Why do we need Solutions to Global Warming?

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ABSTRACT

The atmosphere is the most valuable resource on the planet and as such every effort needs to be made to protect and manage it. Unfortunately the rise in greenhouse gases since the industrial revolution, and the intimately linked change in climate, is proving to be a most difficult environmental problem. Even though the strongest scientific evidence tells us that the anthropogenic release of greenhouse gases is responsible for climate change, there has been little success in emissions reduction. The reasons behind this failure are complex but the outcome is not; the regions of the Earth inhabited by humans are on average getting hotter and extreme weather is becoming more frequent. Since mitigation efforts against climate change are failing, the arguments for the possibility of geoengineering become louder. Geoengineering is a contentious issue which evokes strong reactions within all levels of society. Solar Radiation Management (SRM) technologies are more controversial than Carbon Dioxide Removal (CDR) technologies, since they do not solve the root cause of the problem, they do, however, potentially offer a more rapidly deployed solution. At present no geoengineering technology is fit for purpose or ready for deployment. However, geoengineering research is rapidly increasing with hundreds if not thousands of scientists and engineers working on the topic worldwide. As such, geoengineering research has now likely passed through its infancy, and conclusions are being reached about

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the efficacy, benefits and disadvantages of the different proposals. It seems increasingly likely that geoengineering technologies could be developed that will reduce climate change. These benefits need to be carefully weighed against the negative aspects. A true assessment of geoengineering cannot be achieved until we better understand the environmental, technological, economic and governance issues associated through its use.

On May 9, 2013 the daily mean concentration of atmospheric carbon dioxide levels passed 400 ppm at Mauna Loa according to independent measurements taken by both the National Oceanic and Atmospheric Administration (NOAA) and the Scripps Institution of Oceanography. NOAA had announced last year that its global cooperative air sampling network had detected 400 ppm for the first time over all its Arctic sites, just a prelude to what is now being detected over Mauna Loa. According to NOAA, locations throughout the Southern Hemisphere will follow over the next few years, as the increase in Northern Hemisphere levels is always a little ahead of the Southern Hemisphere, due to the fact that the majority of carbon dioxide producing behemoths are found in the Northern Hemisphere.[1]

1 Introduction – Life and the Evolution of the Earth's Atmosphere

Life and the Earth's current atmosphere are intimately linked. You can't have one without the other. Imagine what would happen to the atmosphere if life was wiped out by the gamma rays of a supernova or by a supervirus that killed every living cell on the planet. The Earth would slowly convert, over 100 million years or so, to a planet much like Venus.[2] It would be hotter than the Earth's atmosphere before life, as the sun was about 30% fainter then, than it is now. Thus the atmosphere, weather and climate that we enjoy today are completely dependent on the abundance of life. Lovelock[3,4] powerfully shows us, through the metaphor of Gaia, that the Earth carefully self-regulates the thin layers of land, ocean and atmosphere to provide a flourishing environment for life. However to achieve a lasting symbiosis of mutual benefit to both the host (Earth) and the invader (life) can we prevent an eventual 'Tragedy of the Commons'?[5] The human population continues to exploit and pollute the atmosphere and 'foul its own nest', for the pursuit of energy and growth, supposedly for the benefit of today's 7 billion citizens and the 9 billion citizens expected by 2050. As a result, the Earth's climate is changing and we have already seen a rise in the planet's surface temperature of 0.8 °C due to radiative forcing caused by greenhouse gas emissions and land-use changes. This global warming is predicted to raise global mean surface temperatures by up to 5 °C by the end of this century if emissions of greenhouse gases continue to rise in a 'business as usual' fashion. Global warming is set to double even if we cease to emit any further pollution, due to the slow release of energy already stored in the oceans. This additional energy available to the atmosphere has already led to an increase in extreme weather around the globe and agreement that a realistic limit of 2 °C could well be surpassed.

