1

Prolegomenon: A Geoengineering Primer

Martin Beech

Department of Physics, Campion College at the University of Regina, Regina, Saskatchewan, Canada

Abstract

Geoengineering encompasses many potential actions that set out to deliberately lower the aggregate temperature of the Earth's atmosphere. Such actions typically look to enhance the Earth's albedo, thereby causing a greater fraction of sunlight, over and above that at the present time, to be reflected back into space. Other actions seek to limit solar insolation by directly blocking sunlight, or by increasing cloud cover. This introduction seeks to examine not only how but why geoengineering might be deployed, but seeks to position it as a necessary part of future efforts directed towards combating global warming. A review is made of the various methodologies and protocols necessary for the future development and deployment of geoengineering actions.

***Keywords*:** Global warming, geoengineering, tipping points, solar radiation management

COPYRIGHTED MATERIAL

1.1 Introduction

Geoengineering [1.1] [1.2] [1.3] is a big, bold and brash idea, possibly now coming of age. It is a human-directed process, taking-on many potential forms, all of which act upon the environment with the specific aim of changing the environment. The primary reason for and goal of geoengineering[1] is to attempt the re-establishment of a common good—that is, to bring about a cooler Earth. Furthermore, geoengineering sits amongst the suite of actions that seek to address the principle causes of global warming [1.4]. This being said, geoengineering is often considered a controversial action, in part, because of the fact that it seeks to enhance human engagement with the environment, rather than reduce it. Importantly, however, while geoengineering seeks to cool the Earth's atmosphere, it does not address the root cause issues that are driving the global warming problem. While geoengineering is a strategic ameliorating action, it is limited in scope.

That a decision concerning the deployment of geoengineering must to be made, and made very soon, reflects a remarkable, and inherently unsatisfactory state of affairs—a state of affairs that has grown out of past and present-day inaction. This stubborn inaction is related to the prolonged political and societal failure in addressing the underlying causes of global warming—especially in the form of greenhouse gas emissions derived from the

---

Email: beechm@uregina.ca

[1] Also called climate control, climate management, and climate intervention.

Martin Beech (ed.) Geoengineering and Climate Change: Methods, Risks, and Governance, (1–30) © 2025 Scrivener Publishing LLC

burning of fossil fuels. It is now established beyond any reasonable doubt that the Earth's average temperature is increasing, and compared to past millennia, it is increasing very rapidly. In the past one-hundred years alone, the global average temperature has increased by about 1.1 °C [1.1] [1.2] [1.3]. Global warming, in spite of tergiversate counter arguments, is indisputably happening, and it will be with us for many centuries to come. Indeed, even if all anthropogenic derived greenhouse gas emissions stopped this very instant, the present levels of atmospheric CO_2 will continue to drive a significant increase in the Earth's temperature. The question is not whether global warming will continue to occur, but rather, what can be done now, and over the next several decades, to offset the worst of the changes that are latent within Earth's climate system [1.4] [1.5].

1.2 The Paris Agreement

While the reasonability of using the Earth's average temperature as the only measure of climate change is questionable [1.6], this quantity has, none the less, become the *de facto* measure of change. In this manner global warming is measured relative to the average temperature derived over the time interval from 1850 to 1900 (see Figure 1.1). This parameterization builds upon the notion that human actions (beginning with the onset of the modern industrial era) are at the core of the global warming phenomenon, and it further sets the goal of limiting future increases in temperature (above pre-industrial levels) to be as small as possible. Article 2(a) of the Paris Agreement contains the key motivation with respect to international efforts to curb global warming [1.7] [1.8], specifically, the aim being to:

> *[Hold] the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change.*

As with most political agreements, and especially international ones, the language promotes the positive, and downplays the devil in the details. The devil, in this case, is how to achieve the success of Article 2(a). The problem is not so much how to achieve this—of course, the solution is in fact quite clear—rather, the problem is how to overcome the political inertia (even outright hostility from some quarters) to enact and abide by policies that will dramatically reduce the emission of greenhouse gases due to anthropogenic actions. The Paris Agreement may well indicate a landmark moment in political diplomacy, but the proof by which it will be judged in the future will depend entirely upon the meaningful and timely actions taken by individual governments over the next several decades. Indeed, it is highly likely that the goals of Article 2(a) will not be achieved [1.9], with the global average temperature most likely exceeding 1.5 °C above pre-industrial levels by the mid-point of this century, if not sooner (Figure 1.1).

Geoengineering is motivated according to the dramatic increase in the Earth's average temperature during the last century (as per Figure 1.1)—the desire being to reduce its continued increase prior to the implementation of direct actions to limit and sequester greenhouse gas emissions. While the average global temperature provides a measure of how much the Earth is warming, detailed computer modeling and ground-based observations indicate

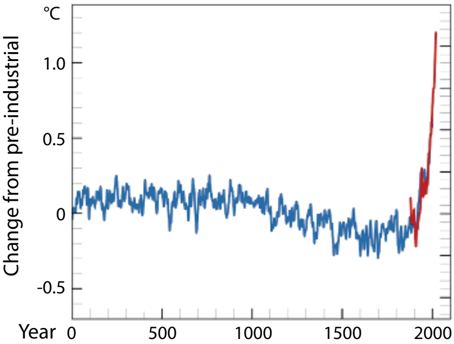

Figure 1.1 Change in global average temperature during the past 2000 years, inferred (blue line) from proxy tree-ring, coral growth, and ice-core data [1.10], and measured (red line) since 1880. (Image adapted from https://commons.wikimedia.org/wiki/File:Common_Era_Temperature.svg)

that the warming is not uniform across the globe. Indeed, warming is most pronounced in northern latitudes and especially so over land masses. Figure 1.2 shows the results from a series of detailed model calculations, performed under the guise of the Coupled Model Intercomparison Project Phase 6 (GMIP6). At a 1.5 °C temperature increase over the (1850–1900) average—similar to the Earth's present status—it is seen that the northern boreal and Arctic regions are seeing the greatest temperature increases, with the equatorial and southern hemisphere temperatures seeing smaller temperature changes. At 4 °C average temperature change, the northern latitudes are still most dramatically affected, but now all landmasses and the Antarctic regions begin to see significant temperature increases. In general, at a given latitude, the landmass temperature increase is about twice that found over the ocean. This is partly a result of the oceans having a larger thermal inertia, and partly due to mixing with deeper, colder water layers that have not been exposed to surface warming.

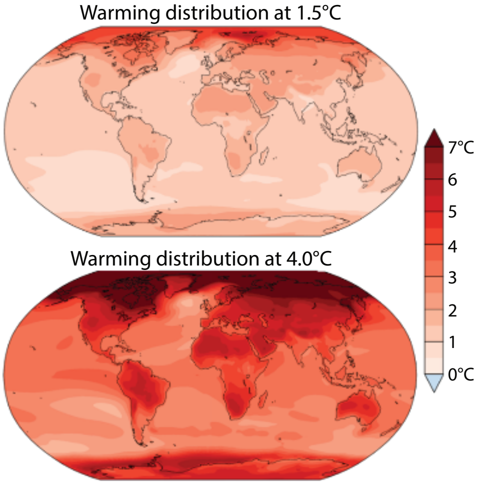

Figure 1.2 Projected changes in regional temperature (relative to 1850–1900) for global average warming amounting to 1.5 °C (top) and 4.0 °C (bottom). (Diagram based on Coupled Model Intercomparison Project Phase 6 (CMIP6) calculations)

Changes in the Arctic are larger than those at mid-latitudes in part due to a strong temperature/albedo positive-feedback mechanism that operates there. The regional effects of temperature change are complex and difficult to model in detail, but are generally discussed in terms of tipping points.

1.3 Tipping Points – Where Are We?

Current projections by the Intergovernmental Panel on Climate Change (IPCC) indicate that the Earth is likely to warm by at least 2 to 3 °C by the end of this century, and this increase will risk, if not fully guarantee, the triggering of multiple highly consequential tipping points. Indeed, tipping points delineate and underscore the risks associated with global warming. They highlight those moments and conditions under which an abrupt and rapid change, from one system state to another, takes place in an irreversible manner [1.11]. Tipping points are a characteristic phenomenon of nonlinear systems, and once breached they cannot be reset by simply reversing the driving parameters that caused the change in the first place. In the passing of a tipping point, what were previously system-stabilizing, negative feedback, mechanisms become overpowered by system-destabilizing, positive feedback mechanisms, with the system experiencing continuous change until a new equilibrium state is found. Problematically, the Earth's climate-determining system is composed of numerous nonlinear, subtly interacting subsystems, each operating on different size and time scales, and, as such, it is an extremely complicated system to model. A recent study by McKay *et al.*, however, has identified 16 tipping point thresholds that may be breached by 2100 [1.12]. These include the collapse of polar ice sheets, large-scale permafrost thawing, large-scale forest and coral reef diebacks, monsoon disruption, and the collapse of ocean

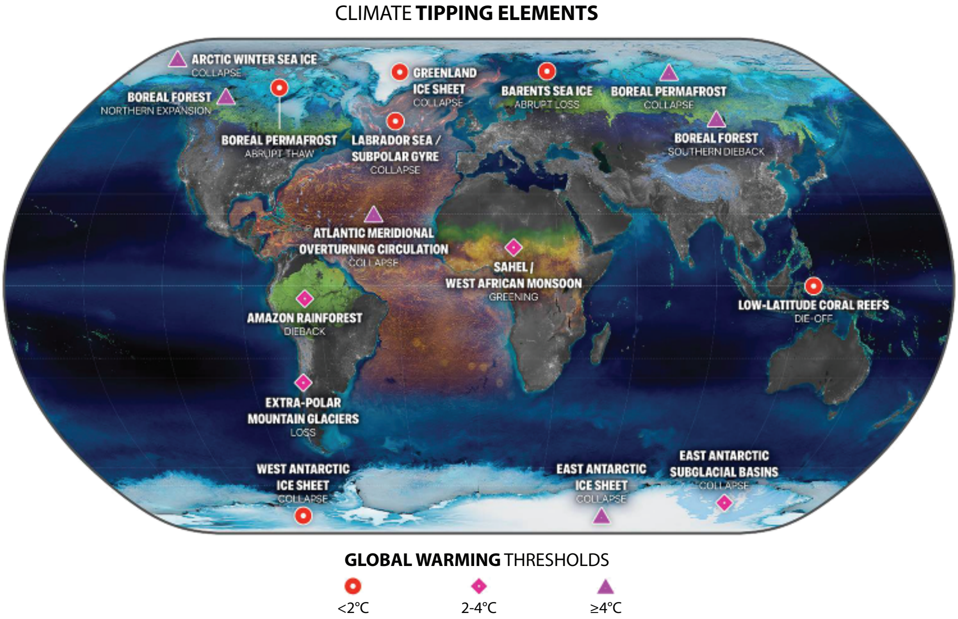

Figure 1.3 Locations of climate tipping points. (Image courtesy of Stockholm University [1.12])

circulation currents (Figure 1.3). Passing the threshold for any one of the tipping points listed by McKay *et al.* would be cause for concern, and it appears that some may have already been set in motion. Even at the present 1.1 °C warming over pre-industrial levels, it is likely, according the McKay *et al.*, that five tipping points have been triggered, putting low-latitude coral reefs, boreal permafrost zones, polar ice sheets (including the Greenland ice sheet, the ice on Barents Sea, and the West Antarctic ice sheet) and the subpolar (Labrador Sea) gyre, at risk of collapse. Indeed, McKay *et al.* find that even at the 2 °C limit set by the 2015 Paris Agreement, multiple additional tipping point thresholds could be triggered, including those of Amazon Forest dieback, mountain glacier loss, and West African monsoon change. At global warming in excess of 4 degrees of pre-industrial levels, the tipping point threshold for the collapse of the entire Antarctic ice sheet could be breached. In light of the slow progress in achieving meaningful greenhouse gas reductions, geoengineering may well be the best near-term option with respect to avoiding the worst outcomes with respect to tipping point-driven changes.

