Science Progress (2009), 92(2), 139–162 doi: 10.3184/003685009X461495

'Geoengineering' – taking control of our planet's climate

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ABSTRACT

There is international consensus that 'dangerous' climate change must be avoided. Yet without radical changes in energy sources and usage and global economies, changes that so far society has been unable or unwilling to make, it seems highly likely that we will start to experience unacceptably damaging and/or societally disruptive global environmental change later this century. What actions can be taken to safeguard future environmental quality, ecosystems, agriculture, economy, and society? A new science – 'geoengineering' – that until recently would have seemed pure science fiction, promises an alternative way of temporarily regaining control of climate. Colossal engineering schemes to shade the sun, make the atmosphere hazier, modify clouds, even throw iron into the ocean, are all being promoted as possible ways out of our dilemma. This article considers the state of this new science, and its implications for society.

Keywords: *geoengineering, bio-geoengineering, climate, global warming, CO_2, mitigation, terraforming, carbon sequestration, albedo*

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1. Introduction

The idea of deliberately manipulating the climate of a planet has long been a recurring theme in science fiction writings. Known as ‘terraforming’, cold planets such as Mars, or even the Moon, are warmed by the addition of greenhouse gases to the atmosphere, or given increased sunlight by the positioning of giant mirrors in space, with the aim of making the planet habitable for life (Figure 1). In reverse, too-hot planets such as Venus would have their atmosphere progressively stripped of excessive greenhouse gases and the strength of solar radiation reduced by sunshades. The increasing awareness and concern about the potentially dire consequences of a much warmer future Earth has led to a recent explosion of interest in applying terraforming to Earth – ‘geoengineering’ – the deliberate modification of the Earth’s climate to counter-act global warming and climate change.

The history of geoengineering actually pre-dates much of the science fiction literature of terraforming. The Swedish scientist Svante Arrhenius (1859 – 1927), who first recognised the important link between carbon dioxide (CO_2) in the atmosphere and climate (later termed the ‘greenhouse effect’), apparently considered the climatic implications of industrial activities and the burning of coal rather good things because of the harsh winters in Sweden[1]. He logically wondered whether coal should thus be burned more quickly to accelerate the warming! The first serious consideration of geo-engineering had to wait until the 1960s and 70s, when at the height of the Cold War the former USSR considered ways to warm its vast icy tundra in the hope of generating fertile farm land. The spirit of this planned intervention is captured in ‘‘Man Versus Climate’’, a book describing the weather and climate modification plans of the USSR at the time[1]. Today, the feasibility and desirability of geo-engineering are being seriously assessed by researchers and governments as a means of altering the Earth’s climate system to ameliorate (reduce) the global warming impacts of continuing fossil fuel CO_2 emissions[1].

In this paper, we review the engineering technologies that might give us the ability to retake control of our planet’s climate and reduce global temperatures. We will discuss the climate benefits of these schemes, as well as the side-effects and risks they pose. We will also touch on the economics and ethics of geoengineering – critical facets of the debate, yet ones that have to date very much lagged behind the maturation of the physical science. We will also briefly outline the possibilities for addressing the root cause of

Fig. 1. *Image showing the potential terraforming of Mars to an earth-like state as viewed from Phobos. Copyright © David A. Hardy/www.astroart.org*

global warming and how CO_2 might be removed from the atmosphere. But we will start by summarising the underlying science of climate change, which provides the background to how geoengineering schemes actually 'work' (*i.e.* how they interact with the climate system).

1.1 Climate and the greenhouse effect

The Earth's climate system is driven by sunlight (Figure 2). Averaged over the year, the Sun provides 417 Wm^2 at the Equator, 237 Wm^2 at latitude 60°N, and only 173 Wm^2 at the poles[2]. The tilt of the Earth's spin axis means that incident solar radiation varies over the year as the Earth orbits the Sun, driving seasonal changes in sunlight which become stronger the farther from the Equator you are[2]. Together, this means that there is a latitudinal and seasonal disparity in the strength of solar energy reaching the planet, which is critical in setting the characteristics of our climate system. Not all this energy is absorbed – a proportion of sunlight is reflected back (called 'albedo'). Clouds have an albedo in the range 0.3–0.9 (*i.e.*, 30–90% reflected), meaning that not all solar energy reaching the Earth reaches the ground – about 74% on average[3].

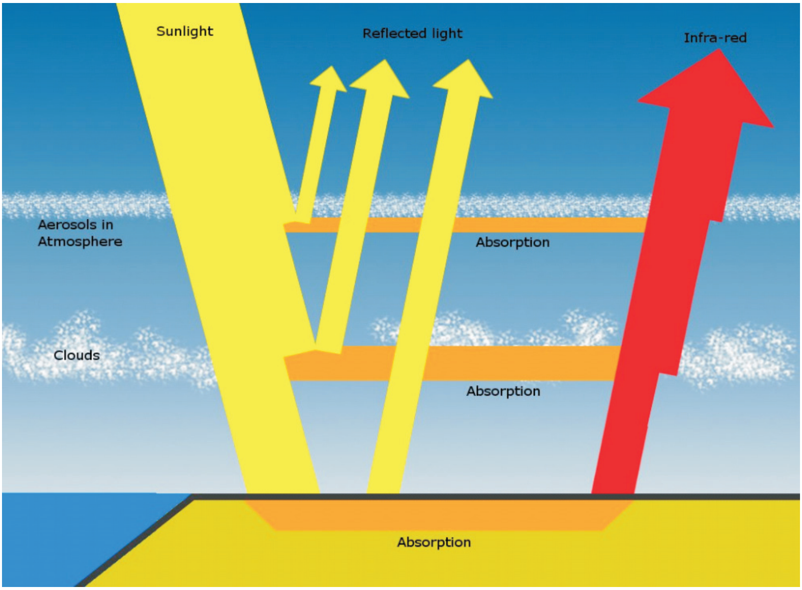

Fig. 2. *Diagram showing the radiation balance of the earth with the absorption and re-emission of solar energy. The yellow lines show incoming or reflected light; orange lines show absorption in the atmosphere, at cloud-level and at the ground; and red lines show re-emitted thermal radiation.*