The Intergovernmental Panel on Climate Change (IPCC) was set up in 1988 by two United Nations organisations: the World Meteorological Organisation (WMO) and the United Nations Environment Programme (UNEP) to critically assess the scientific, technical and socio-economic consequences of climate change and to examine options for society to mitigate greenhouse gas emissions and adapt to changing weather and climate. The IPCC is in the process of submitting its fifth set of *Assessment Reports* (AR1 in 1990, AR2 in 1995, AR3 in 2001, AR4 in 2007 and AR5 in 2014, http://www.ipcc.ch/) to support the *United Nations Framework Convention on Climate Change (UNFCCC, https://unfccc.int/kyoto_protocol/items/2830.php)*, an international treaty that set up the Kyoto Protocol which became effective in 2005. In the first commitment period (2008–2012), the Kyoto Protocol sought to set binding targets for 37 industrial countries and 15 European Union (EU-15) countries, on four greenhouse gases: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), sulphur hexafluoride (SF_6) and two groups of ozone depleting gases: hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs).

The binding targets were modest and even so the results have been disappointing. Progress towards a new agreement (2012–2020) has been unsatisfactory because of the impasse in limiting the growth of greenhouse gas emissions. Alternative approaches (Plan B) such as geoengineering and the United Nations initiative *Sustainable Energy for All (SE4ALL)* are therefore being seriously considered.[6]

The focus of this chapter is on the options to sustainably manage this problem to prevent the atmosphere being polluted to such an extent that changes to the climate will be irreversible and damaging. Time is running out for solutions to be found that can be implemented in a sustainable way.

Firstly, we will scrutinize the value of the services that the atmosphere provides for society and their sensitivity to change. Secondly, we will look at how the climate is changing due to anthropogenic activity and the impacts that it is having on examples such as extreme weather, sea level rise, melting glaciers and ice caps. Thirdly, we will define geoengineering, and fourthly, we will examine the broad arguments for and against geoengineering, and the likely success of geoengineering as an instrument to manage the atmosphere should the mitigation of greenhouse gases fail to deliver.

2 The Atmosphere – The Most Valuable Resource on the Planet

Today's atmosphere has evolved slowly over more than 4 billion years. Changes in the composition of the atmosphere to what it is today are directly attributable to the development of living micro-organisms. Deliberate and inadvertent interventions, by forms of life, into the composition and behaviour of the atmosphere are consequently not new. Animal life (including humans) has evolved to become totally dependent on the atmosphere. The word 'animal' comes from the Latin word *animalis*, meaning 'having breath'. Typically on average we humans breathe about 15 m^3 of air per day. Without the air that we breathe we would die within minutes. Yet we take the atmosphere totally for granted. It is not just the air that we breathe that is vital. The atmosphere provides us with a whole range of 'atmospheric services' that are more valuable than any other resource on the planet.[7] Table 1 lists 12 of these services that are key to all life on Earth.

Typically the atmosphere is portrayed in the media as a hazard with almost daily tragedies caused by floods, droughts, gales, tornadoes, typhoons/

Table 1 The twelve atmospheric services.[7]

Rank in Value	*Atmospheric Services*	*Usage Trend*	*At Risk*	*Entity*	*Service Type*
1	The air that we breathe	++	**	O_2, N_2 *etc.*	Provisioning
2	Protection from radiation, plasma and meteors	+	**	Density, ozone layer	Supporting
3	Natural global warming of 33 degrees Celsius	+	*****	CO_2, CH_4, N_2O, H_2O^{++}	Supporting
4	The cleaning capacity of the atmosphere and dispersion of air pollution	+	*	OH, wind, temperature	Regulating
5	The redistribution of water services	+	**	H_2O	Supporting
6	Direct use of the atmosphere for ecosystems and agriculture	+	*	CO_2, N_2, filtered solar	Provisioning & Supporting
7	Combustion of fuel	–		O_2	Provisioning
8	Direct use of the atmosphere for sound, communications and transport	+	*	Density, pressure	Supporting
9	Direct use of the atmosphere for power	++		Wind, wave	Provisioning
10	The extraction of atmospheric gases	+		O_2, N_2, Ar *etc.*	Provisioning
11	Atmospheric recreation and climate tourism	+	*	Sun, temperature, wind, snow	Cultural
12	Aesthetic, spiritual and sensual properties of the atmosphere, smell and taste	+		Sky, clouds, rainbows *etc.*	Cultural