1.4 The Size of the Problem

As indicated earlier, the driving force behind global warming is the anthropogenic release of greenhouse gases—especially carbon dioxide through the burning of fossil fuels. While the onset time for such emissions can be dated back to the 18th century, and the beginnings of the industrial revolution, it is really the relentless emission activity during the past half-century that has seen global warming reach problematic levels. Furthermore, during this same time interval a distinct disconnect between human society and nature has come about, with human society increasingly acting as a self-regulating entity distinct from, and exterior to, the natural world, which in turn is seen as a pure resource to indiscriminately exploit [1.13, 1.14]. Indeed, during the past century, human society, industry, and governments have increasingly positioned themselves as the owners of nature, to do with, and use as they please. This positioning stands in stark contrast to the fact that human beings are an evolved and integral part of the natural world, towards which they could act as a much better guardian, and steward. These seemingly ingrained attitudes, putting short-term gain over long-tern governance, have resulted in the unmitigated failure of society and governments to act, in any meaningful and truly substantive way, against the continued onslaught of greenhouse gas emissions. It has been the slow progress in addressing the long-term solution to such emissions that has opened the door to geoengineering options, making it an important, if not vital, part of our considerations moving forward.

By identifying anthropogenic actions as the primary cause of global warming, the solution to the problem is also identified. Indeed, to reiterate, the only long-term solution to global warming in the present epoch is for humanity to move beyond the indiscriminate use of fossil fuels. Not only must the means be found to curb greenhouse gas emissions, so too must ways be found to extract excess greenhouse gases (especially CO_2 and CH_4) from the atmosphere. This latter task, however, will require a massive investment in new technologies, and a Herculean cleansing program that will occupy the efforts of multiple human generations well into the future. The atmospheric concentration of CO_2 (as of May 2022) amounts to 421 ppm, which translates to an atmospheric mass fraction of about 3.2 teratons (the total mass of Earth's atmosphere is about 5 petatons). At the present time, human activities result in something like 40 gigatons of CO_2 being added to the atmosphere annually, and the total estimated CO_2 emissions since the beginning of the industrial revolution (that is, since circa 1760) is of order 2.2 teratons. To remove, say, 4 gigatons of CO_2 from the atmosphere (i.e., about 0.1% of the total mass of CO_2 at present), some 0.5% of the entire mass of the atmosphere (of order 25 teratons in total) will need to be sampled and scrubbed (assuming 100% efficiency in CO_2 removal).[2] And, this massive sampling, removal, and sequestration process will need to continue year upon year, for centuries, in order to bring the present-day atmospheric CO_2 concentration down to near pre-industrial levels. While CO_2 reduction and sequestration are usually discussed in terms of capture from the atmosphere, there is no reason why it cannot additionally be drawn down by extraction from the oceans, and/or by enabling enhanced weathering by surface rocks. All three of these sequestration actions (and others) will need substantive development, however, in order to reduce CO_2 concentrations.

While the abundance of atmospheric CH_4 (presently determined as 1895 ppb) is much lower than that of CO_2, it is a much more potent greenhouse gas. Indeed, it is some 80 times more potent than CO_2 during its first 20 years following release into the atmosphere, and about 30 times more potent a century after release [1.15] [1.16] [1.17] [1.18]. Furthermore, it is estimated that by the mid-point of this century, the radiative forcing from methane will be on-par with that of CO_2 in spite of its much lower atmospheric abundance [1.18]. There are in principle many ways in which CO_2 and CH_4 could be scrubbed from the atmosphere; the problem, however, is how to make the processes a) affordable, and b) buildable on a scale large enough to be globally effective [1.19].

1.5 Geoengineering – Where, When, and How?

The process of geoengineering is old, and in many ways, human society has been changing the landscape and atmosphere through farming, land clearance, water management, and industrial pollution for thousands of years [1.20]. In its modern guise, however, geoengineering is generally seen as the initiation of directed human actions to lower the Earth's temperature. The first important study on climate change, which additionally introduced the idea of geoengineering as a means to combat it, can be found in the US President's Science Advisory Committee report for 1965 [1.21]. This report identified the future long-term threat of global warming, and correctly identified anthropogenic CO_2 emissions as the key driving agent for such warming. Ironically (in retrospect) the report further reasoned that geoengineering actions could be applied to limit global warming, but made no recommendations to actually curb greenhouse gas emissions. Geoengineering, as a deliberate action, was brought to the forefront of attention in a series of articles published by Paul Cruzen [1.1] in the early years of this century, and since that time numerous geoengineering actions have been identified and proposed as a means of reducing Earth's temperature.

---

[2] The calculation is slightly complicated by the fact that removing CO2 from the atmosphere will result in a CO2 exchange with the oceans and land ecosystems. This equilibrium forcing results in a factor of 2 increase in the total amount of CO2 that will need to be physically removed from the atmosphere. Accordingly, to reduce the atmospheric loading by 4 gigatons, some 8 gigatons of CO2 will have to be removed from the land-ocean-atmosphere system.

Indeed, Figure 1.4 indicates 5 domains in which geoengineering actions might be deployed. Region 1 is the Earth's surface, where in principle both the land and ocean reflectivity at shorter wavelengths of radiation can be increased—this enhances the Earth's albedo term. Region 2 looks to enhance the Earth's albedo by increasing the reflectivity of marine clouds in the lower troposphere. Region 3 takes us to the stratosphere, where the introduction of specific aerosols can be deployed to enhanced atmospheric albedo. Region 4 is above the atmosphere and here methods seek to interpose some form of physical shield (or light diffusing system) between the Earth and the Sun, thereby reducing the level of insolation. The final region, Region 5, illustrated in Figure 1.4, might see attempts to decrease the amount of high-altitude (upper troposphere) cirrus cloud, this action allowing for the enhanced escape of longer wavelength infrared radiation from the Earth's surface.

While it is reasonably clear that the Earth's temperature can be moderated by direct anthropogenic actions, the general consensus has been that such actions should only be initiated as a last resort—although when such a threshold for action might be attained has never been clearly articulated. In a very real sense, there appears to be a tipping point for the onset of geoengineering. The reluctance to initiate geoengineering options, on a global scale or even at a local level, is understandable since it does not address the root cause of global warming [1.2] [1.3]. Indeed, many of the geoengineering methodologies seek to introduce substances (e.g., iron and sulfur dioxide) into the oceans and atmosphere that carry their own burden of potential health risks and environmental degradation. Injecting aerosol particles into the stratosphere, for example, may enhance ozone destroying reactions, and result in enhanced acid rain deposition. Furthermore, computer models indicate that while the initiation of geoengineering actions might benefit some nations and regions,

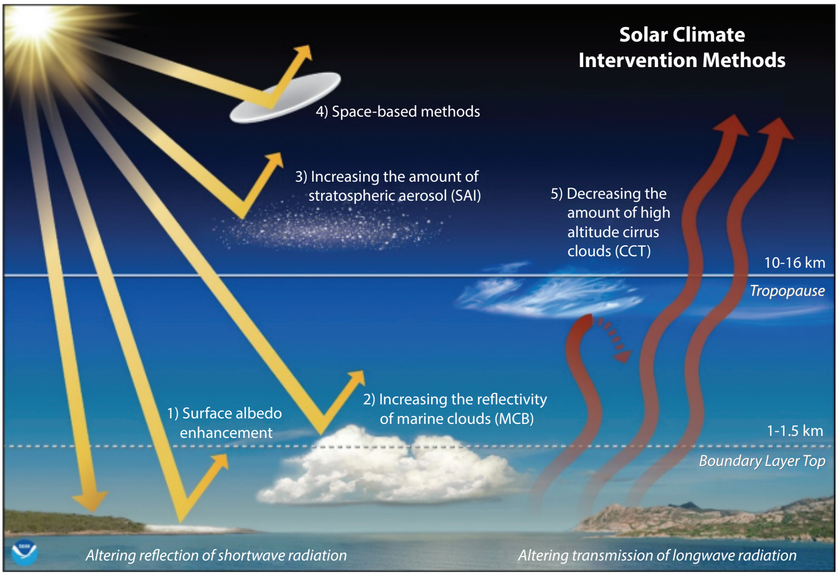

Figure 1.4 A schematic illustration of several geoengineering options. The regions in which geoengineering takes place is either above the atmosphere, as in the deployment of space-based shields, or in the stratosphere, tropopause, and lower atmosphere, right down to the land and ocean surface. (Image courtesy Chelsea Thompson, NOAA/CIRES)

it could be disastrous to the peoples and economies of others, and accordingly the aim of working towards a common good becomes highly debatable [1.5]. Indeed, while there are many unknowns, it is the unknown unknowns (Rumsfeld's second kind of unknows[3]) that currently bedevil many aspects of geoengineering modeling.

Although not specifically defined, the triggering threshold for introducing geoengineering actions has already, many would argue, been breached. Accordingly, it is perhaps time to reframe the notion of geoengineering [1.22]. Rather than seeing it as a last-ditch action, geoengineering could be reinterpreted as a useful first response, and a vital component in the toolbox of options looking to limit the effects of global warming. Indeed, geoengineering can be reframed as a means not only of moderating the Earth's temperature, but as a way of extending the timeframe for the establishment of practical protocols that will see nations move away from fossil fuel dependency. Furthermore, the initiation of geoengineering options could provide additional time for the development and deployment of those technologies aimed at removing and sequestering atmospheric CO_2. Under this reframing, geoengineering is seen as a temporary action and not as a permanent solution to global warming. In this manner, by including geoengineering options early on as an integral part of Earth-cooling initiatives, working in tandem with CO_2 sequestration and emission reduction options, the current slow progress towards meaningful societal and political change might be accommodated. Accordingly, part and parcel of any reframed geoengineering option should be a clear understanding of how long it might be applied for, in combination with progress of sequestration methods, before it can be stopped. The goal of geoengineering should not be to enter into a permanent state of climate control,[4] although it seems reasonably clear that the timescale for such actions will be at least of the order of centuries [1.23]. Geoengineering is, if nothing else, a multigenerational commitment.

Figure 1.5 indicates the potential role of geoengineering within the context of future CO_2 emission projections [1.2]. The horizontal axis indicates the passage of time, from the recent past on into the relatively near future, with the middle of the time axis corresponding to, say, 2100. The vertical scale schematically indicates the impacts of global warming—with an increase along this axis taken to mean more extreme weather conditions, crop failures, food shortages, and worsening biosphere degradation. The business-as-usual curve shown in Figure 1.5 indicates the situation if no reductions are imposed upon fossil-fuel consumption and emissions. In this case, global warming, and all its associated ill effects will continue to grow. The effect of cutting greenhouse gas emissions is illustrated by the (black) curve in Figure 1.5. The effect of cutting greenhouse gas emissions and actively developing sequestration and CO_2 removal technologies is illustrated by the green curve. The potential benefits of adding a geoengineering option to the greenhouse gas reduction and sequestration efforts is illustrated by the blue arrows. The key (schematic) action in this case is to lower (indeed, "shave-off") the peak of the CO_2 emission cuts and sequestration (green) curve [1.2]. What geoengineering brings to the narrative, therefore, is a potential easement of the worst effects of climate change that otherwise lies ahead of us [1.2] [1.3] [1.7]. Once the atmospheric CO_2 levels have been reduced to near pre-industrial

---

[3] In a now infamous 2002 speech, US Secretary of State Donald Rumsfeld distinguished between known unknowns and unknown unknowns.

[4] This is in contrast to terraforming, where the aim is to specifically and permanently manipulate some form of climate control on a world (e.g., Mars or Venus) that is otherwise entirely hostile to surface life.

