Problems with geoengineering schemes to combat climate change

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The accelerated rate of increase in atmospheric CO_2 concentration in recent years has revived the idea of stabilizing the global climate through geoengineering schemes. Majority of the proposed geoengineering schemes will attempt to reduce the amount of solar radiation absorbed by our planet. Climate modelling studies of these so called 'sunshade geoengineering schemes' show that global warming from increasing concentrations of CO_2 can be mitigated by intentionally manipulating the amount of sunlight absorbed by the climate system. These studies also suggest that the residual changes could be large on regional scales, so that climate change may not be mitigated on a local basis. More recent modelling studies have shown that these schemes could lead to a slowdown in the global hydrological cycle. Other problems such as changes in the terrestrial carbon cycle and ocean acidification remain unsolved by sunshade geoengineering schemes. In this article, I review the proposed geoengineering schemes, results from climate models and discuss why geoengineering is not the best option to deal with climate change.

Keywords: Carbon cycle, climate change, geoengineering schemes, global warming, ocean acidification.

ONE of the major conclusions of a recent report by the Intergovernmental Panel on Climate Change[1] is 'Most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations'. The dominant greenhouse gases (GHGs) are CO_2, CH_4, N_2O and the chlorofluorocarbons (CFCs). The primary source for these gases in the industrial era is anthropogenic emission driven by the fossil-fuel demand in the energy sector, cement production and land-use changes.

Atmospheric CO_2 is the most important anthropogenic GHG because it has a long lifetime in the atmosphere (~100 years). CO_2 concentration is now almost 100 ppm (parts per million) above its pre-industrial value of 280 ppm. Current annual emissions of CO_2 from fossil-fuel burning, and land-use change are estimated to be about 8 GtC (giga tonnes of carbon) and 2 GtC respectively[2]. With oceans and terrestrial ecosystems taking up about 40–50% of the annual emissions, the current annual mean CO_2 growth in the atmosphere is about 2.5–3 ppm per year (1 ppm of $CO_2 \approx 2$ GtC).

Relative to the pre-industrial period, the average temperature of the planet[1] has risen by about 0.8°C in 2001–05. In tandem, the ocean heat content and the atmospheric water vapour content have increased, sea levels have risen, mountain glaciers have receded and snow cover has declined. This warming is predicted to continue into the future. Though there is large uncertainty in the projection of the amount of future global warming, the best estimates[1] suggest further warming in the range 1.8–4°C in the 21st century. The uncertainty primarily stems from the uncertainties in the global economic growth, emission patterns, and the response of the climate system. Burning all the available conventional fossil resources by the year 2300 and releasing CO_2 into the atmosphere have been estimated[3] to lead to a global mean warming of about 8°C.

The warming of the global climate has severe consequences for mankind, and for both terrestrial and marine ecosystems. More frequent heat waves, droughts and flooding, more intense tropical cyclones, increase in sea levels, contraction in snow cover and depth, shrinking glaciers and sea-ice extent, and acidification of the ocean are some of the direct consequences of climate change driven by the growth in the atmospheric CO_2 content and other GHGs. These changes are already evident from observations of increase in global average air and ocean temperatures, widespread melting of snow and ice, rising global average sea level and declining alkalinity of the ocean waters[1].

Rising energy demand in the future is likely to lead to increase in the emission of CO_2 and other GHGs into the atmosphere. In fact, GHG emissions have been rapidly rising in the past decade and are expected to lead to a faster rate of warming in this century[2]. Annual emissions of CO_2 from fossil-fuel burning and cement production[2]

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increased from a mean of 6.4 GtC/yr in the 1990s to 7.2 GtC/yr during 2001–05. Attempts to slow down the emission rates have been unsuccessful.