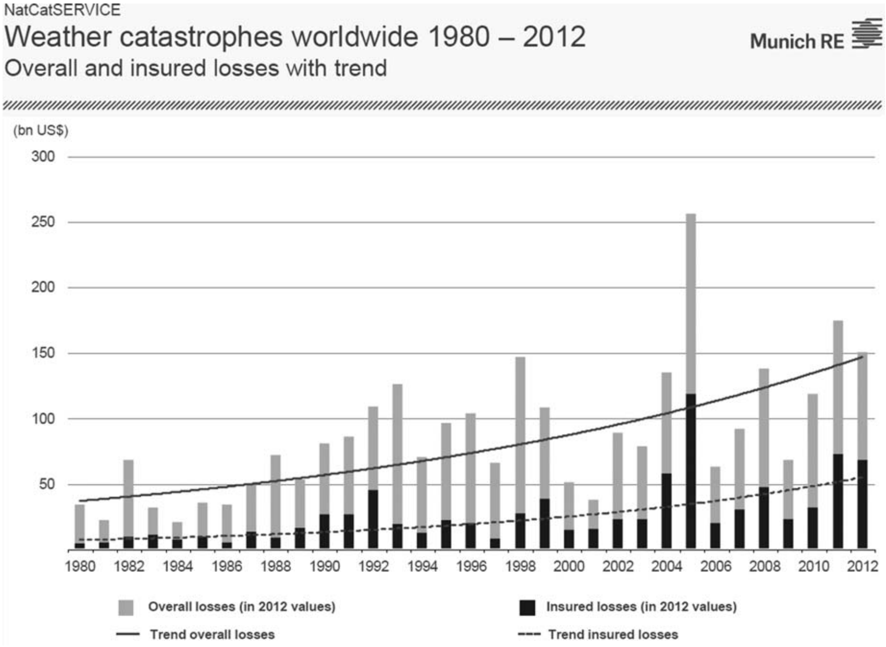

Figure 1 Overall and insured losses for weather catastrophes worldwide 1980–2012. (Data from Munich Re). (http://www.munichre.com/en/reinsurance/business/non-life/georisks/natcatservice/default.aspx)

hurricanes, heat waves, snow and ice storms. The insurance group, Munich Re, compiles the best database of the worldwide number and costs of such hazards. During the period 1980–2012 they have estimated that there have been 18 200 weather catastrophes costing US$ 2.8 trillion (at 2012 prices) with the loss of 1 405 000 lives. They identify an upward trend that has seen a doubling in the annual number and cost of weather catastrophes since 1990 (see Figure 1). In 2012 there were more than 800 weather catastrophes logged at an estimated cost of US$ 150 billion.

Poor air quality is another vital issue that adds to the annual cost of breathing a polluted atmosphere. The World Health Organisation (WHO) considers clean air to be a basic requirement of human health and well-being. The European Commission has declared 2013 to be the 'Year of Air' and will take the opportunity to review current European air quality legislation. A recent estimate suggests that poor air quality is responsible for more than two million deaths worldwide each year:[8]

> *We estimate that in the present-day, anthropogenic changes to air pollutant concentrations since the preindustrial era are associated annually with 470 000 (95% confidence interval, 140 000 to 900 000) premature respiratory deaths related to ozone, and 2.1 (1.3 to 3.0) million CPD (cardiopulmonary*

> *disease) and LC (lung cancer) deaths related to* $PM_{2.5}$*... We estimate here that 1500 premature respiratory deaths related to ozone and 2200 CPD and LC deaths related to* $PM_{2.5}$ *occur each year due to past climate change.*

The number of weather catastrophes is undoubtedly increasing due to climate change whereas the impact of climate change on air pollution is relatively small. Overall the impact of the atmosphere as a hazard to human life would be much worse if the atmosphere did not disperse air pollutants. In total, however, the atmosphere is worth orders of magnitude more as a resource than it costs as a hazard.[7]

The well mixed atmosphere is approximately 100 km deep, which is very thin in comparison to the size of the Earth. Indeed the troposphere, the lowest part of the earth's atmosphere is only about 8–12 km over the poles and 15–18 km deep over the equator and most of the life on the planet survives within the lowest 5 km which comprises half the atmosphere by weight. The effective atmosphere is therefore extremely thin, vulnerable and fragile and has been compared in size to the varnish on a globe. Hence the atmosphere is always taken for granted as it is effectively invisible and free.

