ASTROBIOLOGY PERSPECTIVES ON LIFE IN THE UNIVERSE

Geoengineering and Climate Change

Methods, Risks, and Governance

Edited by

Martin Beech

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Publishers at Scrivener
Martin Scrivener (martin@scrivenerpublishing.com)
Phillip Carmical (pcarmical@scrivenerpublishing.com)

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

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Contents

Preface

Geoengineering is an action intended for the betterment of humankind. There, I have written it. Let the debate begin. Certainly not everyone will agree with my opening statement, and indeed, there are many very good arguments for not initiating geoengineering as a means of addressing the problems of global warming. For my part, however, I would argue that it is time to embrace geoengineering (in all its many guises) for what it really is, and that is a set of well-defined, innovative actions that can be deployed, monitored, and controlled, and which work towards achieving a better future for humanity—indeed, a better future trajectory than the one we are currently moving along. The time to begin the serious contemplation, planning, investment, field-testing, and initiation of geoengineering actions is pressingly upon us. Indeed, time is of the essence, since effective, affordable, large-scale carbon capture and retrieval capabilities are currently nonexistent, and meaningful global carbon emission reductions have not come about. Fortunately, the way forward is relatively clear, and, along with dramatically reducing our dependency on fossil fuels and eventually extracting excess CO_2 from the atmosphere, various forms of geoengineering will be needed to counter the ever-growing, long-term detrimental effects of global warming on the environment. Importantly, geoengineering provides us with the possibility of "peak shaving," thereby ameliorating the worst of the inevitable, already inbuilt and set to appear, consequences of global warming. Again, not everyone will agree with what I have just written. Indeed, one counter argument that is often leveled against geoengineering is that it typically exploits the same physical processes that have resulted in the current acute situation of global warming. With no distinction being drawn between the harmful release of CO_2 and pollutants by cars, airplanes, ships, agriculture, and industry, and those relatively benign compounds used in, say, stratospheric aerosol injection—a key geoengineering action demonstrably capable of cooling the Earth. There is, I would argue, a great fallacy in confusing these two actions. The former being a known set of relatively unregulated harmful byproducts of life choices and industrial processes that are unequivocally linked to present-day global warming. The latter, in contrast, being a deliberate, temporary, and controllable set of actions, directly aimed towards the achievement of a greater common good—that is, a cooler Earth for all. The argument that runs along the lines that past and present human actions have directly caused the current global warming crisis, and *ipso facto*, that we (that is humanity) must be excluded from all future engagement with the climate system, is, I would contest, ill-founded. Indeed, the actions of past generations in no way negates the promise and potential of present-day human actions putting the situation right in the future. The imperative of moving on, remaking, and improving upon what went before lies at the very core of each and every new human generation. To argue, point blank, against the deployment of geoengineering actions denies the scientific advancements, technical developments, teachings, and collective understandings garnered in past decades. This is not to say that geoengineering is a panacea; there are still many technical, ethical, political, medical, and governance issues to hear, solve, and deal with. If geoengineering is to be rejected as a means of addressing global warming, then it must be a reasoned rejection. And, to argue against something, one needs to have hard data and measurements upon which to base a sound discussion. At present, such practical data and experimental experience are lacking, and indeed, one of the underlying themes of this book is to see how such experience and data might be obtained.