Of the solar energy reaching the surface of the Earth, most is absorbed – although fresh snow has an albedo of 0.95 (95% reflected), dark, wet soil has an albedo of only 0.05, while with the sun overhead, the ocean can absorb 97% of solar energy (3% reflected, and albedo = 0.03)[3]. The atmosphere is thus heated from below as air overlying the surface heats up and becomes buoyant and rises ('convection'). Convection redistributes heat energy vertically through the climate system and drives the major circulations in the atmosphere and ocean[2]. Movements of air and water across the globe are affected by the rotation of the Earth and get deflected (the 'coriolis effect'). The major flows in the climate system act to transport heat from the Equator (where solar energy input is highest) northwards towards the poles (where solar energy input is least). The Atlantic Ocean Gulf Stream is a good example of this redistribution of heat energy, and provides a seasonal warming of up to 10°C in land areas bordering the North Atlantic[2].

This is only one side of the climate story: to be in thermal equilibrium, the Earth must on average, emit as much energy as it absorbs[4]. Absorbed solar energy cannot be re-emitted back to space in the same visible wavelengths as it was received, because the Earth is (fortunately) so much cooler than the surface of the Sun (5500°C!). Instead, energy is re-emitted at infrared wavelengths – this is the warmth you feel from a distance from a hot water radiator even though you can see nothing if you turn off the lights. However, to escape the Earth, infrared radiation originating at the land and ocean surface must pass through the atmosphere. This is also where 'greenhouse gases' such as carbon dioxide (CO_2) come into the picture.

The CO_2 molecule is important because it has a special property – trapping certain wavelengths of the infrared radiation that is trying to escape to space[2]. Water vapour is also a good absorber of infrared radiation, as is methane (CH_4) that is released from decaying vegetation in swamps and as cows digest grass, and nitrous oxide (N_2O)[5]. Much of the infrared spectrum is blocked by water vapour, and the Earth finds it difficult to lose heat at these frequencies. However, there is an important 'window' region through which most infrared radiation escapes to space. The concentration of CO_2 in the atmosphere has a particularly important effect on climate because one of the frequencies it absorbs most effectively at sits right up against this window[5]. Adding more CO_2 molecules to the atmosphere takes a bigger 'bite' out of the window.

The presence of CO_2 in the atmosphere along with water vapour and CH_4 means that the Earth's surface is warmer than it would be if there were no infrared-absorbing gases at all in the atmosphere[2]. This process is what is known as the 'greenhouse effect', although this is something of a misnomer because greenhouses work primarily by preventing the loss of heat energy by convection. The presence of a greenhouse effect on Earth is a natural phenomenon and the average surface temperature of the Earth in the absence of infrared absorbing gases in the atmosphere would be about −19°C(!), compared to about 14°C with them[4]. The concern today over 'global warming' is the rapid build-up of more and more CO_2 in the atmosphere due to the burning of fossil fuels and deforestation, which is progressively enhancing the strength of the greenhouse effect[5].

1.2 Fossil fuel CO_2 emissions and our future climate

Human influences on the Earth's surface (land use change) and the fossil fuel emissions since the Industrial Revolution (*ca*. the year 1765) have altered the concentrations of gases in the atmosphere.

Concentrations of the important greenhouse gases: CO_2, CH_4, and N_2O have all increased dramatically. CO_2 concentrations were at 379 ppm (parts per million) in 2005, compared with pre-industrial concentrations of ~280 ppm[5], while CH_4 has more than doubled and N_2O increased by ~20%[5].

The atmospheric burden of sulfur dioxide (SO_2) and carbon soot, released as by-products in the burning of coal and other fossil fuels, have also increased since the Industrial Revolution[5]. However, unlike greenhouse gases, these aerosol particles can also interact with incoming sunlight, and while they can have significant health impact and poison ecosystems ('acid rain'), they act to cool the Earth by reflecting sunlight[5].

We can calculate the importance of increasing CO_2 (and other greenhouse gases) and changes in aerosols, together with natural perturbations such as solar variability and volcanic eruptions, using computer models[4]. Modelling of the climate is a relatively new field in science and has developed rapidly with the advent of computing power. In a climate model, the atmosphere, ocean, and land surface are split into discrete cells, with the flows of heat, radiation and mass between these cells calculated. These models are then tested against measured historical changes in surface temperatures to see whether the necessary physics has been included in them[4]. All climate models agree that the temperature signal resulting from natural phenomena alone, such as volcanic eruptions and variability in the activity of the Sun, produce a very poor fit to historical instrumental observations (Figure 3)[5]. Only when enhanced greenhouse warming due to increasing green house gases and cooling due to SO_2 emissions are taken into account is the instrumental record reasonably reproduced.