3 The Greenhouse Effect and Global Warming

The natural greenhouse effect is responsible for keeping the global mean surface temperature 33 °C warmer than it would otherwise be. Without the atmosphere the mean temperature of the Earth would be -18 °C but with the atmosphere the mean global surface temperature is +15 °C. This natural greenhouse effect is caused by greenhouse gases in the atmosphere that are basically transparent to incoming solar radiation but trap and re-emit the Earth's thermal infrared radiation at certain wavelengths. This warms the atmosphere and the analogy of the workings of a greenhouse has been adopted for simplicity by policy makers (in reality the warming effect of a greenhouse depends on other factors too such as sheltering the air inside from the wind). Water vapour in the atmosphere is the most important natural greenhouse gas accounting for approximately 29.4 °C (89%) of the 33 °C. Carbon dioxide is only responsible for about 7.5% of the remaining 11% of natural warming.

On May 9, 2013 the daily mean concentration of atmospheric carbon dioxide levels passed 400 ppm at Mauna Loa, a background site in the middle of the Pacific Ocean, well away from industrial sources. Figures 2 and 3 show the steady upward rise of atmospheric CO_2 at Mauna Loa. There is no sign of a levelling off despite Kyoto, the global recession and other global attempts at mitigation. Annual CO_2 emissions from fossil fuel combustion and cement production were about 9.5 GtC (giga tons of carbon) in 2011, an increase of 54% over 1990 levels. From 1750 to 2011, cumulative global anthropogenic CO_2 emissions amount to approximately 545 GtC, of which 240 GtC have accumulated in the atmosphere, 155 GtC have been taken up

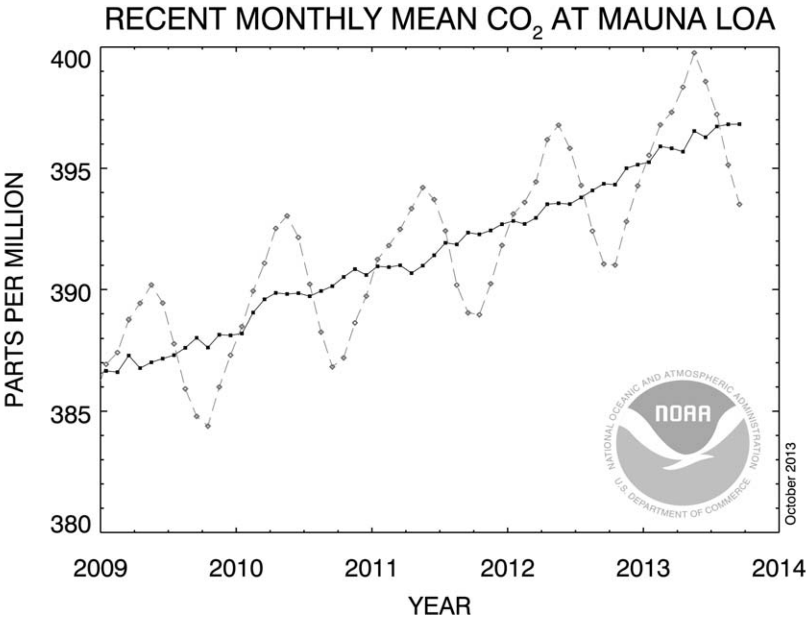

Figure 2 Recent monthly mean CO_2 at Mauna Loa.
(Data from the NOAA Earth System Research Laboratory, http://www.esrl.noaa.gov/gmd/ccgg/trends/).