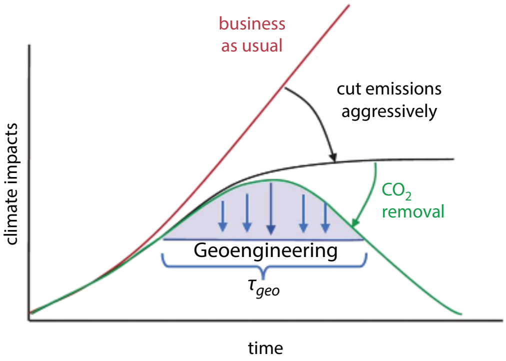

Figure 1.5 Schematic trajectories for future climate change outcomes. The action of geoengineering (indicated by the downward blue arrows) is to "shave the peak," and thereby lessen the climate impacts that would otherwise come about. The timescale of geoengineering actions t_{geo} is dependent upon how soon meaningful emission cuts begin and upon the development timescale for CO_2 removal technologies. See text for details. (Image adapted from [1.2])

levels, geoengineering actions can be halted—this introduces the (finite) geoengineering time scale t_{geo}. Admittedly, t_{geo} is presently a poorly constrained quantity, but this is largely a result of there being no good timescale estimates for initiating a meaningful move away from our fossil fuel dependency, and on the development and deployment times for introducing effective CO_2 extraction and sequestration technologies. The longer these latter two timescales run on, the longer t_{geo} will need to be.

Reframing geoengineering actions within the context of reducing greenhouse gas emissions and implementing vigorous sequestration programs, reenergizes the need for research (and the funding of that research) in potential Earth-cooling initiatives. Furthermore, the reframing requires the development of clear protocols for testing and developing geoengineering options: who will oversee such trials, how much will they cost, who will pay for them, and who should be in charge of any eventual implementation. Indeed, it is still far from clear if any of the proposed geoengineering options can be realistically made to work at the large scale required to produce a meaningful Earth-cooling effect. In addition to developing these new research directions, it will also be vital to determine what are the short- and long-term risks, both to the environment and human societies, associated with geoengineering actions [1.24] [1.25]. In parallel with Newton's third law of motion, for every action there is an equal and opposite reaction: geoengineering is neither a neutral nor an equitable option. Indeed, geoengineering, if implemented rashly and/or inappropriately, could make the present climatic situation much worse [1.6] [1.26].

Figure 1.6 illustrates an attempt to arrange the anticipated effectiveness and costs of several potential geoengineering options [1.2] [1.3]. In the upper right-hand corner of the diagram are the most effective, but most expensive options, and here we presently find the carbon reduction and sequestration (CO_2 capture) strategies. Ideally, these strategies would plot to the upper left in the diagram, but such is not our present reality. In terms of estimated high effectiveness, the orbital sunshades [1.27] [1.28] and stratospheric aerosol injection methods take us through the medium to lower cost options. Grouped in the middle of the diagram, in terms of estimated costs and ease of deployment, along with an estimate of their effectiveness, are the cloud albedo enhancement, and ocean iron fertilization options.

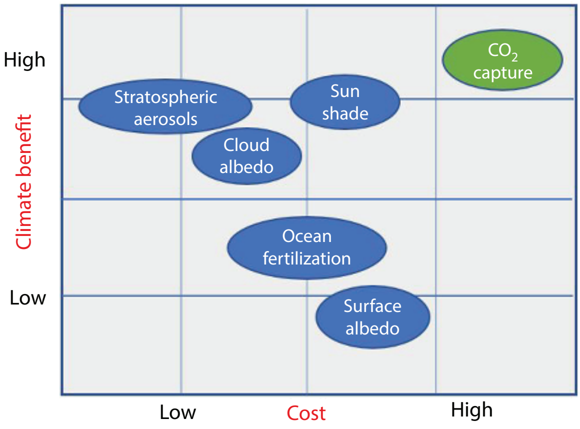

Figure 1.6 A schematic comparison of geoengineering options in terms of their estimated implementation and running costs versus the estimated climate benefits that would result from their implementation. (Diagram adapted from [1.2] [1.11])

Techniques for the modification of surface albedo are estimated to come in at a mid-range cost, but are deemed to have a relatively low climate modification benefit.

At the present time, the leading geoengineering proposal, in terms of estimated costing and climate cooling effectiveness (i.e., a process plotting in the upper left-hand corner of Figure 1.6) is that of stratospheric aerosol injection [1.2] [1.3]. This particular option is based upon presently available technologies (e.g., aircraft, balloons, and artillery shells), and is in principle ready for rapid (on a timescale of decades) deployment. Smith [1.29] has outlined a detailed operations plan, starting 2035 to 2040, for the deposition of sulfur dioxide, or sulfuric acid, into the stratosphere via high-flying aircraft. Smith envisions that by 2100 a fleet of some 100 to 1000 such aircraft (similar in design to the B-47 Stratojet) would be making daily flights, each with payloads of some 15.7 tons, to altitudes of about 20 km. Once the aircraft fleet has been assembled, the estimated cost of running the program will amount to some $18 billion per year per degree of cooling being sought.

There is a natural analog to stratospheric aerosol injection in the form of volcanic outburst emissions [1.30]. Key to the process is the injection of sulfur dioxide (SO_2) high into the atmosphere, where it can react chemically to produce sulfuric acid (H_2SO_4) aerosols (Figure 1.7). These latter aerosols act to enhance the atmospheric albedo by reflecting additional sunlight back into space. In practice, and in contrast to stratospheric aerosol geoengineering, the short-term (of the order of years) cooling effect from volcanic sulfur dioxide release, can be off-set by the longer-term warming resulting from the concomitant emission of carbon dioxide [1.31]. Recent studies further suggest that the cooling/warming response that follow an eruption are modulated according to the level of prior stratospheric heating. The warmer the atmosphere, so the higher the tropopause, and the smaller the amount of SO_2 required to induce cooling [1.32].

An illustrative model of the combined actions of cutting greenhouse gas emissions with the addition of a stratospheric aerosol injection program has been considered by MacMartin, Ricke, and Keith [1.2]. These authors first assumed a scenario in which greenhouse gas emissions are rapidly cut in the near future, and that atmospheric CO_2 peaks

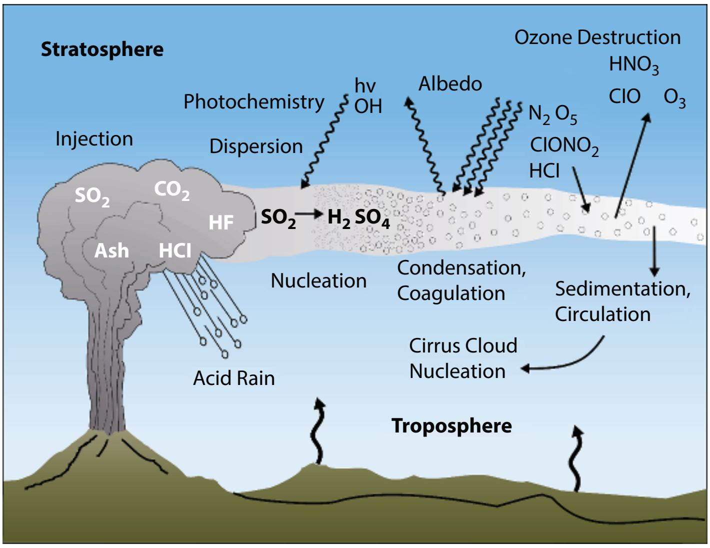

Figure 1.7 Geoengineering by stratospheric aerosol injection seeks to mimic volcanic outburst plume-atmosphere interactions. The volcanic plume deposits such components as ash, carbon dioxide, sulfur dioxide, hydrogen chloride, and hydrogen fluoride into the lower stratosphere. Aerosol formation results in a direct increase in the Earth's albedo and in the production of cirrus cloud condensation nuclei. (Image courtesy of USGS)

at twice its pre-industrial value in the year 2070. Under this scenario, with no geoengineering, the global temperature increase would amount to some 3 °C over pre-industrial levels by the turn of the century—two times larger than the preferred limit set by the Paris Agreement. This future warming, however, could be ameliorated and held to a global temperature increase of no more than 1.5 °C, by starting a program, in 2030, of stratospheric aerosol injection. The amount of aerosol injection would ramp upwards to a maximum of some 5 megatons of sulfur per year in 2070, and decline thereafter, with the entire geoengineering program coming to a close circa 2300.

The global warming response to the doubling of atmospheric CO_2 levels with and without the addition of stratospheric aerosol injection is illustrated in Figure 1.8. The computer simulations show the steady warming of the Earth, relative to 2020, under the business-as-usual scenario for the years 2040 and 2080 (recall Figure 1.5). These computer simulations show a dramatic increase in polar temperatures (by 5 to 7 degrees) under the doubling of atmospheric CO_2 concentrations. The computer models further indicate, however, that these temperature increases, can be offset through the injection of appropriate amounts of sulfur dioxide into the stratosphere [1.33].

While the computer models [1.2] indicate that "peak shaving" (recall Figure 1.5) of otherwise dialed-in global warming can be accomplished through geoengineering actions, they also reveal unwanted effects. These include such adverse societal/farming issues as annual rainfall reduction, and monsoon shift [1.5] [1.20] [1.24]. Indeed, while Figure 1.8 provides a good pictorial example of how, under the guise of computer modeling [1.2], geoengineering is an effective way of cooling the Earth, the resultant benefits are not necessarily distributed uniformly across the globe. Furthermore, while such computer simulations

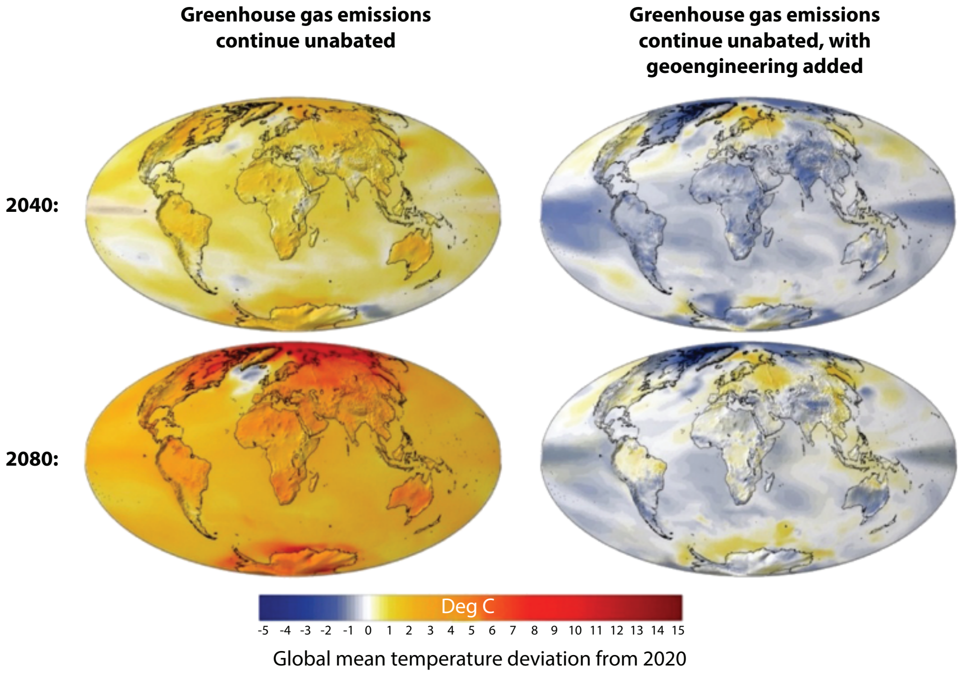

Figure 1.8 The simulations shown to the left indicate the expected change in global temperature if no cuts are imposed upon greenhouse gas emissions—the business-as-usual model. To the right are simulations showing how the temperature increase can be stabilized by the injection of sulfur dioxide into the stratosphere, even under business-as-usual conditions. (Image courtesy of UCAR [1.33])

