A Combined Mitigation/Geoengineering Approach to Climate Stabilization

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Projected anthropogenic warming and increases in CO_2 concentration present a twofold threat, both from climate changes and from CO_2 directly through increasing the acidity of the oceans. Future climate change may be reduced through mitigation (reductions in greenhouse gas emissions) or through geoengineering. Most geoengineering approaches, however, do not address the problem of increasing ocean acidity. A combined mitigation/geoengineering strategy could remove this deficiency. Here we consider the deliberate injection of sulfate aerosol precursors into the stratosphere. This action could substantially offset future warming and provide additional time to reduce human dependence on fossil fuels and stabilize CO_2 concentrations cost-effectively at an acceptable level.

In the absence of policies to reduce the magnitude of future climate change, the globe is expected to warm by ~1° to 6°C over the 21st century (*1*, *2*). Estimated CO_2 concentrations in 2100 lie in the range from 540 to 970 parts per million, which is sufficient to cause substantial increases in ocean acidity (*3*–*6*). Mitigation directed toward stabilizing CO_2 concentrations (*7*) addresses both problems but presents considerable economic and technological challenges (*8*, *9*). Geoengineering (*10*–*17*) could help reduce the future extent of climate change due to warming but does not address the problem of ocean acidity. Mitigation is therefore necessary, but geoengineering could provide additional time to address the economic and technological challenges faced by a mitigation-only approach.

The geoengineering strategy examined here is the injection of aerosol or aerosol precursors [such as sulfur dioxide (SO_2)] into the stratosphere to provide a negative forcing of the climate system and consequently offset part of the positive forcing due to increasing greenhouse gas concentrations (*18*). Volcanic eruptions provide ideal experiments that can be used to assess the effects of large anthropogenic emissions of SO_2 on stratospheric aerosols and climate. We know, for example, that the Mount Pinatubo eruption [June 1991 (*19*, *20*)] caused detectable short-term cooling (*19*–*21*) but did not seriously disrupt the climate system. Deliberately adding aerosols or aerosol precursors to the stratosphere, so that the loading is similar to the maximum loading from the Mount Pinatubo eruption, should therefore present minimal climate risks.

Increased sulfate aerosol loading of the stratosphere may present other risks, such as through its influence on stratospheric ozone. This particular risk, however, is likely to be small. The effect of sulfate aerosols depends on the chlorine loading (*22*–*24*). With current elevated chlorine loadings, ozone loss would be enhanced. This result would delay the recovery of stratospheric ozone slightly but only until anthropogenic chlorine loadings returned to levels of the 1980s (which are expected to be reached by the late 2040s).

Figure 1 shows the projected effect of multiple sequential eruptions of Mount Pinatubo every year, every 2 years, and every 4 years. The Pinatubo eruption–associated forcing that was used had a peak annual mean value of –2.97 W/m^2 (*20*, *21*). The climate simulations were carried out using an upwelling-diffusion energy balance model [Model for the Assessment of Greenhouse gas–Induced Climate Change (MAGICC) (*2*, *25*, *26*)] with a chosen climate sensitivity of 3°C equilibrium warming for a CO_2 doubling (2 × CO_2). Figure 1 suggests that a sustained stratospheric forcing of ~–3 W/m^2 (the average asymptotic forcing for the biennial eruption case) would be sufficient to offset much of the anthropogenic warming expected over the next century. Figure 1 also shows how rapidly the aerosol-induced cooling disappears once the injection of material into the stratosphere stops, as might become necessary should unexpected environmental damages arise.

Three cases are considered to illustrate possible options for the timing and duration of aerosol injections. In each case, the loading of the stratosphere begins in 2010 and increases linearly to

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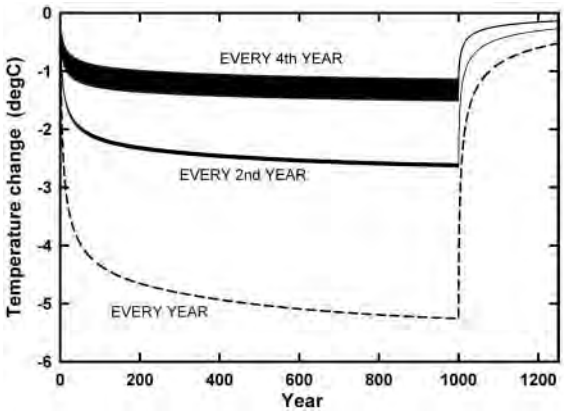
–3 W/m^2 over 30 years. The options depart from each other after this date (Fig. 2). These geoengineering options are complemented by three future CO_2 emissions scenarios: a central "no climate policy" scenario from the Special Report on Emissions Scenarios (SRES) (*27*) data set, namely the A1B scenario; an ambitious scenario known as WRE450 (*7*) in which CO_2 concentration stabilizes at 450 ppm (the present level is ~380 ppm); and an overshoot scenario in which CO_2 concentration rises to 530 ppm in 2080 before declining to 450 ppm. [Because an atmospheric CO_2 concentration of 450 ppm "produces both calcite and aragonite undersaturation in most of the deep ocean" (*4*), a level even less than this may ultimately be desirable.]