Limiting warming to 2°C above pre-industrial levels with a relatively high certainty[4] requires the equivalent concentration of CO_2 to stay below 400 ppm. Conversely, if concentrations were to rise to 550 ppm CO_2 equivalent, then it is unlikely that the global mean temperature increase would stay below 2°C. Several critical temperature levels and rates of change for damage from climate change have been reported in the literature[4]. These vary for the globe, specific regions and sensitive ecosystems. For example, a regional increase above the present level of 2.7°C may be a threshold that triggers melting of the Greenland ice-cap, while an increase in global temperature of about 1°C is likely to lead to extensive coral bleaching. In general, surveys of the literature suggest increasing damage if the globe warms about 1–3°C above the current levels. Serious risk of large-scale, irreversible system disruption[4], such as reversal of the land carbon sink and possible destabilization of the Antarctic ice sheets is more likely above 3°C. Such levels of warming are well within the range of projections for the century[1].

How do we tackle the climate change problem? By far, the best way to solve the climate change problem is to reduce fossil-fuel emissions. This can be achieved through promotion of conservation, development of energy-efficient technologies, and large investments in alternate energy resources. Sources of carbon-free energy include nuclear, hydroelectric power, geothermal, wind energy, solar and biodiesel[5]. Today, these alternatives to fossil fuel provide only about 15% of the current global energy requirement of 15 terra Watt. More investments in research and development would be required to increase the fraction of energy from these alternatives. However, since attempts to achieve ambitious emission reduction targets have been unsuccessful, options to mitigate climate change or adaptations to climate change are seriously considered.

Geoengineering

Climate geoengineering has been proposed as a viable option to mitigate future warming induced by anthropogenic emissions of GHGs[6–9]. Any intentional, large-scale modification and manipulation of the natural systems for the benefit of mankind is generally known as a geoengineering or macro-engineering scheme. Geoengineering schemes are, therefore, by definition, intentional and implemented on a large scale[10]. The proposed schemes (Figure 1) can be classified into two categories. The first class, the sunshade schemes, involves reducing the solar radiation that reaches the surface of the earth by an amount that balances the reduction in outgoing longwave radiation due to increase in atmospheric CO_2. The other class of schemes typically removes atmospheric CO_2 and sequesters it into terrestrial vegetation, ocean, or into deep geologic formations. In this article, I restrict my discussion only to schemes that reduce solar insolation.

The possibilities of deliberately bringing about countervailing climatic changes were suggested in the 1965 US President's Scientific Advisory Committee report[11]. It suggested that a change in the radiation balance in the opposite direction to that which might result from the increase of atmospheric CO_2 could be produced by raising the albedo, or reflectivity, of the earth. Such a change in albedo could be brought about, for example, by spreading small reflecting particles over large oceanic areas.

About ten years later, methods based on increasing the aerosol content in the lower stratosphere for climate modification were proposed by a Russian scientist, Budyko[12]. Sulphur could be injected by aircraft, rockets, or missiles. An alternative to direct injection is to increase the sulphur content of the jet fuel. Budyko suggested that the circulation in the stratosphere should be assessed for location and time of ejection. The main concern raised by Budyko[12] was about its effects on the ozone content in the stratosphere. A large number of flights in the stratosphere can also lead to changes in the stratospheric climatic conditions.

Sulphur injections in the troposphere were not recommended by Budyko for the following reasons: Aerosols in the troposphere have a lifetime of only weeks, while stratospheric aerosols have a lifetime of 1–2 years; tropospheric injection would require 100 times more sulphur than injections into the stratosphere. In the presence of clouds, the effects of artificially injected aerosols in the troposphere will be small; the effect could be half that in the stratosphere. The injection of sulphur in the troposphere would pollute the troposphere and degrade ecosystems. Furthermore, the absorption of shortwave radiation by the tropospheric aerosols partially offsets the cooling effect from scattering. This warming effect from strato-

