily by future generations. The fundamental political challenge of CO$_2$ emissions reduction is to create institutions that would make it in the self-interest of the vast majority of actors to sharply curtail their CO$_2$ emissions \textit{(Barrett 2003)}, starting from the condition wherein benefit accrues rapidly to the emitter and the climate costs are borne primarily by others distant in space and time.

Of course, it would be strongly preferable to obtain international consensus and cooperation before deployment and operation of any climate engineering system. However, unlike CO$_2$ emissions reduction, the success of climate engineering does not depend fundamentally on such consensus and cooperation. Putting aside the question of whether or not such a course of action would be wise, a climate engineering scheme could be deployed and operated unilaterally by a single actor, perhaps at remarkably low economic expense. As already observed, the cost of climate engineering may be several orders of magnitude smaller than the ‘2 per cent forever’ cost of emissions reduction just hypothesized. Just as with substantial CO$_2$ emission reductions, climate engineering is likely to result in relative winners and losers; all such circumstances are pregnant with political tensions.

Modelling of climate engineering is in its infancy. However, continued growth in CO$_2$ emissions and atmospheric CO$_2$ concentrations, combined with preliminary numerical simulations such as those presented here, constitute a \textit{prima facie} case for exploring climate engineering options—and associated costs, risks and benefits—in greater detail.

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\textbf{References}


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