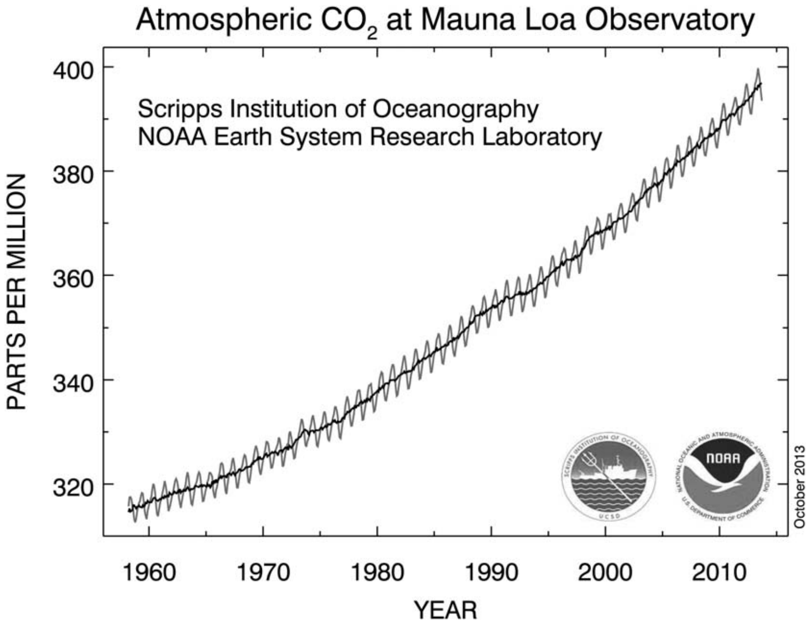

Figure 3 Atmospheric CO_2 at Mauna Loa observatory 1958–2013.
(Data from the Scripps Institution of Oceanography and NOAA Earth System Research Laboratory, http://www.esrl.noaa.gov/gmd/ccgg/trends/).

by the ocean and 150 GtC have accumulated in natural terrestrial ecosystems.

Global warming is the increase (0.8 °C so far) in the mean global surface temperature, above the 33 °C caused by the natural greenhouse effect, due to the human emitted greenhouse gases and also aerosol particles that directly absorb solar radiation. Carbon dioxide is responsible for nearly half of this increase. Figure 4 shows the latest estimate (for 2011) of radiative forcing caused by emissions of greenhouse gases and other drivers of change such as aerosols and black carbon. Radiative forcing of the climate drives climate change across the planet due to the uptake of additional energy into the climate system. The solar constant is on average 1365 Wm^{-2} and the additional total anthropogenic radiative forcing relative to 1750 is estimated by the IPCC (AR5) to be 2.29 (1.13 to 3.33) Wm^{-2}. This estimate is 43% higher than the estimate in AR4 (2005) due to the continued increase in greenhouse gases and an adjustment to give a weaker negative forcing caused by aerosols. There is not a simple linear relationship between radiative forcing and the global mean surface temperature increase as shown in Figure 5. Natural variability of the climate means that the global warming signal is superimposed on the noise of the natural greenhouse effect. However the IPCC (2013) state:[9]

> *Warming of the climate system is unequivocal and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, sea level has risen, and the concentrations of greenhouse gases have increased.*[9] *(p.2)*

What are the measurable impacts of global warming so far on the climate and the Earth's surface environment? Although the mean surface temperature rises have been observed across most of planet there is less certainty about precipitation.[9] There is some evidence for increased precipitation since 1901 over land areas in the northern hemisphere with greater intensities of precipitation also in North America and Europe. Over the oceans, however, more evidence is needed. Since 1950 more extreme weather and climate events have been observed. On the global scale the number of warm days and nights has increased, as have the number of heat waves. The number of cold days and nights has decreased despite a number of recent cold winters in the northern hemisphere.