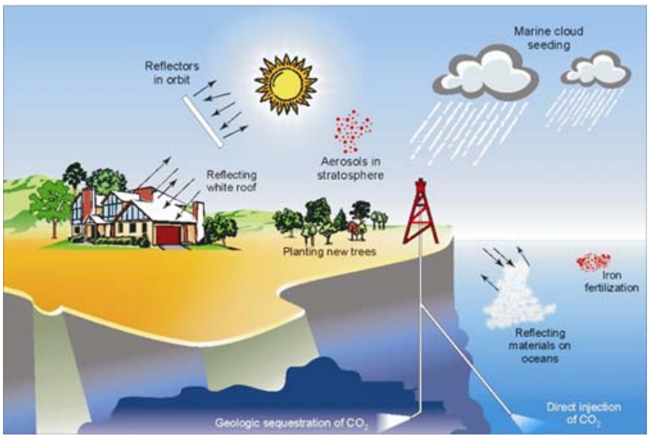

Figure 1. Schematic representation of various geoengineering proposals.

spheric aerosols, however, is local in nature and does not warm the surface.

In 1992, a report by the US National Academy of Sciences (NAS)[13] on geoengineering noted that dust is a better choice compared to sulphur, because dust is from natural soil and so should have no noticeable effect on the ground as it gradually falls into the troposphere and rains out. It estimated that about 10^{10} kg dust would be required to mitigate the warming from a doubling of atmospheric CO_2 or about 1 kg dust per 100 t of carbon emissions.

Instead of sulphur and dust, it has been also proposed to launch reflecting, small balloons or mirrors, or to add highly reflective nanoparticles of materials other than sulphur[13–15]. These reflectors would be placed at a high enough altitude so that they do not interfere with air traffic. The cost estimate is about 20 times as much as the distribution of dust in the stratosphere[13], making these schemes economically unviable. The large number of reflectors and the trash problem posed by their fall make the system unattractive.

Increasing the coverage of marine stratocumulus clouds by artificially increasing the abundance of cloud condensation nuclei (CCN) has been proposed to enhance planetary albedo to counter global warming[13,16–19]; approximately 4% increase in cloud cover would be sufficient to offset CO_2 doubling. About 30% increase in CCN over the oceans would be necessary[20] to increase the fraction of cloudiness or albedo of marine stratocumulus by 4%. This can be achieved by seeding the marine, low clouds with H_2SO_4 CCN, from a fleet of ships or by building power plants out in the ocean.

Placement of reflecting mirrors, sunshades, or a cloud of small spacecrafts at the L1 Lagrange point between the earth and the sun has also been suggested[6,21,22]. At the L1 point, the gravitational force vanishes and therefore reflectors could be maintained at a minimal cost. The L1 point is at a distance of 1.5×10^6 km from the earth, about four times the distance between the moon and the earth. Earlier estimates[21] suggested that to reduce the surface temperature of the planet by 2.5 K, would require reflection of the solar radiation by 3.5%. This would be achieved by a reflector with an area of 4.5×10^6 km^2. The reflector could be made of aluminum with a density of 10 g m^{-2}, for a total requirement of 45 mt. The cost estimate for placing the reflector was 6% of the world gross domestic product (GDP) equivalent to the then (1980s) world's military expenditure. The drawback of this scheme is that the L1 point is an unstable position and the mirror has to be stabilized actively. More advanced concepts in optical design, transportation methods and stabilization techniques have been recently proposed, which show that the cost could be as little as 0.2% of the world GDP (US$ 0.1 per year per ton of mitigated carbon)[6].

The NAS report[13] discussed a low-altitude alternative to the L1 Lagrange point. The idea is to place a low orbit (~200 km) parasol or a set of mirrors in space. A single mirror or parasol should have an area of 5.5×10^6 km^2 to counter climate change from a doubling of CO_2. The cost estimate range was US$ 5.5–55.0 trillion, or US$ 5.5–55 per tonne of mitigated carbon emissions. These estimates assume that an emission of 1000 billion tonnes of carbon increases the atmospheric CO_2 content by approximately 300 ppm (or carbon content by 600 billion tonnes) and this amount of increase in CO_2 corresponds to a doubling relative to the pre-industrial levels. The remaining 40% of the emissions is supposedly taken up by oceans and land ecosystem. A single mirror would be unmanageable and would probably create problems in the regions where its shadow fell as it moved around the earth. If a small set of mirrors with sizes of 100 km^2 is deployed, about 55,000 mirrors would be required. The NAS report[13] concluded that this poses a difficult, if not unmanageable, tracking problem.