What makes the geoengineering issue particularly challenging is the chorus, even cacophony, of voices for and against it. There is no escaping this, but it is important that all voices are heard, and appreciated—they are all valuable, and consensus on future actions can only be achieved through dialog. The collection of articles presented here spans the spectrum of opinions, the yeas, nays, and maybes, concerning the initiation of geoengineering actions, and it also attempts (especially in the last several chapters) to broaden the topic beyond the domain of Earth's atmosphere. In the opening section, we have a number of positioning articles. Chapter 1 provides an introduction to the topic of geoengineering, looking at its possibilities, aims, and future requirements. Chapter 2, in contrast, looks at how the geoengineering position has evolved over the past decades. Following this, in Chapters 3 through 10, various voices and approaches are presented. As will be seen, the hard, indeed, very hard part of geoengineering, is not the science (as such), but rather the scale, deployment, risk management, and moral philosophy behind what is actually being done. People's lives, health, and livings are literally at risk, and this changes the dialog, moving it away from a decision-making process based purely upon the strict logic of equations, physics, and chemistry, to a process including politics, human justice, human health, and human well-being. How we (that is humanity in the here and now) resolve these intertwined issues, and how we attempt to find a consensus viewpoint, is going to be crucial for our collective future, and indeed, they will literally define where humanity goes in the latter half of the 21st century. The authors of Chapters 11 through 20 forge ahead, however, and explore a number of possible geoengineering actions, all of which aim towards the cooling of Earth and/or the restoration of a degraded environment. Chapters 11 and 12 look at various theoretical issues with respect to the application and control of geoengineering processes, examining, head-on, the complexity of the issues at hand. Chapters 13 through 19 present the details behind several specific geoengineering actions, looking at their rationale, testing, and means of possible deployment. More than just looking at the mechanics, however, these later chapters also consider how geoengineering actions might be tested, monitored, and regulated. The final section, Chapters 21 through 27, look towards the much deeper future, and the deployment of yet hardly imagined technologies to address future global warming issues. These options are generally space-based, and will entail humanity adopting a direct, ongoing, and active role in the stewardship of the Earth. The deep future will inevitably require that our descendants move towards a complex, proactive, and large-scale technofix engagement with the Earth's climate system. The long journey ahead of us, however, is predicated on what it is that we do in the here and now. Most of all, perhaps, humanity will need to find a unity of purpose, in a cooperative global sense, as never before achieved in history. In our current unsatisfactory situation, the denial of environmental geoengineering is nothing less demanding than that of a boxer that must enter an upcoming prize fight with both hands tied behind his back. Global warming requires that humanity acts, and acts quickly, deploying and wisely using all possible means of climate amelioration that are available. Well, these are some of my thoughts. Not everyone will agree with them—and "so it goes."

Martin Beech, PhD
Professor Emeritus, Department of Physics, Campion College and University of Regina, Regina, Saskatchewan, Canada

Acknowledgments

Four hundred years ago, in 1624, John Donne, poet and vicar at St. Dunstan-in-the-West, argued in a devotional work that, “No man is an island, entire of itself; every man is a piece of the continent, a part of the main”. This oft quoted piece (its masculine specificity aside) is prescient with respect to our times, and especially so with respect to the problem that is global warming. The idea of a book being written by a single author also finds resonance in Donne’s words, and in this case, it is very much the situation that many researchers have contributed to its assembled pages. As editor I thank all the contributing authors for their thoughts, ideas, ingenuity, enthusiasm, and conversations.

The impetus for starting what has become this book grew from conversations with Joseph Seckbach, Richard Gordon, and Martin Scrivener, and I thank them for all their help, patience, and assistance in this project. Many reviewers, and correspondents provided insightful, timely, and highly pertinent responses to my emails and questions as this book was in development. Other correspondents offered highly impertinent responses – but, such is the nature of the passions insighted by the topic at hand. To all, however, thank you, and perhaps the most important point is that the dialog continues. After all, it will only be through a merging of all voices, that we shall find the ways and means to negate, and reverse, the seemingly relentless climate, and ecological harms being wrought by both human actions, and inactions.

It is usual to provide a short personal dedication to a book such as this, but it seems appropriate, given the nature of its topic, to dedicate this book to the Roman god Janus, overseer of beginnings, and transitions, passages, and endings. Janus is typically shown with two opposing faces, to depict his ability to simultaneously see into the past, and also read the future, and it is this characteristic, to appreciate the lessons of history, and to work in good faith towards a better future, that humanity very much needs in the here and now. There is work to be done.

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

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.

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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

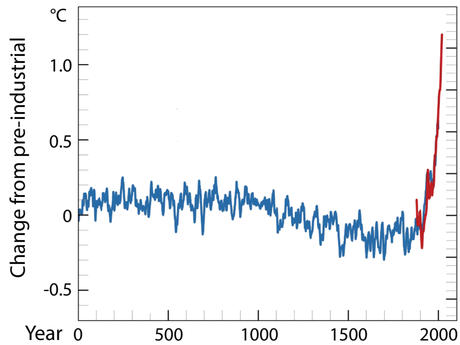

Figure 1.1 Change in global average temperature during the past 2000 years, inferred (blue line) from proxy tree-ring, coral growth, and ice-core data [1.10], and measured (red line) since 1880. (Image adapted from https://commons.wikimedia.org/wiki/File:Common_Era_Temperature.svg)

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.