[1.2] illustrate the potential benefits of geoengineering, it remains a fact that the computer models, while certainly sophisticated [1.34] [1.35], are far from complete and/or fully predictive. Indeed, while computer modeling is currently key to the development, understanding, and "testing" of geoengineering actions, the models continue to require the use of approximate input physics. In this latter respect, one topic that appears to require particular attention is that concerning the modeling of cloud formation. Rather than modeling cloud distribution and formation according to a detailed physical prescription, climate codes generally parameterized such effects according to simplified formulae, and this has important consequences with respect to their ability to predict the direction of future climate change. The crucial uncertainty relates to the type of clouds that might preferentially form as the atmosphere warms, and whether such clouds will amplify or offset temperature change. Low-level, bright clouds, for example, will tend to reflect more sunlight back into space, thus cooling the atmosphere. High-level, cirrus cloud, in contrast, acts to trap reradiated infrared radiation, and this will result in an enhanced greenhouse warming. In short, the question is, will future climate change result in more low-level or more high-level cloud formation? Tim Palmer (Oxford University) has recently framed this very question as being, "the biggest unsolved problem in physical climate change science" [1.36]. Presently, there is no evidence that global cloud coverage is changing in any systematic way—importantly, however, neither is there any evidence to show that it isn't changing. For all this, however, the effects of cloud coverage upon global warming opens up several channels for potential geoengineering actions. One such scenario is to enhance the formation and global coverage of low-level reflective clouds, and another is to inhibit the growth of high-level cirrus cloud. As James Lovelock has emphasized [1.37], however, when it comes to modeling such complex systems as the Earth's climate, we should be wary of falling into a Pygmalion state—that is, relying upon the predictions of a favorite computer model, pretending that it truly describes the real world. While Lovelock is right to warn us against such a trap, what his argument really underscores is the important need for developing protocols under which real-world geoengineering actions can be field tested, and by which the computer predictions can be put to the test against actual data.

Marine cloud brightening is a geoengineering action that seeks to enhance the albedo contribution (that is, reflectance) of low-level clouds. Here the mechanism builds upon introducing seed nuclei (chemical aerosols or fine seawater droplets) to promote enhanced cloud formation. This effect is observed with respect to cloud formation in the exhaust trails associated with ocean-going ships (Figure 1.9). That marine cloud brightening might be an effective way of cooling the Earth was first outlined in 1990 by David Latham [1.38], who envisioned fleets of autonomous ships roaming the oceans and constantly spraying saltwater plumes into the lower atmosphere. The key idea in this action is to increase the number of small cloud condensation nuclei, relying on the so-called Twomey effect, which dictates that the optical depth and albedo of a cloud is directly related to the number density and size distribution of cloud droplets.

In contrast to low-level cloud enhancement, cirrus cloud thinning has been proposed as another way to cool the atmosphere, and it seeks to reduce the lifetime of cirrus clouds in the upper troposphere. Rather than increasing the coverage and brightness of such clouds by seeding, the idea here is to disrupt the natural formation mechanism by encouraging

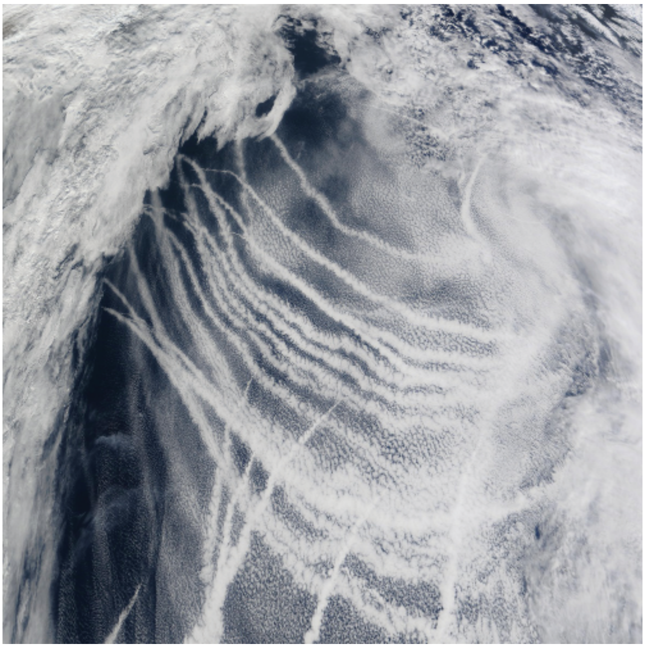

Figure 1.9 Cloud formation trails induced by aerosol emissions from ocean-going ships. Satellite image from March 4, 2009 over the northern Pacific Ocean. (Image courtesy of NASA)

fewer and larger ice crystals to form. This will reduce the optical depth, and the lifetimes of any cirrus clouds that form, thereby reducing the radiative forcing that would otherwise come about under non-geoengineered cirrus cloud formation conditions. It has been suggested that cirrus cloud thinning could be achieved through the spraying of bismuth triiodide by high-flying drones [1.39]. Computer modeling of the large-scale effects of cirrus cloud thinning appears to indicate that while cooling of the atmosphere can be achieved, significant changes to seasonal and regional rainfall will also occur [1.40].

Related to the issue of cirrus cloud thinning is the opposing effect of radiative forcing from aircraft contrails. These latter trails act to encourage the growth of cirrus clouds, and engine emissions of soot, sulfur compounds, CO_2, H_2O, and NO_x molecules (Figure 1.10) make for a significant contribution to greenhouse gas forcing and ozone generation [1.41] [1.42] [1.43]. Indeed, in 2015 it is estimated that some 160 megatons of aviation fuel was consumed worldwide, resulting in the emission of 506 megatons of CO_2 (accounting for about 5% of the total anthropogenic radiative forcing [1.44]) along with some 2.5 megatons

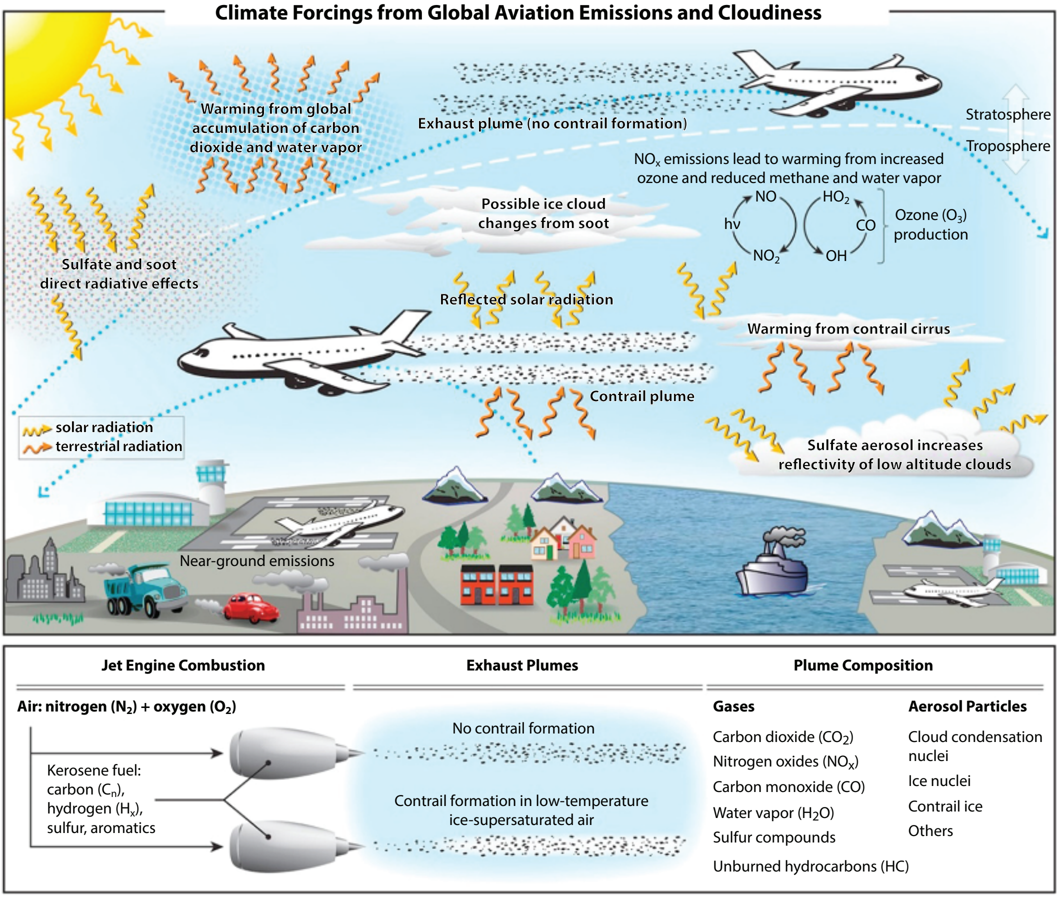

Figure 1.10 Schematic summary of the ways in which aviation emissions interact with the climate system. A net positive warming happens due to the injection of CO_2, water vapor, NO_X, soot, and contrail cirrus. A net cooling contribution occurs from sulfate aerosol formation. (Image courtesy of Lee *et al.* [1.41] and Manchester Metropolitan University)

of nitrogen oxides [1.45]. In 2018 over 4 billion passengers[5] were carried on scheduled airplane services worldwide, and some 58 million tons of freight traffic was transported by aircraft [1.45]. Clearly, the aviation industry is an important contributor to the global economy [1.46], and, in principle, the climate impact of aircraft emissions can be limited by adopting such straightforward strategies as passengers taking fewer flights, aircraft adopting higher cruising altitudes, following optimal trajectories, avoiding short-haul flights, using alternative "green" fuels, and by introducing specialized and innovative aircraft wing and fuselage designs [1.47] [1.48] [1.49] [1.50].

Part and parcel of any geoengineering and carbon sequestration program is the voluntary, large-scale reduction in the carbon footprint of individuals in the course of their daily lives. Indeed, a major contribution to anthropogenic CO_2 emissions is due to vehicle usage. Of the 40 gigatons of CO_2 emitted by human activity every year, about 10% can be attributed to emissions from private car usage [1.51]. It is estimated that at present there are some 630 million cars in private usage worldwide, and each one of these cars (typically) emits on the order of 0.25 kg of CO_2 per 1 km traveled. If each of these cars were driven 50 km less per week than at present, then this would potentially reduce CO_2 emissions by some 410 megatons per year—amounting to a 10% reduction in the annual CO_2 emissions from privately owned vehicles. Problematically, however, there appears to be little will or appetite by members of society to reduce car usage by even the 50 km per week discussed above. One could argue that the change-over from gasoline engines to electric ones will reduce CO_2 emissions from private vehicle usage, but this must be offset by the additional power generation capacity that will be needed to recharge EV batteries. Production of the batteries themselves will additionally require a massive development in mining activities related to critical-metal (e.g., lithium, nickel, cobalt and manganese) requirements [1.52]. Changing human behaviors, with respect to even simple voluntary actions (such as driving less) is unlikely to significantly reduce CO_2 emissions in the foreseeable future. Indeed, there are no historical or even recent examples of the general public (anywhere in the world) fully endorsing and freely abiding by voluntary cutbacks. Such societal change can (in principle) be mandated by national governments, but individuals will typically only accept such rationing of choices and reduction in freedoms if the mandates are egalitarian in nature [1.53], and, as witnessed during the COVID-19 pandemic, many individuals will still refuse to accept mandates even when they are applied equally across society [1.54]. There is, it would seem, a much better chance of reducing the carbon footprint of individuals by investing in better public transport, developing rail travel networks, and introducing innovative urban redevelopment. Indeed, it seems worth reiterating the point that humans will not in this century, and likely not for many centuries to come, live in a zero CO_2 emission, or fossil-fuel-free, world. The technology available for carbon dioxide removal may eventually result in a net-zero emissions state, but even this situation is unlikely to come about without dramatic cutbacks in greenhouse emissions being both mandated and actively enforced [1.55].