Non-sunshade geoengineering possibilities discussed by NAS[13] to combat climate change include afforestation to increase the storage of carbon in the vegetation, iron fertilization[23] of the ocean to stimulate photosynthesis by the phytoplankton in the Southern Ocean, and removal of atmospheric CFCs. Direct injection of CO_2 into the deep oceans[24,25], geologic sequestration of CO_2 into geologic formations of oil[26,27], and sequestration of crop residues[28] have been also proposed as options to mitigate climate change.

The conclusion of the 1992 NAS report[13] was that most geoengineering schemes, though feasible, are impractical, cumbersome to manage, or too expensive. It suggested some further study, but did not find it worthy of great effort. In support of this conclusion, Schneider[29] suggested to reduce slowly our economic dependence on carbon fuels, rather than try to counter the side effects using risky options such as centuries of injecting sulphur into the atmosphere or iron into the oceans.

While acknowledging that all geoengineering schemes have serious flaws, Keith[10] judged that this century is likely to see serious debates about geoengineering. The serious debate indeed started when Nobel laureate Paul Crutzen[8] published his influential editorial article on geoengineering. Since the attempts to curb fossil-fuel emissions have been unsuccessful, Crutzen suggested that the usefulness of artificially enhancing the planetary albedo to counteract the climate forcing of growing CO_2 emissions might again be explored and debated. In a series of editorial comments[8,30–33], broad recommendations were made to pursue scientific research on the effects of geoengineering schemes.

However, Bengtsson[34] expressed his reservations against geoengineering schemes for the following reasons. (1) There is a lack of accuracy in climate prediction. (2) There is large difference in the timescale between the effects of CO_2 and the effects of aerosols, forcing us to commit to the artificial release of aerosols for several hundred years. (3) There are serious environmental problems such as ocean acidification, which are not mitigated by the albedo-enhancing geoengineering schemes. To address the last two issues, Wigley[7] advocated a combination of mitigation and geoengineering to prevent both climate change and ocean acidification. And thus the debate on combating climate change via geoengineering continues[35–37].

Climate modelling of geoengineering

How do we verify whether the climate geoengineering techniques discussed in the previous section will mitigate the anthropogenic climate change? Climate models are the only experimental tools that can be employed to investigate future changes to the global climate system. Unlike in a chemistry or biology laboratory, where one can perform multiple controlled experiments, we cannot afford to perform experiments with global climate. If the outcome of an experiment with our climate system goes awry, the consequences could be devastating. Indeed, the current debate on climate change stems from the unintentional experiment that we are performing on the planet; growth of atmospheric GHGs and aerosols from the burning fossil fuels and deforestation. We have got only one planet to live in and we need to save and preserve it from any catastrophic climate change.

The physical climate system is composed of the atmosphere, the oceans, the land surface and the sea-ice. As a result of the invention of the electronic computer in mid-twentieth century, it is now possible to solve the equations governing the planetary fluid motions numerically and hence simulate climate. Contemporary climate models have comprehensive three-dimensional numerical representation of the major components of the climate system and the interactions and feedbacks between them. Climate models are also known as general circulation models (GCMs). The early GCMs solved only atmospheric equations of motion, and they are called atmospheric general circulation models (AGCMs). The contemporary models couple the oceans to the atmosphere, and they are called coupled models or coupled atmosphere–ocean general circulation models (AOGCMs). The state-of-the-art in climate modelling is to couple the physical climate model to the global carbon and nitrogen cycles. The next generation of models is expected to include interactive atmospheric aerosols and chemistry. An excellent introduction to climate modelling is given in Washington and Parkinson[38].