What do these models predict for the future? The Intergovernmental Panel on Climate Change (IPCC), the body of climate change experts that the United Nations has tasked with scrutinising and evaluating available observations and models, predicts a further 2–4.5°C increase in global annual average surface temperature by the end of this century if nothing is done to limit CO_2 emissions[5]. Appreciating the implications of this warming is difficult, because the outside air temperatures we experience in our daily lives are often much larger from day-to-day (or midnight compared to midday). To put it into perspective– the last ice age was only 4°C cooler on a global annual average, yet cities like Edinburgh (UK) and New York would have been buried under 1 km of ice[2]! Details of the potential regional and seasonal changes in temperature and precipitation, and associated heat

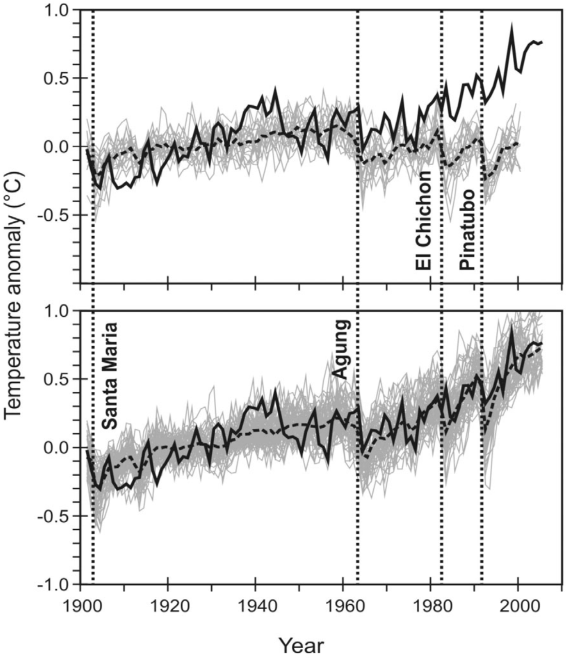

Fig. 3. *Diagram showing a comparison between observed and model-predicted global mean surface temperatures since 1900. The upper panel shows the individual predictions of a range of atmospheric GCMs (thin grey lines) when including only solar variability and volcanic eruptions as external forcings, with the mean of the models as a black dashed line. The lower panel shows the individual predictions of the same GCMs but with the effect of increasing greenhouse concentrations in addition to solar variability and volcanic eruptions and with the model mean. In both panels the instrumental observations from 1900 to present are indicated by a continuous black line. All temperatures are plotted as anomalies relative to the period 1901–1950. Major eruptions are marked with dotted lines and labelled. Adapted from IPCC (2000)*[5].

waves, droughts, and floods associated with a 2–4.5°C warming, could fill an entire volume (and indeed it does–the IPCC's 4th assessment report![5]).

Despite the likely very serious disruption to ecosystems and economies, farming and health of continuing unrestricted fossil fuel usage, the international response to emissions targets has been poor and emissions continue to rise at an accelerating rate. In a strategic energy review in 2008, the EU set itself the target of a 80% reduction of CO_2 emissions compared to 1990 levels by 2050, with the aim of avoiding a 'dangerous' climate warming of 2°C[6]. However, these cuts would need to be carried out globally, with developed nations making larger cuts than developing countries. If only a 60% reduction was achieved globally by 2050, there would still be a 2°C warming by the end of the century[6]. Is there another way of limiting or reversing rising atmospheric CO_2?

1.3 Putting the genie back into the bottle

Since the industrial revolution we have released over 244 Pg of carbon ($PgC = 10^{15}$ g carbon $= (12 + 16 + 16/12) \times 10^{15}$ g of carbon dioxide (CO_2) gas) into the atmosphere[5], equivalent to 894,670,000,000 tonnes of CO_2 gas! To put this into perspective: current human emissions of CO_2 to the atmosphere from the burning of fossil fuels is over 7 PgC yr^{-1} and remaining oil reserves amount to around 340 PgC[7]. The consequences of land use change, as forest and natural vegetation are cleared for crop and pasture land has resulted in another 100–180 PgC released[8]. However, of these emissions, a little less than half has remained in the atmosphere–ocean uptake, as CO_2 gas will dissolve in seawater, and vegetation growth elsewhere, 'fertilised' by higher atmospheric CO_2, together account for the 'missing' carbon[5]. Hence, the natural cycle of carbon on Earth acts to transfer excess CO_2 in the atmosphere into the oceans and vegetation and soils on land. The ability of the oceans and land to soak up emissions is not unlimited, however, and more than one quarter of all CO_2 emissions will still be in the atmosphere after a thousand years[9]. Only very slow acting geological process can remove this final fraction[2]. The multitude of processes at work gives us some scope for the selective and deliberate tweaking of certain pathways to further reduce the CO_2 fraction in the atmosphere, in effect: fine-tuning the engine of the global carbon cycle[9].

One of the most widely discussed methods for fine-tuning the global carbon cycle involves fertilising microscopic plants ('phyto-plankton') in the ocean[10]. The principal of ocean fertilisation is simple: find an area of ocean in which nutrients such as phosphate and nitrate are insufficient to support maximum photosynthesis and phytoplankton growth, add the limiting nutrient. Hopefully, the resulting increase in photosynthesis captures additional CO_2, with dead phytoplankton taking it with them to the deep ocean and temporarily out of harm's way[10]. However, a recently proposed commercial test of urea fertilisation by the Ocean Nourishment Corporation was cancelled after warnings that it would cause a boom in the population of dinoflagellates, a species of plankton that releases a poisonous substance into the waters killing fish[11]. Over-fertilising also runs the danger of causing local anoxia, where oxygen levels drop as other sea creatures respire dead phytoplankton as food, and areas almost devoid of marine life can result[10]. Other scientists have suggested the deployment of giant pipes anchored in the ocean, which would use wave power to drive nutrient rich water from hundreds of meters down to the surface, although doubts have been raised about its potential efficacy and implementation[9].

Elsewhere in the ocean, phosphate and nitrate are abundant, but the growth of phytoplankton is still limited – now by lack of the micro-nutrient iron. Iron-limited regions of the World's ocean include the Southern Ocean, Eastern Equatorial Pacific, and North Pacific[10]. A variety of experiments, both in the laboratory and also out in the open ocean, have demonstrated that adding iron results in increased phytoplankton productivity and uptake of phosphate and nitrate[9]. However, the magnitude of CO_2 that would be locked up in the deep ocean (and thus isolated from the atmosphere) is much more uncertain – recent model simulations predict a maximum carbon drawdown of between 26 PgC and 70 PgC[10], equivalent to no more than 4 – 10 years of current emissions[7].