Situated towards the lower right-hand corner of Figure 1.6 are a whole host of geoengineering options that are generally taken to be expensive to develop and costly to deploy, with low climate-change impact. This labeling is being applied, however, on a singly acting global stage [1.2]. For all this, at the local and regional level these options may well be the

---

[5] While many, of course, were repeat-journey passengers, this number is equivalent to more than half of the world's total population.

Figure 1.11 Illustration of a polar umbrella as envisioned by Derek Pirozzi (2013). Living quarters, research, desalination and energy generation modules will be housed several hundred meters across a floating polar umbrella. Fleets of umbrella structures are envisioned as a potential way to begin the regeneration of polar ice fields. (Image courtesy of D. Pirozzi)

first geoengineering actions put into practice. These options include such straightforward actions as applying reflective paints, films and/or metamaterials [1.56] to building rooftops. This action directly enhances their albedo, reflecting more sunlight back into space, and consequently cooling the local environment. Indeed, by their very nature, such localized geoengineering actions make for highly useful testbeds against which computer models can be developed, and calibrated. More "natural" forms of surface albedo enhancement include glacial outflow engineering [1.57] [1.58], resurfacing of ice fields [1.59] (Figure 1.11), enhanced weathering by rock exposure [1.60], ocean "whitening" via microbubble generation, and genetically engineering more reflective (higher albedo) strains of commonly grown commercial crops [1.61] [1.62]. Afforestation [1.63] [1.64] and reforestation are additional geoengineering options that can be applied regionally, these actions not specifically changing the surface albedo, but acting to decrease the amount of atmospheric CO_2 uptake. Indeed, many governments are depending upon surface albedo modification and afforestation options to meet and maintain their Paris Agreement commitments [1.65].

Perhaps the most controversial geoengineering action that has (so far) been enacted[6] is that of ocean iron fertilization. The idea is straightforward, relatively cheap to apply (see Figure 1.6), and constitutes the application of micronutrient iron to the surface layers of

---

[6] The controversy largely being related to the fall-out from the privately funded iron fertilization program conducted in the costal waters off Haida Gwaii by Russ George in 2012.

the sea. First suggested as a practical means of removing and sequestering atmospheric CO_2 by John Gribbin in 1988 [1.66] [1.67], the process of iron fertilization acts to enhance phytoplankton growth, which in turn results in enhanced CO_2 uptake. Importantly, however, upon dying these same phytoplankton will sink to the ocean floor, thereby acting to sequester their carbon burden. Problematically, however, a number of attempts have been made in the past to enact ocean iron fertilization without due diligence being applied to public dialog, and without clear measuring and testing protocols being put in place. The field testing to date, however, does indicate that iron fertilization can produce plankton blooms (a result that no one actually doubted), but it is far from clear whether the final action of CO_2 sequestration is effective, and indeed, actually takes place. In comparison to ocean iron fertilization, the allied action of ocean liming [1.68] has provided more substantive results. In this latter case, calcium hydroxide (lime) is added to standing bodies of water, thereby allowing CO_2 to combine with the calcium to form calcium bicarbonate. Usefully, this latter action reduces the acidity of the water, resetting its chemistry, and the CO_2 is eventually sequestered as a carbonate that is typically used in natural shell growth. Field testing of ocean liming has recently been carried out in the waters of Apalachicola Bay off Florida's panhandle [1.69]. Field testing of ocean alkaline enhancement has also been conducted in the waters off Australia's Great Barrier Reef [1.70] [1.71]. These latter field tests added sodium hydroxide (lye) to the surface waters, and found that pH levels were raised, allowing (in principle) natural calcification of the reef to increase [1.72].

One of the simplest (in principle) and arguable most elegant engineering proposals for cooling the sea's epipelagic zone, and drawing down atmospheric CO_2 is that envisioned by James Lovelock and Chris Rapley [1.73]. Here the idea is to use a passive pumping system to bring cooler, nutrient-rich, deep-ocean water to the surface layers, thereby partly lowering the upper-level ocean temperature and, more importantly, encouraging the growth of phytoplankton. The system envisioned consists of a tube, perhaps 100 to 200-m long, and several meters in diameter, attached to a surface buoy (Figure 1.12). Wave action and a simple one-way flow valve then act to enable the pumping process [1.74] [1.75]. The idea is simply

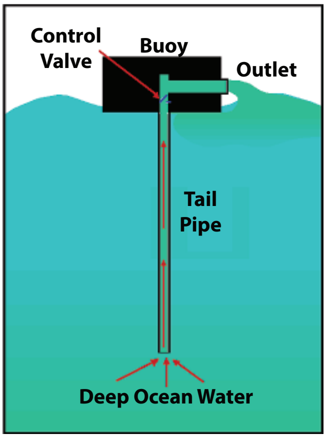

Figure 1.12 Schematic for the design of an ocean (vertical transport) pipe. Cool, deep ocean water enters the bottom of the tail pipe, and through the action of ocean wave uplift working with a one-way flow valve, is brought to the ocean surface. (Image courtesy of AUMIX – University of Hawaii [1.74])

beautiful, and beautifully simple. It is not just their ability to cool surface waters, however, that makes ocean pipe systems worthy of further research and development. Rather, it is the idea that they will act to encouraging algae blooms, which will potentially draw down atmospheric CO_2 (in a manner akin to that in the iron fertilization process), and produce enhanced concentrations of dimethyl sulfide (C_2H_6S). These latter molecules being particularly interesting in that they act as precursor nuclei for low-level cloud formation. By forming more low-level clouds, more sunlight is reflected back into space, and accordingly the atmosphere is cooled. An analogy of this process is presently playing out on the southeast dome of the Greenland ice sheet, where the reduction in sea ice coverage, as measured over the past 55 years, has resulted in a discernable increase in the seasonal levels of dimethyl sulfide [1.76]. Here, the greater amount of open water in the summer season has resulted in the enhanced growth of phytoplankton, and hence the production of dimethyl sulfide. It is not as yet clear if this enhanced nucleation has resulted in enhanced low-level cloud coverage. Intriguingly, however, the observations may point to a "natural," Daisyworld-like [1.77] (see Chapter 26) cooling mechanism for the Arctic, with the negative radiative forcing from enhanced cloud coverage acting to mitigate the positive albedo feedback process resulting from ocean warming ice loss. As with all good ideas, however, there are always negative unforeseen consequences, and in the case of ocean pump cooling this problem was identified by Kwiatkowski, Ricke and Caldeira [1.78]. Specifically, these authors made a study of the effects that ocean pumps might have on the ocean thermocline. The computer models were highly idealized, as such studies must currently be, but the results suggested that while cooling of the atmosphere was initially possible, in the long term (on timescales of 50 to 100 years) atmospheric temperatures rose. The model results are not, however, real-world definitive, and much more research work should be directed towards the modeling of ocean pipe technologies as a regional geoengineering option.

1.6 Moving Forward

Within the debate concerning geoengineering options, the voice of those opposed to such actions must be heard. Indeed, geoengineering falls squarely under the guise of what Horst Rittel and Melvin Webber have called a "wicked problem" [1.79]. The wickedness is not specifically in its ethical content, but in the very definition of what the problem actually is, the framing of its reach, and even the recognition of what the solution to the problem might be. Is geoengineering the wrong solution to the wrong problem? Furthermore, there is no escaping the fact that in a world of some 8 billion people, comprising 195 (currently recognized) independent nations, no unanimous decision on what should be done is remotely likely.[7] Indeed, not only is there reasoned opposition to the initiation of geoengineering actions, there is additionally reasoned opposition to funding geoengineering research [1.24] [1.80]—the argument for the later situation being that it encourages complacency, and draws attention away from those actions by which society and industry could reduce their respective carbon footprints. Furthermore, even if some compromise consensus can be established in the near future, there is no reason to suppose it will be acceptable 25,

---

[7] Ultimately, one fears the words of Samuel Johnson will ring true: "Nothing … will ever be attempted, if all possible objections must be first overcome." This suggests a future state of pragmatism is likely to evolve.

50, or 100 years from now. Even so, all voices, stakeholder questions, and possible actions should be continuously articulated, heard, and responded to. It is vital that the aims of any geoengineering actions, along with those of carbon removal and sequestration, are continuously examined and adjusted according to prevailing knowledge and consensus (if possible) opinion. Additionally, it should be questioned if geoengineering actions are being taken to simply preserve the capitalist system, the system that generated the global warming problem in the first place, or are they being performed in order to establish a more sustainable, fairer world for all humanity [1.81]? From an indigenous people's perspective, as pointedly articulated by Kyle Whyte [1.82], the former option constitutes nothing more than a continuation of a colonialist dystopia. In spite of optimistic claims to the contrary, we do not create the future, we stumble into it, and usually arrive at a distant place hardly expected beforehand. Accordingly, before embarking on the journey of geoengineering, it would be a very good idea to have at least some notion of where such actions might take us, and why it is that we want to get there.

Geoengineering presently sits in a largely theoretical domain. Indeed, it is a subject of theory and computer modeling rather than that of physical experimentation and large-scale mechanical action. Indeed, the question that we currently face is, if geoengineering is going to be enacted, how do we bring it into the real world? Present-day computer models provide clear enough predictions, and actions such as how stratospheric aerosol injection theoretically work, and will act to cool down the Earth. The proof of the equations and simulations, however, rests in their physical application, and this begs the question of field testing. How do you test a geoengineering action in a manner that enough control is maintained in order to offset any unforeseen outcomes? Who decides if a field test has been successful? Who makes the decision to endorse an actual geoengineering effort? And, perhaps most importantly, who polices geoengineering actions? None of these questions have a clear or presently agreed upon answer.

The way forward, in spite of extensive debate and posturing, remains unclear. There is presently no consensus on whether to consider initiating geoengineering options or not, and yet the problems of global warming and climate change are real and looming ever larger. The social and political issues are complex, and one even wonders if the problem is too large for humanity to actually solve—let us hope not. For all this, it is arguably prudent to open up, fund, and pursue public research related to geoengineering options—even if this funding is provided upon the basis of better the devil you know than the one you don't [1.83] [1.84] [1.85]. To aid the forward movement of such research, what have become known as the Oxford Principles have been proposed [1.86]:

- Principle 1: Geoengineering to be regulated as a public good
- Principle 2: Public participation in geoengineering decision-making
- Principle 3: Disclosure of geoengineering research and the open publication of results
- Principle 4: Independent assessment of impacts
- Principle 5: Governance before deployment

The principles are intended to guide experiment design, development and deployment protocols, acting as a minimum framework for moving forward. The principles do not attempt to exclude market-based, private sector involvement in geoengineering, but they do set an expectation and standard to which the actions of nations and/or private companies can be held accountable. The recent bruhaha concerning the geoengineering actions of Make Sunsets [1.87], for example, could be criticized by the very fact that none of the principles outlined above were adhered to by the company executive.