The early modelling studies on geoengineering schemes used comprehensive AGCMs coupled to simple, mixed-layer ocean model and performed equilibrium simulations. These models lacked a full dynamic ocean model. The mixed-layer ocean allows for a simple representation of the interaction between the atmosphere, ocean and sea ice components of the climate system using a spatially and seasonally prescribed ocean-heat transport and spatially prescribed mixed-layer depth, which ensure replication of realistic sea-surface temperatures and sea-ice distributions for the present climate. Since the mixed-layer ocean has a depth of only about 50 m, it comes to equilibrium usually within about 30 years after climate perturbations.

In the first mixed-layer ocean modelling study[39], the solar radiation incident on the earth was diminished to balance the increased radiative forcing from the increase in atmospheric CO_2. The results indicate that despite large differences in radiative forcing patterns (Figure 2), large-scale geoengineering schemes could markedly diminish regional and seasonal climate change from anthropogenic CO_2 emissions (Figure 3). However, some

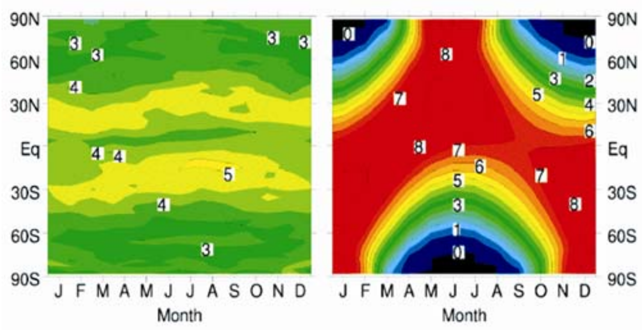

Figure 2. Spatial and temporal distribution of change in net longwave radiative flux at the tropopause when CO_2 is doubled (left panel) and the change in shortwave radiative flux (right panel) that has the same global mean as the longwave flux changes in the left panel. The distribution of longwave fluxes is much more homogeneous than solar radiation, which is the maximum in the tropics and exhibits strong seasonal variations in the middle and high latitudes. However, climate modelling studies[39, 44] have shown that the surface temperature change due to forcing in the left panel can be mitigated on a regional and seasonal basis (Figure 3) by the forcing shown in the right panel (with opposite sign).

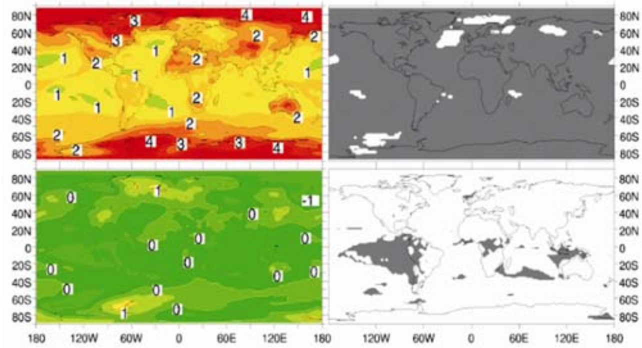

Figure 3. Annual mean surface temperature change when atmospheric CO_2 concentration is doubled (top left panel), and in the geoengineered case when atmospheric CO_2 concentration is doubled and solar insolation is reduced by 1.8% at the top of the atmosphere (bottom left panel). The right panels show regions where the temperature changes are significant at the 5% level. Though solar forcing has a forcing pattern that is vastly different from CO_2 radiative forcing (Figure 2), a reduction in solar radiation by an appropriate amount in the geoengineered case mitigates the temperature response to CO_2 forcing. The results are obtained from an atmospheric general circulation model coupled to a mixed layer ocean model with prescribed ocean heat transport[39].

residual climate changes in the geoengineered climate are indicated in later studies[40–43]: a significant decrease in surface temperature and precipitation in the tropics, warming in the high latitudes is not completely compensated, the cooling effect of GHGs in the stratosphere increases (Figure 4) and sea-ice is not fully restored. Stratospheric cooling is not mitigated in the geoengineered climate, and indeed additional cooling due to geoengineering could enhance stratospheric ozone depletion.