Planting trees (afforestation) or restoring farm or degraded land to natural vegetation cover (reforestation) are obvious ways of utilising plants to store carbon on land[8]. The amount of CO_2 that could be captured in standing biomass and soils varies according to latitude, with tropical forests storing 120 tons of carbon per hectare with temperate and boreal (high latitude) forests holding 60 and 35 respectively[8]. One negative side effect of afforestation is that forests at high latitudes have a lower albedo during the winter than snow-covered ground, absorbing more light, so afforestation would only produce an overall cooling of climate at lower latitudes[8]. Furthermore, afforestation competes for the same scarce resource (land) as agriculture and natural environments.

Carbon captured by plants on land could potentially be stored more permanently in soils or in the ocean rather than left as relatively vulnerable standing vegetation. At the extreme, dumping crop residues or other biomass at sea may produce a semi-permanent storage of carbon; although at the risk of anoxia (see above)[9]. Instead, burning biomass in a low oxygen atmosphere will create charcoal. This biochar can be buried in soils, trapping the carbon perhaps for centuries[12]. The Aztecs used this method to improve soil quality and significant amounts of carbon are still stored in those soils[12]. Initial studies have found that up to 140 tons of carbon per hectare could be stored in this way[12]. If all crop wastes were biocharred, 0.16 PgC per year would be sequestered[12]. Again, while helpful, this amount is tiny compared to the scale of the CO_2 emissions problem (>7 PgC yr^{-1}).

The technology exists to capture CO_2 directly from the air, using industrial chemical processes in huge free-standing 'artificial trees'[13]! Air capture is the only geoengineering scheme that may have the capability to reduce atmospheric CO_2 levels to Pre-industrial values[9]. Note that air capture is distinct from conventional and simpler technologies that exist for removing (and storing) CO_2 from the flue gases of fossil fuel power plants – 'carbon capture and storage' (CCS). CCS is in effect a form of pollution control, and we will not cover it in any further detail here. There have been a number of air capture technologies proposed: Keith *et al.*[13] suggest using sodium hydroxide sprays, while Nikulshina *et al.*[14] proposed using calcium oxide pellets. Both methods seek to regenerate the CO_2-removing reagents so that they can be used over and over again. Global Research Technologies have a patent for a synthetic tree with embedded sodium hydroxide resin panels. However, while the chemicals used are often cheap and abundant, the energy requirements of regeneration (recycling) are considerable[13]. The cost, mainly energy, in one method leads to an estimated cost of $500 per tonne carbon captured, compared to a value of carbon emissions saved of around $20 per tonne on international carbon trading markets[13]. Direct air capture is only viable with a cheap, clean form of energy. As with CCS, captured CO_2 still needs to be stored, either in geological reserves or in the deep ocean. Both kinds of reservoir will 'leak' some CO_2 back to the atmosphere gradually, requiring long-term monitoring and stewardship of the CO_2 reservoirs[9].

2. Technologies for directly cooling the planet

Given the difficulties being faced in achieving substantial CO_2 emissions reductions, whether by changing the day-to-day habits and choices of individuals or creating consensus between government and binding international agreements, and the costs and difficulties of recapturing CO_2 from the air once it has been emitted, it is no wonder that people are starting to ask in earnest: 'is there some other way of taking control of climate and limiting future warming?' This is where 'geoengineering' comes in. In this paper we use a fairly loose definition – the deliberate modification of the Earth's climate system to mitigate (reduce or alleviate) global warming. There are a wide variety of geoengineering ideas, so we

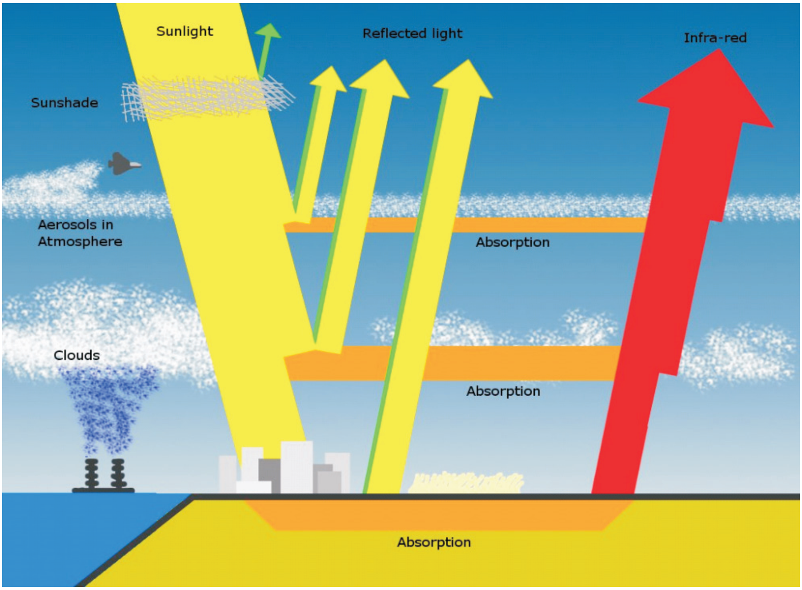

Fig. 4. *Diagram showing the radiation balance of the earth with the effects of some geoengineering schemes shown. The yellow lines show incoming or reflected light; orange lines show absorption; red lines show re-emitted thermal radiation; and green lines show enhanced reflection by geoengineering; in space, in the atmosphere, at cloud-level and at the ground.*

are going to limit the discussion to those that seem more plausible and potentially effective, summarised in Figure 4. (Indirect geoengineering schemes, which produce a cooling via reduced greenhouse gas concentrations, were covered previously in Section 1.3.)