1.7 The Role of Industry

Given that private industry is likely to be heavily involved in any geoengineering actions, the Oxford Principles dictate that a distinct change in behaviors will be required, with such concepts as patent protection, proprietary information, and trade secrets needing to be abandoned. It seems entirely inappropriate (indeed, highly unethical) that either industry or a specific individual should profit from a patented scheme that forms part of any actively deployed geoengineering option. This latter concern was, in fact, one of the ethical issues raised against the Stratospheric Particle Injection for Climate Engineering (SPICE) experiment. Indeed, a proposed (entirely benign) field testing of the equipment in 2012

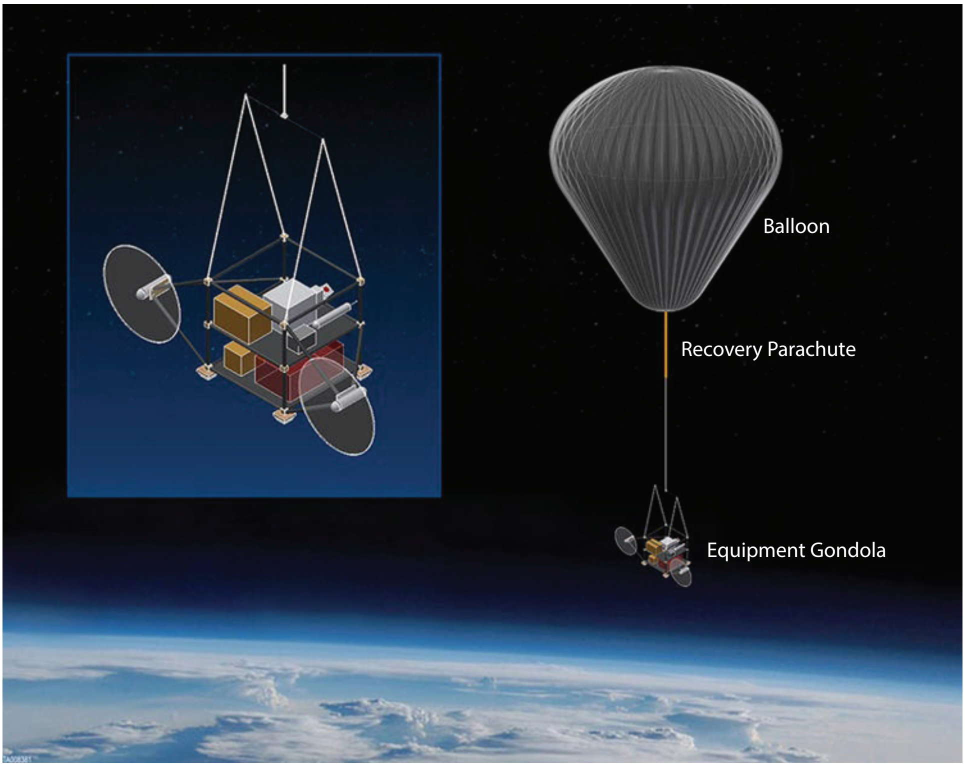

Figure 1.13 Schematic of the Stratospheric Controlled Perturbation Experiment (SCoPEx). The equipment gondola (see inset) is carried aloft by a high-altitude balloon. Propellors attached to the gondola allow for steering, and the formation of a well-mixed aerosol-rich wake. (Image courtesy of the Kreutz Group at Harvard: http://www.keutschgroup.com/scopex)

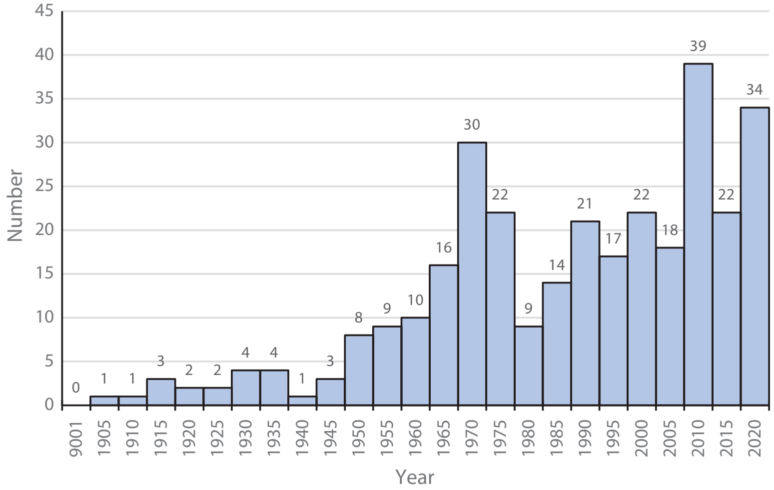

Figure 1.14 Number of US patents related to controlling weather systems (including geoengineering), summed in 5 year-interval bins, from 1900 to the end of 2022. Data from *GeoEngineering Watch* (www.geoengineeringwatch.org).

was canceled due to a perceived conflict of interest by several consortium members[8] [1.88]. Geoengineering, under the guise of the Oxford Principles, enters new territory with respect to the way in which both university-based research is performed and upon how commercial intellectual property development proceeds. Interestingly, while the SPICE field test essentially floundered upon Principle 3, the similarly orientated Stratospheric Controlled Perturbation Experiment (SCoPEx – see Figure 1.13) went adrift (in 2020) according to Principle 2 [1.89]. In an attempt to address the ethical concerns of the commercialization of geoengineering, Jesse Reynolds and co-workers [1.90] have suggested that a "research commons" might be established for "patents and data that are related to solar geoengineering." Collaborating members would then agree to the free and unrestricted exchange of information and data with other commons members, thereby avoiding the duplication of research efforts and the growth of trade secrecy.

In terms of patents awarded for schemes looking to alter the weather, the earliest appears to be that filed by Louis Gathmann of Chicago, in 1891. This patent (US462795DA) concerns an improved "method of producing rain," with the essential idea being to deposit a large quantity of "carbonic-acid gas" (H_2CO_3) into the upper atmosphere, so as to drive a rapid cooling effect, and thereby trigger cloud formation and ultimately rain production. Gathmann indicates that the carbonic acid could be lifted into the atmosphere by a balloon or fired "in a suitable shell" from the ground. Remarkably, the basic methodology and actions, as outlined in Gathmann's patent, apart from the use of carbonic acid, have hardly changed in the past 130 years. Figure 1.14 shows the number of patents filed in the United States with the aim of influencing the weather in one way or another since 1900.

---

[8] The concern centered upon patent number 20120241554: P. Davidson, H. Hunt and C. Burgoyne. Atmospheric Delivery System, being the "apparatus for transporting and dispersing solid particles into the Earth's stratosphere," by "balloon, dirigible or airship."

During the first half of the 20th century, most of the patents related to ideas concerning cloud seeding in order to produce rain, ground fog generation, and ground fog dispersal methods. The uptick in patents filed post-1950 may possible be attributed to the Korean War (1950–1953), when deliberate, weather-altering actions were militarized. Ostensibly the beginning of geoengineering as a topic of concern and potential action can be dated to the 1965 Science Advisory Committee report to President Lyndon Johnson.[9] Moving into the 1970s many patents delt with issues relating to cloud nucleation processes, the production of artificial ion clouds, the dispersal and emplacement of radar-reflecting chaff, aircraft contrail suppression, and the development of solar reflectors. The first geoengineering reports by Edward Teller and co-workers at the Lawrence Livermore National Laboratory appeared in the years surrounding the close of the 20th century [1.91]. Presumably in response to the devastation caused by Hurricane Katrina (in August 2005), many of the patents issued in the first decade of the 21st century focused on ideas relating to hurricane control and suppression. It was in 2006 that Cruzen published his now seminal editorial suggesting that global warming might be combated through stratospheric sulfur injection [1.1].[10] The general trend suggested in Figure 1.13 is one of a steadily increasing interest, from circa 1950 onwards, in engineering research, and in long-term climate change and short-term weather modification. The ethical stance of allowing such technologies to gain protective patents in order that individuals and/or companies can profit from the global warming crisis, is likely to become a topic of important future debate and friction [1.89].

Among the first explicit geoengineering patents to be awarded in the US were those to Hughes Aircraft Company in 1991 (US5003186A), Yoram Palti in 2008 (US2008/0203328A1), and Ryan Neff in 2010 (US2010/0127224A1). The Hughes Aircraft patent advocated the idea of seeding the stratosphere with, so-called, Welsbach particles.[11] Palti's patent was concerned with the construction of a Sun shield made of "bubbles or other thin-walled objects" positioned in space so as to "prevent a portion of the sun's rays from reaching the earth, thereby reducing the global temperature." Neff (private communication) indicates that his patent application drew inspiration from the global cooling that was recorded in the wake of the June 1991 Mount Pinatubo eruption, and proposed the injection of fine-grained silica particles (specifically, diatomaceous earth) into the upper atmosphere (recall Figure 1.7). Other patents, such as that filed by Franklin Chen in 1998 (US5762298A), envisioned a weather modification system built around a fleet of spacecraft, the bulk of which would act to modify solar insolation, with others acting as beamed energy systems. Perhaps most dramatically,

---

[9] This report recognized the issue of a global warming, but made no specific recommendations to cut CO2 emissions. A "bright ocean," enhanced albedo, geoengineering solution was suggested, with the deployment of a multitude of small, ocean-floating, high-albedo spheres being suggested as the ameliorating action [1.21].

[10] It was also in 2006 that the term "Solar Radiation Management" was coined as an alternative, bureaucratic-sounding expression for "geoengineering" [1.92].

[11] Named after Carl Auer von Welsbach, these particles are made of materials that have wavelength-dependent emissivity, with the key idea being that the materials deployed (e.g., aluminum oxide) would have high emissivity in the visible and the far-infrared part of the electromagnetic spectrum, but low emissivity in the near-infrared. Such emission characteristics would reduce the efficiency of greenhouse heating and thereby induce atmospheric cooling. In the modern era one could envision "grains" of metamaterials being specifically designed and fabricated in order to achieve the very specific emissivity properties envisioned in the Hughes Aircraft patent.

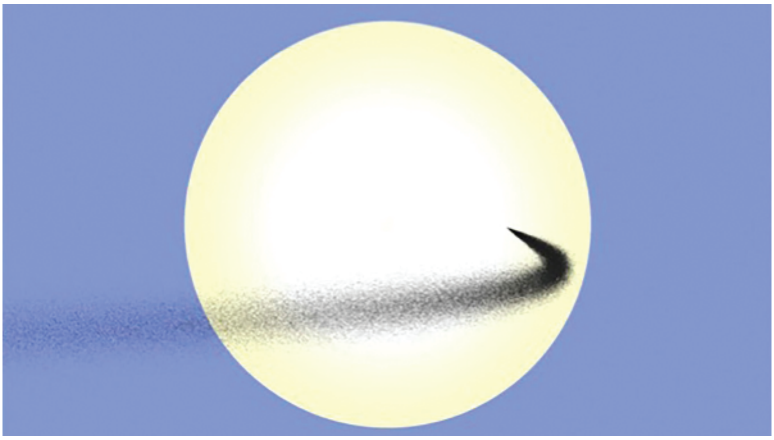

Figure 1.15 Simulated stream of dust launched between the Earth and Sun. The dust cloud is shown as it crosses the disk of the Sun as seen from Earth. Streams launched from space, or from the Moon's surface, can act as a temporary sunshade. The annual dust requirement for the shield will amount to some 10 million tons of material—this is on the order of 700 times more mass being launched per year into space since the Space Age began [1.93]. (Image courtesy of Ben Bromley/University of Utah)

Stephen Trimberger, in 2011, patented the idea of placing dust in the upper atmosphere to reduce solar insolation (US2011/0005422A1). The dust, Trimberger suggests, could be uplifted by either the explosion of multiple nuclear bombs, or by re-directing and crashing a small asteroid into the Earth's surface. An alternative use of dust to reduce solar insolation has been proposed by Bromley, Khan and Kenyon [1.93] who envision the generation of a dust shield at or close to the Earth-Sun L_1 Lagrange point.[12] Here the idea is to send jets of high porosity, fluffy dust grains towards the Earth-Sun L_1 point from the surface of the Moon (or release *in situ* from an in-orbit space-platform) where it will act to block sunlight from reaching the Earth (Figure 1.15). Since the dust will drift out of alignment due to radiation pressure effects fairly rapidly, the shield will need to be reconfigured on an on-going basis. Calculations indicate that about 10 million tons of dust will need to be launched each year in order to form an effective dust cloud at L_1 and reduce the solar irradiance by about 2% [1.93]. Although the development and deployment of sunshades (whether made of bubble clouds, moon dust streams, or thin films) is generally considered an expensive option to counter global warming (recall Figure 1.6), it is arguably a very efficient, and indeed, preferable way to do so. Sunshades, in whatever mechanical guise, can achieve the reduction of solar insolation necessary to cool the Earth, and importantly, they do not specifically require any continued human manipulation of the atmosphere, oceans or landmass surfaces.[13] Because they solve the present-day problem and are external to Earth's atmosphere, they are fully deserving of continued research funding and development. Furthermore, as discussed in

---

[12] The first Lagrange point L1, lies along the line between the Sun and the Earth, and is situated at that point where the gravitational attractions of the Earth and the Sun are in equilibrium.