Another mixed-layer modelling study[44] has investigated the impact of climate stabilization schemes on the terrestrial biosphere. It indicates that climate geoengineering would tend to limit changes in distribution of vegetation type, but would not prevent CO_2-induced changes in net primary productivity or biomass. If CO_2 fertilization is an important factor, a CO_2-rich geoengineered world would have higher net primary productivity than our current world. Therefore, sunshade geoengineering schemes would not prevent changes to the terrestrial carbon cycle.

The first modelling study on the transient climate response to geoengineering[41] suggests that the climate system responds quickly to artificially reduced solar radiation. Hence there may be little cost to delaying the deployment of geoengineering strategies until such time as 'dangerous' climate change is imminent. This study also notes that a failure of the geoengineering scheme could lead to rapid

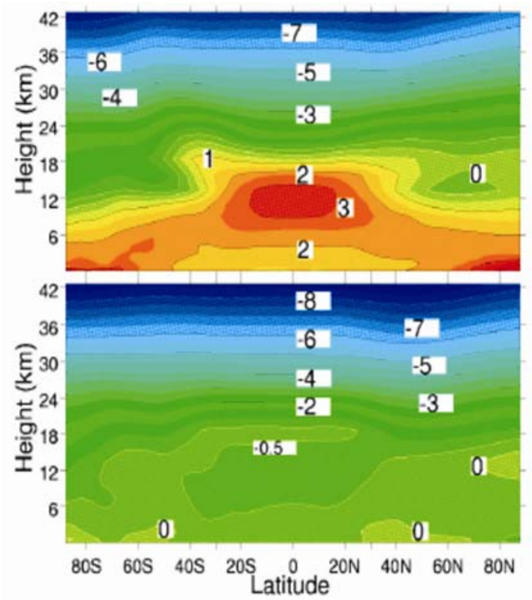

Figure 4. Zonally averaged annual mean temperature change when atmospheric CO_2 concentration is doubled (top panel), and in the geoengineered case when atmospheric CO_2 concentration is doubled and solar insolation is reduced by 1.8% at the top of the atmosphere (bottom panel). While warming is mitigated in the troposphere (height up to 10 km) in the geoengineered case, cooling of the stratosphere is not. Rather, cooling is enhanced in the stratosphere, which could aggravate the depletion of ozone in the stratosphere. The results are obtained from an atmospheric general circulation model coupled to a mixed layer ocean model with prescribed ocean heat transport[39].

climate change, with warming rates up to 20 times greater than present-day rates: the global mean surface temperature in the geoengineering-failed case reaches the non-geoengineered warming case in a short time-span of one or two decades. While the non-geoengineered warming case warms slowly with the slowly increasing CO_2, the geoengineering-failed case instantaneously experiences a large climate forcing at the point of geoengineering failure and responds to this larger forcing on a timescale of 10–20 years (the timescale of the mixed-layer ocean for instantaneous forcing), with larger warming rates. This transient climate change study uses a comprehensive dynamic ocean model coupled to a simple, one layer energy-balance atmospheric model, and interactive terrestrial and oceanic carbon cycle models.

The viability of injecting aerosol particles into the stratosphere to counteract climate warming has been also modelled using an AGCM coupled to a mixed-layer ocean model with comprehensive aerosol–climate interactions[42,45]. It was found that stratosphere–troposphere exchange processes change in response to GHG forcing and respond to geoengineering by aerosols[42]. More aerosol precursor must be injected than would be needed if the stratosphere–troposphere exchange processes did not change in response to GHGs or aerosols. Further, more aerosol is required to counteract greenhouse warming, if aerosol particles are as large as those seen during volcanic eruptions (compared to the smaller aerosols found in quiescent conditions), because the larger particles are less effective at scattering incoming energy, and trap some outgoing energy.

More recent studies on geoengineering have used fully coupled atmosphere and models[43,45]. One of these studies[43] found significant cooling of the tropics, warming of high latitudes and related sea-ice reduction, a reduction in intensity of the hydrological cycle, reduced ENSO variability, and an increase in Atlantic overturning when the climate was geoengineered via sunshade scheme. The other study found that both tropical and Arctic SO_2 injection would disrupt the Asian and African summer monsoons, reducing precipitation essential for the food supply for billions of people[45].