CO_2 concentrations and corresponding fossil fuel emissions for these three CO_2 scenarios are shown in Fig. 3. Emissions for the stabilization cases were calculated with the use of an inverse version of MAGICC, which accounted for climate feedbacks on the carbon cycle. The WRE450 scenario is an archetypal mitigation-only case, stabilizing at a level that many researchers believe would avoid "dangerous anthropogenic interference" with the climate system (*28*). The overshoot scenario is introduced here to be considered in conjunction with the three geoengineering options. It allows much larger CO_2 emissions and a much slower departure from the A1B no-policy scenario baseline. Although the rate of decline of emissions in the mid- to late 21st century is more rapid in the overshoot scenario than in WRE450, these reductions begin 15 to 20 years later in the former scenario, allowing additional time both to phase out existing CO_2-emitting fossil fuel energy technologies and to develop and deploy energy sources that have net-zero CO_2 emissions (*7–9*).

Figure 4 shows global mean temperature and sea-level projections for the no-policy scenario (A1B), the mitigation-only scenario (WRE450), and the overshoot CO_2 scenario combined with the three alternative geoengineering options (HIGH GEO, MID GEO, and LOW GEO). For the decades immediately after 2010, changes in aerosol forcing in all three GEO options occur more rapidly than forcing changes for the CO_2 scenarios, so the net effect is cooling. After 2040, the HIGH GEO–associated cooling tends to balance the warming from the overshoot CO_2 stabilization scenario, eventually leading to a slight cooling that would bring global mean temperatures back to near their preindustrial level. The MID and LOW GEO options lead to temperatures stabilizing at approximately 1° and 2°C relative to temperatures in 2000 (*29*). After 2100, the LOW GEO option (where injection into the stratosphere is decreased to zero by 2090) closely matches the WRE450 mitigation-only scenario but requires less-stringent emissions reductions.

The sea-level results (Fig. 4B), derived from models used in the Third Assessment Report



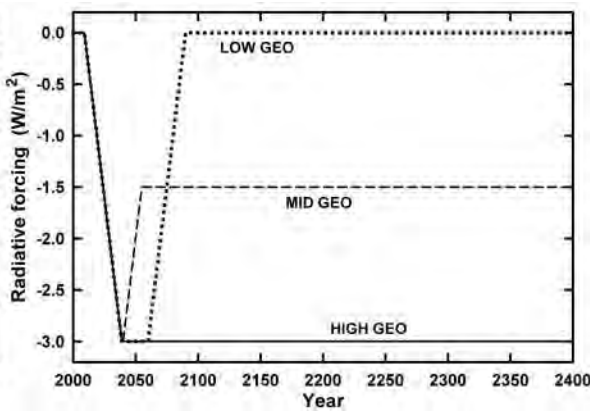
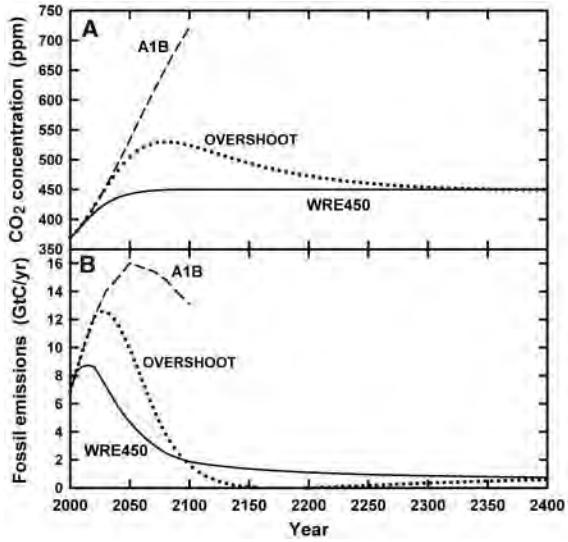


Fig. 1. (left) Global mean temperature response to multiple volcanic eruptions. The standard eruption used was that of Mount Pinatubo [forcing data from Ammann *et al.* (*20*, *21*)], and eruptions were assumed to occur every 4 years (top curve), every 2 years (middle curve), or every year (bottom curve). The results shown are annual mean values plotted year by year. In the 2- and (especially) 4-year cases, the forcing varies considerably from year to year, leading to noticeable interannual temperature variations. These appear as bands of values because the abscissa scale in the graph is insufficient to resolve these rapid variations. A climate sensitivity of 3°C equilibrium warming for 2 × CO_2 is assumed. **Fig. 2. (right)** Radiative forcing scenarios for the three geoengineering options considered. The HIGH GEO option corresponds approximately to the steady-state forcing that would result from eruptions of Mount Pinatubo every 2 years.