[13] They still require our movement away from fossil fuels and CO2 removal sequestration. Indeed, there is no escaping these requirements, no matter the geoengineering technique.

Chapter 26, the future increase in the Sun's luminosity (on a timescale of many thousands of years hence), and its influence on warming the Earth, can only be combated by off-Earth, sunlight-blocking structures. While sunshades are a space-based technofix to present-day global warming, they will tie humanity to a continued monitoring and adjustment of the Earth's insolation level (indeed, for the sunshade option $t_{geo} \approx t_{biosphere} \approx 1$ billion years), but at least they do this in an atmospherically neutral way. Furthermore, the development of Sun-shading structures moves us in the direction of finding technologies that will eventually be vital to the continued existence of life on Earth.

Clearly, many of the patents that have been filed over the past quarter-century are non-starters with respect to the practical geoengineering of a cooler Earth. For all this, however, they all express ideas that might, in principle, work, and from within their disassembled and reworked ranks something actually workable might eventually emerge.

1.8 What Now?

Climate change and global warming are complex problems writ large upon and over the landscape, and in the present epoch they are directly caused by human actions [1.2] [1.3] [1.94]. How the future will play out with respect to resolving the political impasse attached to global warming remains unclear, even though the actual solution to the problem is entirely clear and has been articulated on numerous occasions. The goal of the Paris Agreement, so dramatically negotiated in 2015, is already faltering, with global warming likely to exceed 1.5 °C above pre-industrial levels by the mid to late 2020s [1.9] [1.95]. Geoengineering is one possible way to achieve the goals of the Paris Agreement, and to additionally lessen the impacts of global warming that will, without such reducing actions, come about. History tells us that civilizations rise and fall, and that, indeed, some civilizations fall because of climate and environmental change [1.5] [1.6] [1.13] [1.37]. As never before, human expectations, behaviors, and actions require a massive re-examination; and, as never before, humanity will either rise to the challenge, finding pathways to curtail global warming and dilute its associated societal burdens, or it will be fated to suffer the consequences of its own inactions [1.96]. The debate concerning geoengineering is presently polarizing [1.24] [1.97] [1.98], and there are strong and clear voices for and against its deployment. This situation needs to be addressed in an urgent manner, and a means must be found to enable both inclusive dialog and consensus building. It seems most likely that the first large-scale geoengineering option that might be deployed, if indeed deployment ever takes place, is that of stratospheric aerosol injection [1.29] [1.88] [1.89]—it is a relatively cheap option based upon currently available technologies. Alternatively, early geoengineering might proceed through the injection of ice-nucleating particles to reduce atmospheric water vapor concentrations [1.99]. In terms of long-term development, however, this author would suggest that Sun-shading technologies offer a much better, less environmentally intrusive, means of addressing global warming problems.

In spite of more than 50 years of research, innovation, and debate [1.52], geoengineering is still a science in its infancy, and has yet to move in any meaningful real-world sense beyond laboratory and computer model virtual simulation. If some form of geoengineering is to proceed in the near future, then government funding for research will need to be made available to researchers. Likewise, protocols for field testing will need clear and transparent development, and, indeed, field testing of methodologies will need to proceed [1.100]. If, on the other hand, it is decided to marginalize future research on geoengineering methodologies, and direct all future research actions towards carbon dioxide capture and storage [1.6] [1.15] [1.18] [1.51] [1.65] [1.101], then this too must be a debated and deliberate action. For all this, we presently run the risk that our descendants may doubly curse us (that is, the apolaustic "us" in the here and now), firstly for allowing the global warming situation to come about, and second for not doing enough to stop the more extreme outcomes of global warming from being realized [1.102] [1.103] [1.104] [1.105], with poorer nations, in particular, being left to struggle with the direct effects of a global warming problem that they did little to nothing to bring about [1.106] [1.107]. Furthermore, there is still a strong percentage of people, in spite of all the clear evidence for it, who deny that the Earth is actually warming due to present-day human activity. This percentage, in the United States, for example, runs at some 30% [1.108] of the populace. More worryingly, perhaps, than just this simple denial of the facts, is the possibility of resent results presented by Stoetzer and Zimmermann [1.108], who find evidence (in a survey group of 4000 US citizens) to support the hypothesis that climate change deniers actually define themselves by the very fact they are climate change deniers (recognizing themselves as a distinct group within society), and that they have no interest in responding to, or even engaging with those members of society and researchers with a contrary stance. How one engages with such a disengaged audience remains unclear. As every historian throughout human history has stated, "we live in tumultuous times." However, for the first time in history, what humanity does in regard to the mitigation of global warming in the next half-century, will indeed be pivotal to our long-term collective well-being.

References

[1.1] Cruzen, P., Albedo enhancement by stratospheric sulfur injections: a contribution to resolve a policy dilemma? *Clim. Change*, 77, article 211, 2006.

[1.2] MacMartin, D.G., Ricke, K.L., Keith, D.W., Solar geoengineering as part of an overall strategy for meeting the 1.5°C Paris target. *Philos. Trans. R. Soc., A* 376, 20160454, 2018.

[1.3] Climate intervention: reflecting sunlight to cool Earth. Report of the National Research Council, 2015.

[1.4] Dyer, G., Intervention Earth: life-saving ideas from the world's climate change engineers. Random House Canada, Toronto, 2023.

[1.5] Steel, D., DesRoches, C.T., Mintz-Woo, K., Climate change and the threat to civilization. *Proc. Natl. Acad. Sci.*, 2022, https://doi.org/10.1073/pnas.2210525110.

[1.6] Hulme, M., *Can science fix climate change?*, Polity Press, Cambridge, UK, 2014.

[1.7] https://unfccc.int/process-and-meetings, 2023

[1.8] https://unfccc.int/sites/default/files/english_paris_agreement.pdf, 2023

[1.9] https://report.ipcc.ch/ar6syr/pdf/IPCC_AR6_SYR_SPM.pdf, 2023

[1.10] Neukom, R. *et al.*, Consistent multi-decadal variability in global temperature reconstructions and simulations over the common era. *Nat. Geosci.*, 12, 643–649, 2019.

[1.11] Lenton, T.M., Tipping points in the climate system. *Weather*, 76, 325–326, 2021.

[1.12] McKay, D.A. *et al.*, Exceeding 1.5 °C global warming could trigger multiple climate tipping points. *Science*, 377, doi: 10.1126/science.abn7950.

[1.13] Adele-Holt, L., Why Shouldn't we cut the human-biosphere umbilical cord? *Futures*, 133, 102821, 2021.

[1.14] Heyen, D., Horton, J., Moreno-Cruz, J., Strategic implications of counter-geoengineering: clash or cooperation? *J. Environ. Econ. Manage.*, 95, 153–177, 2019.

[1.15] Huang, Y. *et al.*, Feasibility of solar updraft towers as photochemical reactors for removal of atmospheric methane – the role of catalysts and rate limiting steps. *Front. Chem.*, 9, 2021, https://doi.org/10.3389/fchem.2021.745347.

[1.16] de Richter, R. *et al.*, Removal of non-CO_2 greenhouse gases by large-scale atmospheric solar photocatalysis. *Prog. Energy Combust. Sci.*, 60, 68–96, 2017.

[1.17] Nzotungicimpaye, C.M., MacIsaac, A.J., Zickfeld, K., Delaying methane mitigation increases the risk of breaching the 2 °C warming limit. *Commun. Earth Environ.*, 4, 2023, article 250, https://doi.org/10.1038/s43247-023-00898-z.

[1.18] Jackson, R. *et al.*, Methane removal and atmospheric restoration. *Nat. Sustainability*, 2, 436–438, 2019.

[1.19] Pires, J.C.M., Negative emissions technologies: A complementary solution for climate mitigation. *Sci. Total Environ.*, 672, 502–514, 2019.

[1.20] Ruddiman, W.F., *Plows, plagues and petroleum – how humans took control of climate*, Princeton University Press, Princeton, 2005.

[1.21] https://www.climatefiles.com/climate-change-evidence/presidents-report-atmospher-carbon-dioxide/.

[1.22] Wigley., T.M.L., A combined mitigation/geoengineering approach to climate stabilization. *Science*, 314, 452–454, 2006.

[1.23] Baur, S. *et al.*, The deployment length of solar radiation modification: an interplay of mitigation, net-negative emissions and climate uncertainty. *Earth Syst. Dyn.*, 14, 367–381, 2023.

[1.24] Robock, A., 20 Reasons why Geoengineering may be a bad idea. *Bull. At. Sci.*, 64, 14–18, 2008.

[1.25] Ross, A. and Matthews, H.D., Climate engineering and the risk of rapid climate change. *Environ. Res. Lett.*, 4, 045103, 2009.

[1.26] Cox, P. and Jeffrey, H., Engineering the Climate. *Phys. World*, September, 2009.

[1.27] Angel, R., Feasibility of cooling the Earth with a cloud of small spacecraft near the inner Lagrange point (L1). *Proc. Natl. Acad. Sci.*, 103, 2006, https://doi.org/10.1073/pnas.0608163103.

[1.28] Sanchez, J.-P. and McInnes, C.R., Optimal sunshade configurations for space-based geoengineering near the Sun-Earth L1 point. *PLoS One*, 10, 8, e0136648, 2015, doi: 10.1371/journal. pone.0136648.

[1.29] Smith, W., *Pandora's Toolbox – the hopes and hazards of climate intervention*, Cambridge University Press, Cambridge, 2022.

[1.30] See e.g., https://www.usgs.gov/programs/VHP/volcanoes-can-affect-climate.

[1.31] Guzewich, S.D. *et al.*, Volcanic climate warming through radiative and dynamical feedback of SO_2 emissions. *Geophys. Res. Lett.*, 49, doi: 10.1029/2021GL096612.

[1.32] Aubry, T. *et al.*, Climate change modulates the stratospheric volcanic sulfate aerosol lifecycle and radiative forcing from tropical eruptions. *Nat. Commun.*, https://doi.org/10.1038/s41467-021-24943-7.

[1.33] For details, see https://news.ucar.edu/129835/new-approach-geoengineering-simulations-significant-step-forward.

[1.34] Fan, Y. *et al.*, Solar geoengineering can alleviate climate change pressures on crop yields. *Nat. Food*, 2, 373–381, 2021.

[1.35] Kravitz, B., Robock, A., Lohmann, U., Modeling the effects of geoengineering. *EOS*, 99, 2018, https://doi.org/10.1029/2018EO103333.

[1.36] Palmer, T., *The Primacy of Doubt*, Basic Books, New York, 2022.

[1.37] Lovelock, J., *The Vanishing Face of Gaia: a final warning*, Penguin Books, London, 2010.

[1.38] Latham, J. *et al.*, Marine cloud brightening. *Philos. Trans. R. Soc. A*, 370, 4217–4262, 2012.

[1.39] Mitchell, D.L. and Finnegan, W., Modification of cirrus clouds to reduce global warming. *Environ. Res. Lett.*, 4, 045102, 2009.

[1.40] Gasparini, B. *et al.*, To what extent can cirrus cloud seeding counteract global warming? *Environ. Res. Lett.*, 15, 2020, https://doi.org/10.1088/1748-9326/ab71a3.

[1.41] Lee, D.S. *et al.*, The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. *Atmos. Environ.*, 244, 117834, 2021.

[1.42] Ryley, T., Baumeister, S., Coultier, L., Climate change influences on aviation: a literature review. *Transport Policy*, 92, 55–64, 2020.