The impact of geoengineering schemes on global hydrology has also been explored from a more fundamental point of view[46]. This study shows that insolation reductions sufficient to offset global-scale temperature increases lead to a decrease in global mean precipitation (Figure 5). This occurs because solar forcing is more effective in driving changes in global mean evaporation than is CO_2 forcing of a similar magnitude. For the same surface temperature change, insolation changes result in relatively larger changes in net radiative fluxes at the surface; these are compensated by larger changes in evaporation. This implies that an alteration in solar forcing might offset temperature changes or hydrological changes from GHG warming, but could not cancel both at once.

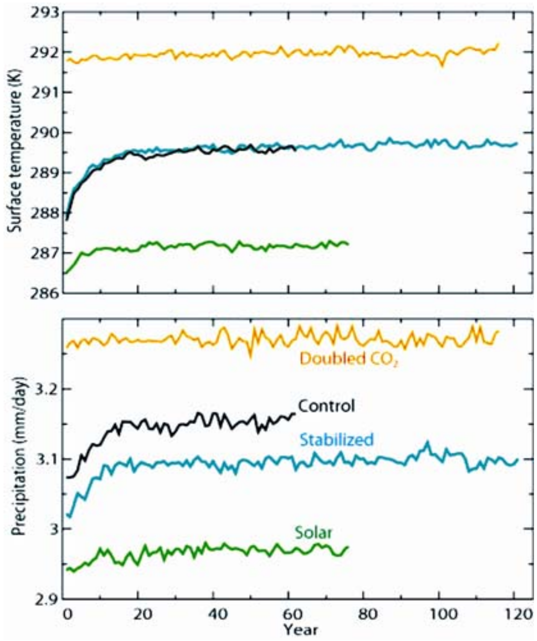

Figure 5. Evolution of annual and global mean surface temperature (top panel) and precipitation (bottom panel) in a simulation with present-day atmospheric CO_2 concentration (control), with doubled CO_2 concentration (Doubled CO_2), with solar radiation at the top of the atmosphere reduced by 1.8% (solar) and with CO_2 doubled and solar radiation reduced by 1.8% (stabilized or geoengineered). While the surface warming is mitigated in the stabilized or geoengineered climate relative to the control simulation (top panel), the hydrological cycle is weakened (bottom panel). The results are obtained from an atmospheric general circulation model coupled to a mixed-layer ocean model with prescribed ocean heat transport[46].

Discussion

What can we infer from climate modelling studies on sunshade geoengineering schemes? The modelling studies to this date suggest that sunshade geoengineering may be effective to counteract most surface temperature changes, as it may not be necessary to replicate the exact radiative forcing patterns from GHGs to largely negate their effects. Though residual changes are significant on a regional scale, they are small[40,43] relative to those associated with an unmitigated rise in CO_2. However, enhancement of cooling in the stratosphere[39] and weakening of the hydrological cycle[46] suggest that it is not sufficient to focus on surface temperature changes alone, but it is important to study the effects of sunshade geoengineering schemes on the individual components (e.g. hydrology, stratospheric chemistry, ocean chemistry, terrestrial carbon cycle, etc.) of the climate system. Surface temperature change alone is not the 'only' proper metric to measure climate change.

The modelling studies thus far suggest that residual changes are small. Caution should be exercised in interpreting the climate modelling results on geoengineering, because many simplifying assumptions are normally used in the models. Feedbacks spanning all spatial and timescales in the natural climate system are not fully represented in the models. More modelling research is required before geoengineering schemes could be considered as possible options to combat climate change. The desirable course of geoengineering implementation should be such that the effect of the schemes on the climate system is within the natural variability of the system and its effects are easily reversible.