2.1 Giant sunshades in space

The most direct way to reduce the amount of sunlight absorbed at the Earth's surface is to intercept incoming sunlight in space. It has been proposed that a cloud of reflective satellites positioned near the L1 Lagrange Point, a place in space where the gravitational pull of the Earth and Sun balance, some 1.5 million km from the Earth (almost 4 times the distance between the Earth and the Moon), could be used to deflect a percentage of the sunlight heading for Earth (Figure 5)[15]. This idea is truly straight out of a sci-fi novel, yet feasibility studies and other research is being conducted into the possibility of doing it. To create a Pre-industrial global temperature in a world with doubled CO_2 in the atmosphere (compared to in

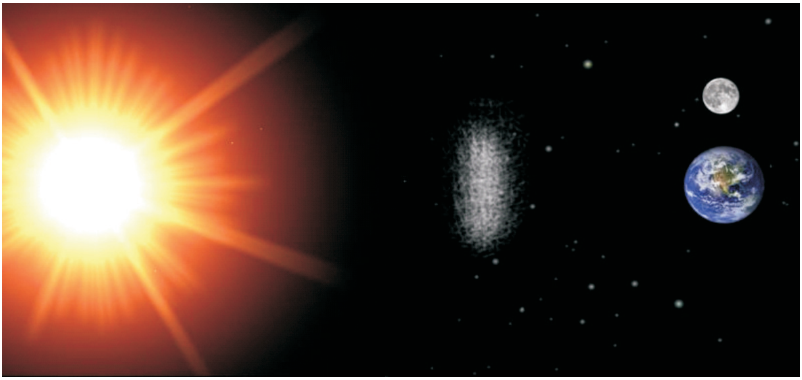

Fig. 5. *Diagram showing the relative position of the sunshade to the Earth, the Moon and the Sun. The sunshade is at approximately 4 times the earth to moon distance. The diagram is not to scale!*

1765), it has been estimated that 1.8% less sunlight would have to reach earth[16]. A design by Roger Angel[15] envisages ∼16 trillion satellites with a total mass of ∼20 million tons achieving this. To make this geoengineering scheme feasible, the current cost to put 1 kg in space of ∼$20000 would need to drop to $50 per kg[15]. This may be achieved by using electric rail guns to launch the satellites into position, with the main cost then being the generation and storage of the electricity. On this basis, the total estimated cost of the system is less than 5 trillion dollars[15] and it could be in orbit in 25 years. Averaged over the lifetime of the system (50 years), this is only 0.2% of predicted global GDP[15].

The impacts of the sunshade on climate are fairly straightforward to model because it involves a simple reduction in the strength of solar energy reaching Earth. Climate models (*e.g.*, Govindasamy *et al.*[16] and Lunt *et al.*[17]) show that the Equator of an optimally sunshaded Earth would be cooler, and the poles warmer, compared to the Pre-industrial era with low CO_2 and no sunshield. This is because the warming produced by elevated atmospheric CO_2 levels is strongest at the poles compared to the Equator, while the cooling produced by a reduction in solar strength is strongest at the Equator[17]. Knock-on effects include a reduction in some ocean and atmosphere circulation intensity and a drop in precipitation as evaporation on land is reduced as a result of lower solar heating[17].

In its favour: sunshade geoengineering is the ‘cleanest’ solution, in as much as it involves no direct major changes in the Earth’s chemistry or biology. The sunshade can be scaled up to deal with very high atmospheric CO_2 concentrations simply by adding more

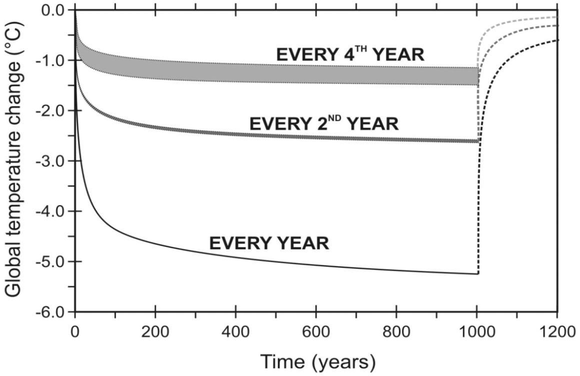

Fig. 6. *Diagram showing the global mean temperature response to multiple volcanic eruptions (or alternatively repeat stratospheric sulfate aerosol geoengineering injections). Warming is rapid when the injections are stopped (year 1000). Adapted from Wigley (2006)*[18].

satellites to the sunshade. Another important aspect of sunshade geoengineering is it can be scaled down or shut off rapidly if unexpected side-effects arise[15].

2.2 Chucking aerosols high in the atmosphere

Mount Pinatubo in the Philippines erupted in June in 1991, injecting a huge quantity of dust and sulfur dioxide (SO_2) high into the atmosphere[18]. SO_2 interacts in the atmosphere to produce tiny droplets of sulfuric acid – highly reflective aerosol. A global cooling of up to 0.5°C was observed in the years following the eruption as the plume of aerosols spread around the World[19]. This volcanically induced cooling was the inspiration for a method to cool the earth by the deliberate and repeated injection of sulfate aerosols into the stratosphere[18,19] (Figure 6[18]).