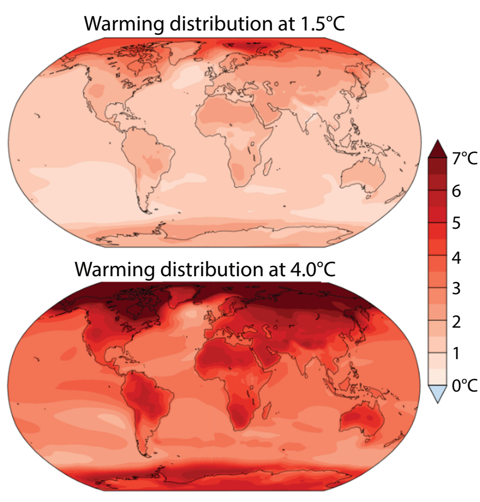

Figure 1.2 Projected changes in regional temperature (relative to 1850–1900) for global average warming amounting to 1.5 °C (top) and 4.0 °C (bottom). (Diagram based on Coupled Model Intercomparison Project Phase 6 (CMIP6) calculations)

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

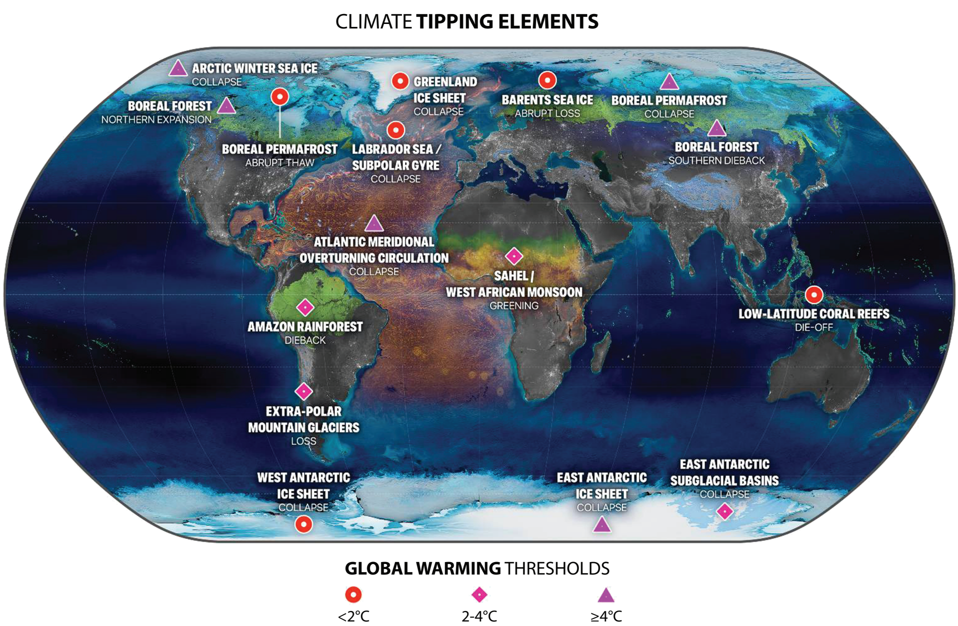

Figure 1.3 Locations of climate tipping points. (Image courtesy of Stockholm University [1.12])

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,

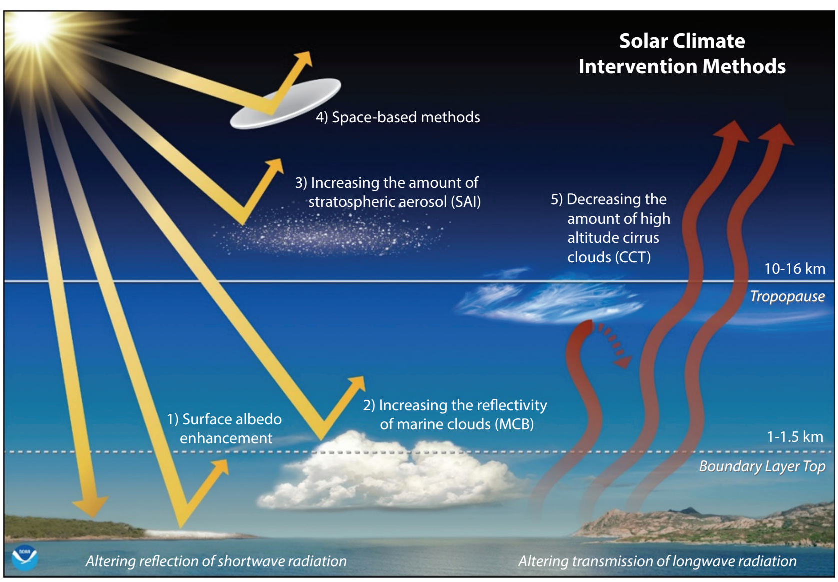

Figure 1.4 A schematic illustration of several geoengineering options. The regions in which geoengineering takes place is either above the atmosphere, as in the deployment of space-based shields, or in the stratosphere, tropopause, and lower atmosphere, right down to the land and ocean surface. (Image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