[1.43] Freemna, S. *et al.*, Trading off aircraft burn and NOX emissions for optimal climate policy. *Environ. Sci. Technol.*, 52, 2498–2505, 2018.

[1.44] Teoh, R. *et al.*, Aviation contrail climate effects in the North Atlantic from 2016-2021. *Atmos. Chem. Phys.*, https://doi.org/10.5194/acp-2022-169.

[1.45] Tasca, A.L. *et al.*, Innovative box-wing aircraft: emissions and climate change. *Sustainability*, 13, 3282, 2021, https://doi.org/10.3390/su13063282.

[1.46] Grewe, V. *et al.*, Evaluating the climate impact of aviation emission scenarios towards the Paris agreement including OCIV-19 effects. *Nat. Commun.*, 2021, https://doi.org/10.1038/s41467-021-24091-y.

[1.47] Kallbekken, S. and Victor, D.G., A cleaner future for flight – aviation needs a radical redesign. *Nature*, 609, 673–675, 2022.

[1.48] Hasan, M.A. *et al.*, Climate change mitigation pathways for the aviation sector. *Sustainability*, 13, 3656, 2021.

[1.49] Baumeister, S., Mitigating the climate change impacts of aviation through behavioral change. *Transp. Res. Procedia*, 48, 2006–2017, 2020.

[1.50] Brazzola, N., Patt, A., Wohland, J., Definitions and implications of climate-neutral aviation. *Nat. Clim. Change*, 12, 761–767, 2022.

[1.51] Murray, E.G. and DiGiorgio, A.L., Will individual actions do the trick? Comparing climate change mitigation through geoengineering versus reduced vehicle emissions. *Earth's Future*, 9, e2020EF001734.

[1.52] Zhang, C. *et al.*, Trade-off between critical metal requirement and transportation decarbonization in automotive electrification. *Nat. Commun.*, 14, article 1616, 2023.

[1.53] Wood, N., Lawlor, R., Freear, J., Rationing and climate change mitigation. *Ethics Policy Environ.*, https://doi.org/10.1080/21550085.2023.2166342.

[1.54] Buck, H. *et al.*, Pandemic politics – lessons for solar geoengineering. *Commun. Earth Environ.*, https://doi.org/10.1038/s43247-020-00018-1.

[1.55] Ho, D.T., Carbon dioxide removal is an ineffective time machine. *Nature*, 616, 9, 2023.

[1.56] Ko, B. *et al.*, Metamaterial-based radiative cooling: towards energy-free all-day cooling. *Energies*, 12, 89, https://doi:10.3390/en12010089.

[1.57] Moore, J.C. *et al.*, Geoengineering polar glaciers to slow sea-level rise. *Nature*, 555, 303–305, 2018.

[1.58] Lockley, A. *et al.*, Glacier geoengineering to address sea-level rise: a geotechnical approach. *Adv. Clim. Change Res.*, 11, 401–414, 2020.

[1.59] Wolovick, M.J. and Moore, J.C., Stopping the flood: could we use targeted geoengineering to mitigate sea level rise? *Cryosphere*, 12, 2955–2967, 2018.

[1.60] Smoliak, B.V., Gelobter, M., Haley, J.T., Mapping potential surface contributions to reflected solar radiation. *Environ. Res. Lett.*, 4, 2022, https://doi.org/10.1088/2515-7620/ac7a25.

[1.61] Singarayer, J.S., Ridgwell, A., Irvine, P., Assessing the benefits of crop albedo bio-geoengineering. *Environ. Res. Lett.*, 4, 2009, https://dio.org/10.1088/1748-9326/4/4/045110.

[1.62] Kaler, J. *et al.*, Assessing the potential for crop albedo enhancement in reducing heatwave frequency, duration, and intensity under future climate change. *Weather Clim. Extremes*, 35, 2020, https://doi.org/10.1016/j.wace.2022.100415.

[1.63] Foster, E.J. *et al.*, Commercial afforestation can deliver effective climate change mitigation under multiple decarbonization pathways. *Nat. Commun.*, 12, 2021, https://doi.org/10.1038/s41467-021024084-x.

[1.64] Mykleby, P.M., Snyder, P.K., Twine, T.E., Quantifying the trade-off between carbon sequestration and albedo in midlatitude and high-latitude North American forests. *Geophys. Res. Lett.*, 44, 2493–2501, 2017.

[1.65] Smith, H., Vaughan, N.E., Forster, J., Long-term national climate strategies bet on forests and soils to reach net-zero. *Commun. Earth Environ.*, 3, 2022, https://doi.org/10.1038/s43247-022000636-x.

[1.66] Gribbin, J., Any old Iron? *Nature*, 331, 570, 1988.

[1.67] Emerson, D., Biogenic iron dust: a novel approach to ocean iron fertilization as a means of large-scale removal of carbon dioxide from the atmosphere. *Front. Mar. Sci.*, 6, 2019, https://doi.org/10.3389/fmars.2019.00022.

[1.68] Renforth, P. and Henderson, G., Assessing ocean alkalinity for carbon sequestration. *Rev. Geophys.*, 55, 636–674, 2017.

[1.69] Mumma, H. *et al.*, Continuous monitoring of net CO2 drawdown from experimental ocean alkalinity additions, https://agu.confex.com/agu/fm22/meetingapp.cgi/Paper/1196208.

[1.70] Kline, D. *et al.*, A short-term *in situ* CO_2 enrichment experiment on Heron Island (GBR). *Sci. Rep.*, 2, article number 413, 2012.

[1.71] Tollefson, J., Ocean acidification reversed on Great Barrier Reef. *Nature*, 2016, https://doi.org/10.1038/nature.2016.19410.

[1.72] Albright, R. *et al.*, Reversal of ocean acidification enhances net coral reef calcification. *Nature*, 531, 362–365, 2016.

[1.73] Lovelock, J.E. and Rapley, C.G., Ocean pipes could help the Earth to cure itself. *Nature*, 449, 403, 2007.

[1.74] White, A. *et al.*, An open ocean trial of controlled upwelling using wave pump technology. *J. Atmos. Ocean Technol.*, 27, 385–396, 2010.

[1.75] Liu, C.K., Research on artificial upwelling and mixing at the University of Hawaii at Manoa, IOA Newsletter, vol. 10, 1999.

[1.76] Kurosaki, Y. *et al.*, Increased oceanic dimethyl sulfide emissions in areas of sea ice retreat inferred from a Greenland ice core. *Commun. Earth Environ.*, 3, 2022, https://doi.org/10.1038/s43247-022-00661-w.

[1.77] Lenton, T.M. and Lovelock, J.E., Daisyworld revisited: quantifying biological effects on planetary self-regulation. *Tellus*, 53B, 288–305, 2001.

[1.78] Kwiatkowski, L., Ricke, L.K., Caldeira, K., Atmospheric consequences of disruption of the ocean thermocline. *Environ. Res. Lett.*, 10, 034016, 2015.

[1.79] Rittel, H. and Webber, M., Dilemmas in a general theory of planning. *Policy Sci.*, 4, 155–169, 1973.

[1.80] Stephens, J.C. and Surprise, K., The hidden injustices of advancing solar geoengineering research. *Glob. Sustain.*, 3, 1–6, 2019.

[1.81] Rahman, A. *et al.*, Developing countries must lead on solar geoengineering research. *Nature*, 556, 22–24, 2018.

[1.82] Whyte, K., Indigenous climate change studies: indigenizing futures, decolonizing the Anthropocene. *Engl. Lang. Stud.*, 55, 153–162, 2017.

[1.83] Cicerone, R.J., Elliot, S., Turco, R.P., Global environmental engineering. *Nature*, 356, 472, 1992.

[1.84] Ricke, K., Solar geoengineering research should get real. *Nature*, 614, 391, 2023.

[1.85] Sovacool, B.K., Reckless or righteous? Reviewing the sociotechnical benefits and risks of climate change geoengineering. *Energy Strategy Rev.*, 35, 2021, https://doi.org/10.1016/j.esr.2021.100656.

[1.86] https://Oxford Geoengineering Programme//Oxford Principles of Geoengineering.

[1.87] https://makesunsets.com.

[1.88] www.spice.ac.uk.

[1.89] https://www.keutschgroup.com/scopex.

[1.90] Reynolds, J., Contreras, J.L., Sarnoff, J.D., Intellectual property polices for solar geoengineering. *WIREs Clim. Change*, 9, 2018, https://doi.org/10.1002/wcc.512.

[1.91] Teller, E., Wood, L., Hyde, R., Global warming and ice ages I. Prospects for physics-based modulation of global change, https://inis.iaea.org/collection/NCLCollectionStore/_Public/29/043/29043613.pdf?r=1.

[1.92] Caldeira, K. and Bala, G., Reflecting on 50 years of geoengineering research. *Earth's Future*, 5, 10–17, 2017.

[1.93] Bromley, B.C., Khan, S.H., Kenyon, S.C., Dust as a solar shield. *PLOS Clim.*, 2, 2, e0000133, 2023.

[1.94] Benjamin, D. *et al.*, Exceptional stratospheric contribution to human fingerprints on atmospheric temperature. *Proc. Natl. Acad. Sci.*, 120, 2023, https://doi.org/10.1073/pnas.2300758120.

[1.95] Diffenbaugh, N.S. and Barnes, E.A., Data-driven predictions of the time remaining until critical global warming thresholds are reached. *Proc. Natl. Acad. Sci.*, 120, 2023, https://doi.org/10.1073/pnas.2207183120.

[1.96] Reynolds, J.L., Is solar geoengineering ungovernable? A critical assessment of governance challenges identified by the Intergovernmental Panel on Climate Change. *WIREs Clim. Change*, 21, e690, 2021.

[1.97] Mcleod-Rogers, J., Why we must embrace geoengineering and other technologies to stop the climate crisis, The Conversation, 2021, https://theconversation.com/why-we-must-embrace-geoengineering-and-other-technologies-to-stop-the-climate-crisis-167330.

[1.98] Skurka, C., Myrick, J.G., Yang, Y., Fanning the flames or burning out? Testing competing hypotheses about repeated exposure to threatening climate change messages. *Clim. Change*, 176, article 52, 2023.

[1.99] Schwarz, J.R. *et al.*, Considering international stratospheric dehydration for climate benefits. *Sci. Adv.*, 10, eadk0593, 2024.

[1.100] Voosen, P., United States tiptoes into solar geoengineering research. *Science*, 379, 628–629, 2023.

[1.101] Hickey, C. *et al.*, A review of commercialisation mechanisms for carbon dioxide removal. *Front. Clim.*, 4, 1101525, 2022, doi: 10.3389/fclim.2022.1101525.

[1.102] Rogelj, J. *et al.*, Credibility gap in net-zero climate targets leaves world at high risk. *Science*, 380, 6649, 1014, 2023, doi: 10.1126/science.adg6428.

[1.103] Perga, M.-E. *et al.*, The climate change research that makes the front page: is it fit to engage societal action? *Global Environ. Change*, 80, 102675, 2023.

[1.104] Technical dialogue of the first global stocktake: synthesis report by the co-facilitators of the technical dialogue, August 2023, https://unfccc.int/documents/631600.

[1.105] Richardson, K. *et al.*, Earth beyond six of nine planetary boundaries. *Sci. Adv.*, 9, eadh2458, 2023.

[1.106] Vecillio, D.J. *et al.*, Greatly enhanced risk to humans as a consequence of empirically determined lower moist heat stress tolerance. *Proc. Natl. Acad. Sci.*, 120, 2023, https://doi.org/10.1073/pnas.2207183120.
[1.107] Wong, C., Rich countries fall short on climate aid for poor nations, November 3, 2023, http://www.nature.com/articles/d41586-023-03463-y.
[1.108] Stoetzer, L.S. and Zimmermann, F., A representative survey experiment of motivated climate change denial. *Nat. Clim. Change*, 2024, https://doi.org/10.1038/s41558-023-01910-2.