The lifetime of sulfur aerosols in the atmosphere depends upon the height at which they are introduced[18]. SO_2 is produced as a by-product of fossil fuel burning with about ~ 55 Tg [10^{12} g] emitted annually[20]. The relatively low height of power station chimneys means that the SO_2 rapidly drops out of the atmosphere and falls as acid rain and contributes to air pollution. Injecting sulfate aerosols at a much higher altitude (in the stratosphere) will increase the lifetime to around 1 or 2 years[19] and thus create a much greater cooling effect per tonne than can be achieved at low altitudes (in the troposphere). It has been calculated that an injection of only 5 Tg yr^{-1} of SO_2 into the stratosphere could offset the warming induced by a doubling of atmospheric CO_2, yet amounts to less than 10% of current (tropospheric) emissions and thus acid rain[21]. Even less mass would be needed if added in the form of hydrogen sulfide which has a molecular mass just over half that of SO_2 (H_2S [1 + 1 + 32] compared to SO_2 [32 + 16 + 16])[21].

A variety of delivery methods for injecting sulfur aerosol precursors into the stratosphere have been proposed: from artillery shells to balloons[21]. A cost analysis by Robock *et al.*[21] showed that release from high-flying aircraft is the most economical method and would cost as little as $225 million per Tg after the purchase of the planes. The cost to offset the warming from a doubling of CO_2 would therefore be ~$600 million per year, or less than (1/1000)% of global GDP.

If the sulfate aerosols can be evenly applied through the atmosphere the effects on incoming sunlight should be nearly equal to the effects of the sunshade, although some outgoing sunlight will be reflected back downwards[16]. In a recent paper, Brovkin *et al.*[22] showed that some areas with a high ground albedo, specifically north Africa (light coloured, dry desert sand), and the Tibetan plateau were warmer than expected in summer by up to 1°C in a simulated aerosol geoengineering experiment. A stratospheric aerosol geoengineered world would also have a reduction in precipitation and reduced equator to pole temperature gradient as per the sunshade[22]. While there is also a risk of unexpected negative effects on the chemistry or cloud formation of the atmosphere, the low cost and relatively low adverse impacts of stratospheric aerosols make it one of the most feasible and attractive radiation geoengineering schemes[9].

2.3 Making clouds over the ocean whiter

John Latham first suggested increasing the albedo of clouds via the Twomey Effect[23,24]. Twomey noticed that clouds above the shipping lanes were whiter than the other clouds of the ocean. The formation of water droplets in a cloud is aided by the presence of particles around which the droplet can be formed, like the particles from a ship's exhaust[24]. The addition of cloud condensation nuclei (CCN) to make more but smaller droplets raises albedo, because the albedo of clouds is dependent on the water droplet concentration[24]. This is the Twomey Effect. Clouds with higher concentrations of water droplets also tend to have more difficulty making rain and thus are longer lived on average[25].

Fig. 7. *Artist's impression of the proposed "spray vessel" of Salter* et al. *copyright © John MacNeill, www.johnmacneill.com, 2009.*

The oceans of the world have a low albedo (as low as 0.03), high area, and unlimited reserves of salt water, making them a good location to treat clouds[23]. A doubling of the droplet number of all susceptible maritime clouds would increase the albedo of those clouds by 0.06 ($\sim$10–20%) and would require a supply of 23 $m^3 s^{-1}$ of micron sized salt water droplets[23]. One embodiment of this scheme envisages a fleet of wind powered ''spray vessels'' (Figure 7) roaming the seas in regions with clouds susceptible to albedo increase and pumping out micron-sized droplets into the air[26]. In calculations by Latham, doubling the natural droplet number would be sufficient to offset the warming produced by a doubling of CO_2[23]. The design of Salter *et al*. requires a fleet of 1500 ships to produce the required volumes of spray to offset a doubling of CO_2 at a cost of \$2–4.5 billion[26].

The greatest cooling induced by cloud albedo enhancement would be in the regions with the most suitable precursor clouds[23]. Although cooling would be spread by ocean and air circulation, the differences in climate between Pre-industrial and a world with enhanced maritime cloud albedo and high CO_2 would be very significant[23]. For instance, cooling would be biased towards the

Southern Hemisphere due to disproportionate area of ocean compared to the North. Because the propensity of a cloud to rain is reduced by having more droplets for the same water content[25], the distribution of rainfall would inevitably be changed[23]. Proponents of cloud albedo enhancement have even cautioned against its use upwind of drought prone areas[26]. A drop in total precipitation would be expected as well, due to cooler oceans and less direct sunlight which would reduce evaporation[16]. Doubts also remain over the complex interaction between aerosols and clouds and it is far from certain that the expected degree of cooling would be produced[23]. Despite these caveats, this geoengineering method may be a cost-effective way to mitigate some of the effects of global warming[9].

2.4 Changing the reflectivity of fields and roofs

Numerous suggestions have been made to cool the Earth by increasing the albedo of parts of the Earth's surface, from manufacturing huge reflective coverings to altering plant cover[9]. The science is extremely simple – if a smaller fraction of solar energy is absorbed by a surface, then the overlying air will be cooler. At the extreme, enormous sheets of reflective foil could be draped over the landscape. In Switzerland, they are actually trying this as a way of reducing the melting of the Gurschen glacier to safeguard the future quality of skiing in the area!

Humans have already altered the properties of a large fraction of the Earth's surface, with vast areas devoted to agriculture and urban spaces[8]. Altering surface albedo would be much easier in these regions and would have a smaller environmental impact than altering the albedo of untouched, natural regions[9]. For instance, it has been suggested that the albedo of urban areas could be doubled from 0.15 to 0.3 by requiring buildings to have roofs with a high albedo and to repave roads with a more reflective material[9]. However, doubling the albedo of urban areas would have an insignificant effect on global temperatures due to the relatively small area of urban settlement but locally it would be of great benefit and would reverse the heat island effect and mitigate some of the damage from heat waves[9].