Sunshade geoengineering schemes impose a variety of technical, environmental and economic challenges[6,13,14,22,47]. For instance, in the case of placing reflectors in space, a doubling of CO_2 requires the interception of about 1.8% of the sunlight incident on the earth, and hence an interception area of $\sim 2 \times 10^6$ km^2 or a disk of roughly 800 km in radius has to be built[39]. Placing small particles or aerosols in the stratosphere will increase the cooling in the stratosphere[39] and this could lead to changes in the stratospheric chemistry and ozone depletion. Mirrors in low-earth orbit will lead to flickering of the sun ~2% of the time, and involve tracking problems so that the mirrors do not collide with each other. The failure of a macro-engineering system could subject the earth to extremely rapid warming (about 20 times the current rate of warming)[41] as the climate system would be subjected to huge climate forcing instantaneously at the point of failure.

Even if geoengineering schemes could largely compensate for the climate change induced by a CO_2 doubling on short timescales, there is no guarantee that long-term climate would remain relatively unaffected. For instance, the uptake of CO_2 by the oceans and the terrestrial biosphere will increase at elevated levels of atmospheric CO_2, irrespective of whether geoengineering schemes are implemented or not. The geoengineering schemes might prevent some changes in vegetation distribution, but would have little effect in preventing changes in the terrestrial carbon cycle. In a stabilized climate, CO_2 fertilization could impact ecosystem goods and services, such as species abundance and competition, habitat loss and biodiversity[48]. The geoengineering schemes that diminish surface solar radiation[49] would not solve the ocean acidification problem from absorbed CO_2. Evaluation of the sunshade geoengineering schemes should account for the long-term consequences of these ecosystem changes.

The effectiveness of non-sunshade geoengineering schemes such as afforestation in the mid- and high latitudes, iron-fertilization of the ocean and direct injection CO_2 into the ocean is also not promising. A modelling study[50] has shown that only tropical afforestation has the potential to mitigate climate warming, when both the climate and carbon cycle effects of forests are into account. New forests in the tropics, in addition to causing cooling through sequestering CO_2, lead to increased evapotranspiration and cloudiness, which reduces the surface solar radiation and causes cooling. Afforestation projects in the mid-latitudes offer marginal benefits and high latitude boreal forests will actually accelerate global warming, because such projects in the seasonally snow-covered mid- and high-latitude regions would decrease the surface albedo and enhance surface absorption of solar radiation. In these regions, the warming caused by this albedo effect is greater than the cooling that would result from the sequestration of CO_2 in the new forests. Modelling and experimental study of ocean iron-fertilization also seems less encouraging[51–53]: the global modelling studies show that atmospheric CO_2 concentrations could be reduced by only 10% under perfect iron-fertilization conditions. Literature on the physiology of deep-living animals indicates that the marine ecosystem is highly susceptible to oceanic CO_2 and pH excursions likely to accompany direct injection of CO_2 into the deep–sea[54]. Microbial populations may be highly susceptible as well. Therefore, with the one exception of tropical afforestation, which has the advantage of being reversible and being within natural variability (the earth's land has had more forests in the past), geoengineering schemes impose a variety of problems.

Many of the sunshade geoengineering schemes are cooperative solutions that require continuous world management for many centuries. Since the timescale of CO_2 in the atmosphere is hundreds of years, most of the schemes would require continuous operation for several hundred years. Is this feasible? The cost could be probably cheaper for developing alternate energy technology over the long term. Given the history of non-cooperation at a global scale in the past, there is little hope for the feasibility of cooperative geoengineering solutions[29]. Given these difficulties, the most prudent and least risky path to combat global warming is to reduce emissions of GHGs, conserve and improve the efficiency of the current energy systems, develop alternate energy technologies, avoid deforestation and reforest the tropics. Nevertheless, we can arm ourselves with an option by performing field experiments and climate modelling studies in geoengineering: we will have the scientific knowledge to mitigate a possible rapid catastrophic global warming without inadvertently creating a larger problem. Therefore, more scientific research (global and regional modelling and field experiments on smaller scales) into geoengineering should be encouraged.

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