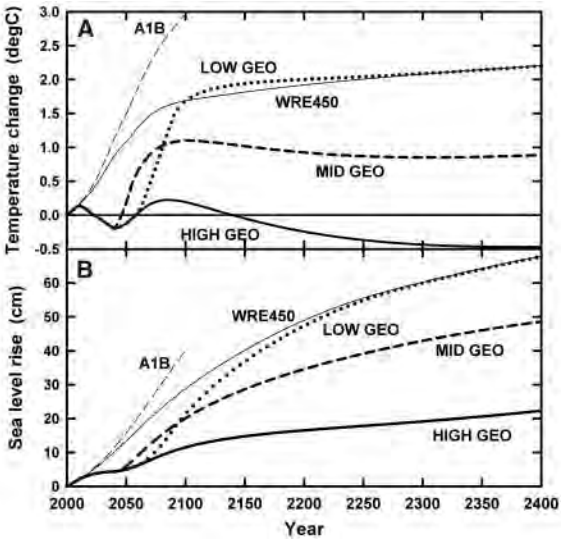


Fig. 3. (left) (**A**) CO_2 concentration projections used in the analysis together with (**B**) corresponding fossil fuel emissions. The overshoot scenario was used in conjunction with the three geoengineering options shown in Fig. 2. A climate sensitivity of 3°C equilibrium warming for 2 × CO_2 is assumed. CO_2 emissions results depend on the climate sensitivity because of climate feedbacks on the carbon cycle. GtC, gigatons of carbon. **Fig. 4. (right)** Global mean temperature (**A**) and sea-level (**B**) changes for the A1B scenario, the WRE450 scenario, and three scenarios combining both mitigation and geoengineering. The latter cases use the overshoot scenario (Fig. 3) and the three increasingly strong geoengineering options (Fig. 2). A climate sensitivity of 3°C equilibrium warming for 2 × CO_2 is assumed.

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of the Intergovernmental Panel on Climate Change (*30*, *31*), show the much larger inertia of this part of the climate system. The LOW GEO option and WRE450 scenario again are similar, with neither tending toward stabilization. Even the HIGH GEO option shows a continuing (but slow) rise in sea level toward the end of the study period, but the rate of rise is small, even relative to changes observed over the 20th century (*30*, *32*).

A combined mitigation/geoengineering approach to climate stabilization has a number of advantages over either alternative used separately. A relatively modest geoengineering investment (*33*, *34*) corresponding to the present LOW GEO option could reduce the economic and technological burden on mitigation substantially, by deferring the need for immediate or near-future cuts in CO_2 emissions. More ambitious geoengineering, when combined with mitigation, could even lead to the stabilization of global mean temperature at near present levels and reduce future sea-level rise to a rate much less than that observed over the 20th century: aspects of future change that are virtually impossible to achieve through mitigation alone.

As a guide to the amount of SO_2 required, the eruption of Mount Pinatubo injected about 10 teragrams of sulfur (TgS) into the stratosphere (*35*, *36*), and the analysis here suggests that an annual flux of half that amount would have a substantial influence. Smaller diameter aerosols would have longer lifetimes and require still smaller injection rates (*15*). Five TgS/year is only ~7% of current SO_2 emissions from fossil fuel combustion (*37*, *38*). Further analysis is required to assess (i) the technological feasibility of the suggested injections of SO_2 [or of more radiatively efficient material (*34*)] into the stratosphere, (ii) the economic costs of this option relative to the reduced costs of mitigation that an overshoot CO_2–stabilization pathway would allow, and (iii) the detailed effects of the proposed SO_2 injections and CO_2 concentration changes on climate [compare with (*39*)] and stratospheric chemistry.

References and Notes

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29. In all options, there is a residual warming tendency arising from the emissions of non-CO_2 gases (such as CH_4, N_2O, halocarbons, and tropospheric aerosols). Emissions from these sources are assumed to follow the A1B scenario to 2100 and then remain constant, leading to a slow but long-term increase in radiative forcing.
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