Alternatively, Ridgwell *et al.*[27] suggested modifying the albedo of the crops that are grown. By choosing higher albedo varieties, an albedo increase of 0.04 may be possible across agricultural land areas. In a climate model, they found that the effect on global temperatures was small: only 0.11°C, but that there was a latitudinal band of concentrated cooling across North America, Europe, and into Asia[27]. This cooling was seasonal in nature and had a maximum reduction of over 1°C in some areas during the northern hemisphere summer when crops are fully in leaf. This would mitigate some of the more worrisome effects of global warming in these regions, reducing heat wave intensity and improving growing conditions through less severe droughts[27]. The costs of switching from one variety to another of the same type of crop would be minimal, although commercially viable varieties of 'climate friendly' higher albedo crops do not currently exist and would have to be bred and/or genetically engineered[27].

3. Should we try to geoengineer our future climate?

Geoengineering is increasingly being assessed in climate modelling research, and engineers are beginning to make serious feasibility studies. These early analyses show that geoengineering by altering the radiation balance of the climate system may be achievable on a global scale in a relatively short time, 25 years minimum for the sunshade for example[15] and perhaps even less for the cloud albedo or stratospheric aerosol schemes[21,26]. However, not all geoengineering schemes are created equally – they vary in the scale and magnitude of their theoretical impact[9]. Some are more inherently risky than others are, and perhaps more practically, the cost of geoengineering schemes varies significantly. We have summarised the major solar energy geoengineering schemes discussed in Table 1.

Global warming is the direct consequence of the accumulation of CO_2 emissions in the atmosphere[5]. The total amount of CO_2 we emit will determine how difficult 'fixing' the Earth's climate in the future will be. CO_2 has a lifetime in the atmosphere that is ultimately measured in hundreds of thousands of years[5]. Solar energy geoengineering schemes thus need to be maintained for as long as a substantial fraction of greenhouse gases in the atmosphere remain – hundreds of years at least in the absence of direct removal of CO_2 from the air (see: Section 1.3)[22]. The large-scale 'failure' of any particular geoengineering scheme during this interval will be serious. Studies have been carried out to investigate the effect of a shutdown of a solar energy geoengineering scheme on the climate[22] and have found that the modelled climate rapidly warms at rates 20 times greater than current warming (also see Figure 6). The impacts of this very rapid global warming would be catastrophic, potentially causing a mass extinction and putting intense pressures on the

Table 1 *Shows the pros and cons of the five geoengineering schemes discussed*

Scheme	Pros	Cons	Risk	Cost
Sunshade	• Clean • Can 'fix' global warming • Scalable • Can be stopped quickly • Easy to predict effects	• Advanced technologies required • Very large energy expenditure • Reduction in precipitation • Changed distribution of heat and precipitation globally	High	~\$5 Trillion for offsetting doubled CO_2
Sulfur aerosols	• Technologies available now • Can 'fix' global warming • Scalable • Can be stopped in 1–2 years	• Reduction in precipitation • Changed distribution of heat and precipitation globally • Warms some areas • Efficacy somewhat uncertain • Uncertain effects on cloud formation and ozone	High	> \$600 Million for offsetting doubled CO_2
Cloud albedo	• Regional deployment • Can 'fix' global warming • Scalable to some extent • Can be stopped within days	• Efficacy uncertain • Changed distribution of heat and precipitation globally • Global precipitation reduction • Concentrated local effects on temperature and precipitation	Medium	\$2–5 Billion for offsetting doubled CO_2
Crop albedo	• Regional/latitudinal cooling • Mitigates some negative climate impacts • Easily implemented	• Globally insignificant cooling • Only benefits certain regions • Reflective crops need to be bred	Very Low	Negligible for crop switch
Urban albedo	• Technologies exist • Mitigates negative effects of warming on cities	• Significant maintenance • Globally negligible cooling • Only benefits immediate area • Somewhat complicated to implement • Aesthetic change to cities	Very Low	~\$ Billions for full application

adaptive capabilities of countries[22]. This means that future international wars or economic collapses could be compounded by disastrous climate change.

The biggest problem with geoengineering is arguably that it does nothing to address 'the other CO_2 problem' – ocean acidification[28]. Since the Industrial Revolution, the oceans have taken up approximately 50% of the CO_2 from fossil fuel burning and cement manufacture[5]. CO_2 forms carbonic acid with seawater and lowers ambient pH in a phenomenon known as 'ocean acidification'[28]. The associated decline in carbonate ions (CO_3^{2-}), a form of dissolved carbon in the ocean that is depleted in the acidification reaction when CO_2 added to seawater, is critical, because the shells and skeletons of many marine organisms are made of calcium carbonate ($CaCO_3$) which dissolves at low carbonate ion concentrations ('under-saturated' conditions). Marine organisms with unprotected shells and skeletons (*e.g.*, most corals) made of aragonite, a relatively soluble form of $CaCO_3$, will be particularly vulnerable to ocean acidification[28].

Despite this, solar energy geoengineering 'fixes' of the climate may become necessary in the near future to avoid a dangerous climate change and perhaps to try and prevent the complete loss of summer-time arctic ice or to stop permafrost melting. The decision to conduct solar energy geoengineering is much more controversial than carbon capture. The effects of solar energy geoengineering may be beneficial locally but are global in scope whereas carbon capturing technologies have a global benefit and local impacts. During the Cold War, the former USSR and the USA both developed techniques to seed clouds and attempted to gain control over the weather for domestic and military purposes[1]. The USA experimented with the military use of weather control during the Vietnam war, which led the United Nations to outlaw the hostile application of climate and weather manipulation in 1977[29]. This is the only international agreement that in some way regulates geoengineering. However, it can be argued that it equally applies to (and is completely ignored for) fossil fuel emissions.

Aerosol and cloud seeding geoengineering schemes are within the technical and financial reach of a number of the countries of the world[30]. The effects of climate change on these countries, their ideas of what a 'good' climate is and their degree of environmental concern vary significantly, which means their attitudes to geoengineering will be starkly different. The vast majority of the countries of the world will not be able to unilaterally implement geoengineering strategies and so would arguably be in favour of banning the testing and implementation of geoengineering schemes[31]. Attempts to reach an effective global consensus on CO_2 emissions have been very difficult and it may be impossible to reach a consensus on geoengineering.

There exists the potential for conflict over the degree of cooling or impacts of geoengineering. Russia, for example, might favour a warmer climate and demand that little or no geoengineering take place. The climate impacts of a geoengineering intervention could also be a cause of tension with countries unhappy about changes in precipitation or weather patterns. To see the climatic effects of a geoengineering strategy is inherently hard due to the large year to year variability in the system and to do so would require a decade or more of careful observations[5]. Reaching international consensus on the necessary safeguards and tests for geoengineering, the liabilities for damage, and the distribution of costs would be very challenging. Unilateral action is thus potentially more likely[31].

Economically, the cost of environmental and economic damage due to un-addressed future climate change will be huge, 0–3% and 5–10% of global GDP for a 2–3°C and a 5–6°C warming, respectively[20]. Despite this, the availability of cheap fossil fuels and lack of political will is delaying the costly change to renewables[7]. The costs of a CO_2 abatement strategy would be in the order of 3% of gross world product (GWP) by 2100[30]. Economic studies of sulfate geoengineering concluded that it has effectively negligible cost[32]. Goes *et al.*[30] find that the economic impacts of sulfate geoengineering in place of carbon cuts is 1% of GWP for continuous application. However, they calculated that the economic impact of a rapid shutdown of geoengineering would be of the order of 6% GWP. The uncertain nature of the risk of a geoengineering shutdown and its immense impact make it very difficult to apply a reasonable cost-benefit analysis to geoengineering[30]. The non-economic arguments against geoengineering at the expense of costly CO_2 reductions are overwhelming; it is a fundamentally dangerous strategy[22].

Geoengineering presents us with a moral conundrum: would the knowledge of the option for a cheap 'fix' for climate change be enough to weaken political will to reduce carbon emissions? Delaying reductions in emissions with knowledge that the damage can be offset will result in greater damage to the environment than from relying less heavily on geoengineering[1]. This moral hazard may remain even if geoengineering is the best way to deal with climate change in the long run. Rapid CO_2 emission reductions will still give rise to a dangerously warm climate in the next century or two and so a (limited) geoengineering intervention may be of benefit[6]. As early as 1977, the Geophysics Study Committee of the National Academy of Science raised the question: ‘‘What should the atmospheric carbon dioxide content be over the next century or two to achieve an optimum global climate?’’[1]. If the way that the carbon dioxide problem is approached changes from a pollution-based to a design-based response then a range of ethical questions are raised, such as: ‘‘what do we want from the climate?’’. The answer to this question will involve trade-offs between environmental concerns, individual rights, and utility. It will also require an ethical framework which can incorporate individual rights and environmental ethics, which locates moral value above the individual, in species and ecosystems[1].

4. Summary

Geoengineering encapsulates a multitude of different schemes and ideas – some practical and costed; some almost pure science fiction. All adopt one of two basic lines of attack on the climate system: (1) removing CO_2 from the air and thus restricting the intensity of the greenhouse effect, or (2) reducing amount of solar energy absorbed by the Earth. The scales and magnitude of impact of the different interventions range from a complete reversal of surface warming globally and the capture of all fossil fuel CO_2 released to date, down to the reduction in the severity of heat waves and drought regionally and seasonally. As geoengineering schemes are increasingly brought into the national and international debate, the distinctions may become critical. Carbon capture deals with the root of the problem – the ‘excess’ CO_2 present in the atmosphere. Yet this option may distract from reducing emissions and moving to a low carbon (or carbon free) energy economy. Radiation balancing schemes might cool the planet but are only addressing the symptoms, not the root cause. The ‘other CO_2 problem’ – ocean acidification, would continue unabated and the current diversity and economic value of marine ecosystems and resources would not be guaranteed. Global radiation balancing schemes should thus arguably only be used as an emergency response. However, small scale schemes and regional deployment, because the costs are generally much lower and the danger of ‘failure’ much less severe, may find a natural place in a mix of efforts to mitigate climate changes. Clearly, the impacts and benefits (and costs) of each scheme must be weighed and assessed. Importantly, there may be unexpected negative side effects of many or all of the proposed geoengineering schemes, and a great deal more research on their effectiveness and impacts, as well as full assessment of the technologies required, is needed before any decision can sensibly be taken.

While we are already progressively modifying our climate system by releasing vast amounts of CO_2 to the atmosphere, the decision to directly intervene in the climate system and implement some form of large-scale geoengineering cannot be taken lightly and is intimately bound up with the welfare of future generations. Short term gain in reduced surface temperatures may result in higher CO_2 in the long term or centuries long commitments to geoengineering. The most important thing is to reduce emissions as fast as possible to allow the most room to manoeuvre. If geoengineering is deemed necessary, the negative consequences and risks will be much smaller if less CO_2 is to be countered. Geoengineering should not be relied on to stop global warming, emissions cuts are key, but we may want to hold the science and technology ready in reserve should policy makers fail to grasp the urgency of the problem and emergency action is required in decades hence.

For decades past, as economies (and CO_2 emissions) grew and technologies improved, we increasingly fantasised through science fiction writings about the possibility of terraforming colder, dead planets and moons to make them habitable. Now the tables are turned, and we find ourselves discussing the terraforming of our own planet to keep it habitable (for humans). Did science fiction writers ever envisage the situation we find ourselves in now ... ?

Acknowledgements

Peter Irvine acknowledges support from NERC in the form of a PhD studentship. Andy Ridgwell acknowledges support from The Royal Society in the form of a University Research Fellowship.

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