> *Ocean warming dominates the increase in energy stored in the climate system, accounting for more than 90% of the energy accumulated between 1971 and 2010.*[9] *(p.6)*

The warming of the upper oceans is especially important and it has been estimated that of this 90%, it is likely that 60% is in the upper oceans (0–700 m) and 30% below 700 m. This energy will eventually be released into the atmosphere and add significantly to global warming this century.

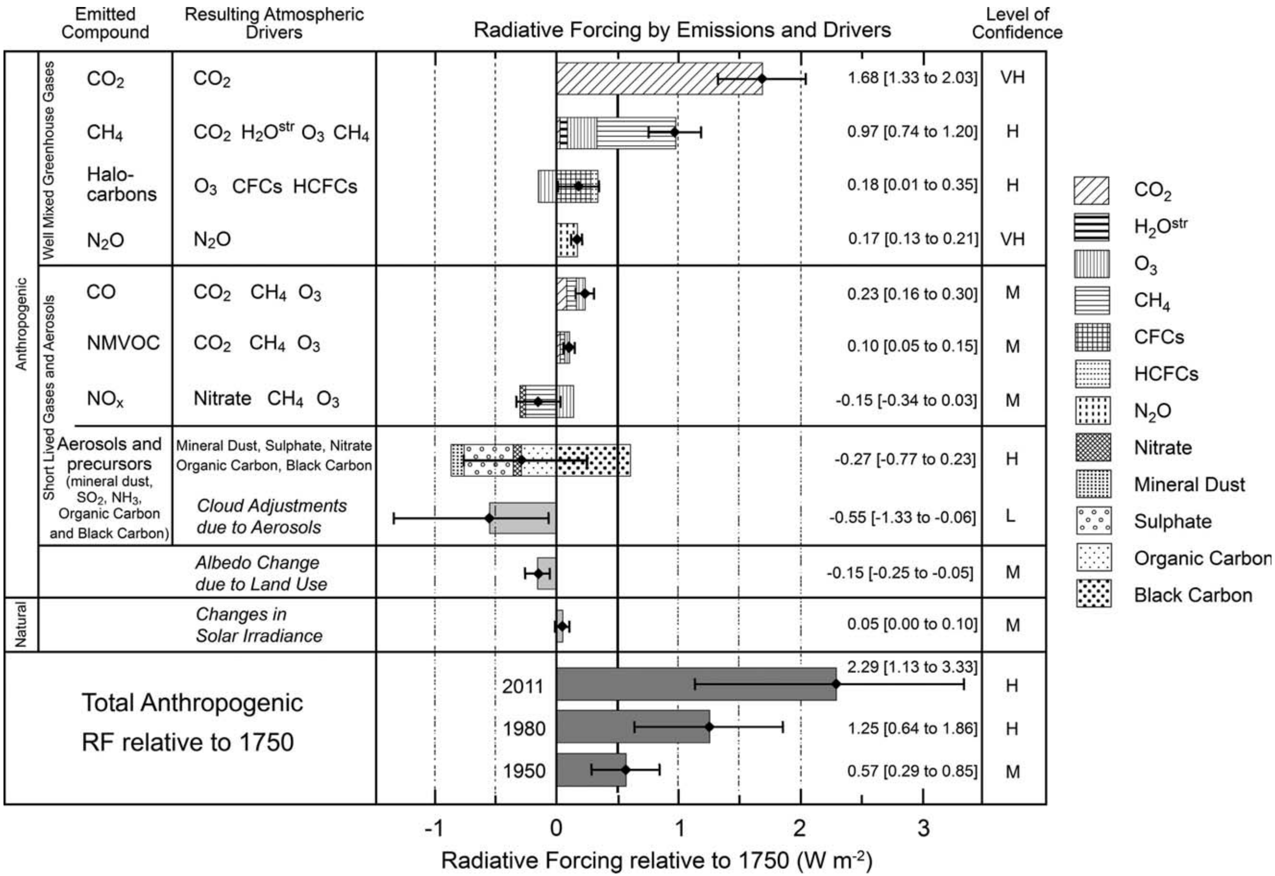

Figure 4 Radiative forcing by emissions and other drivers (IPCC 2013).[9]

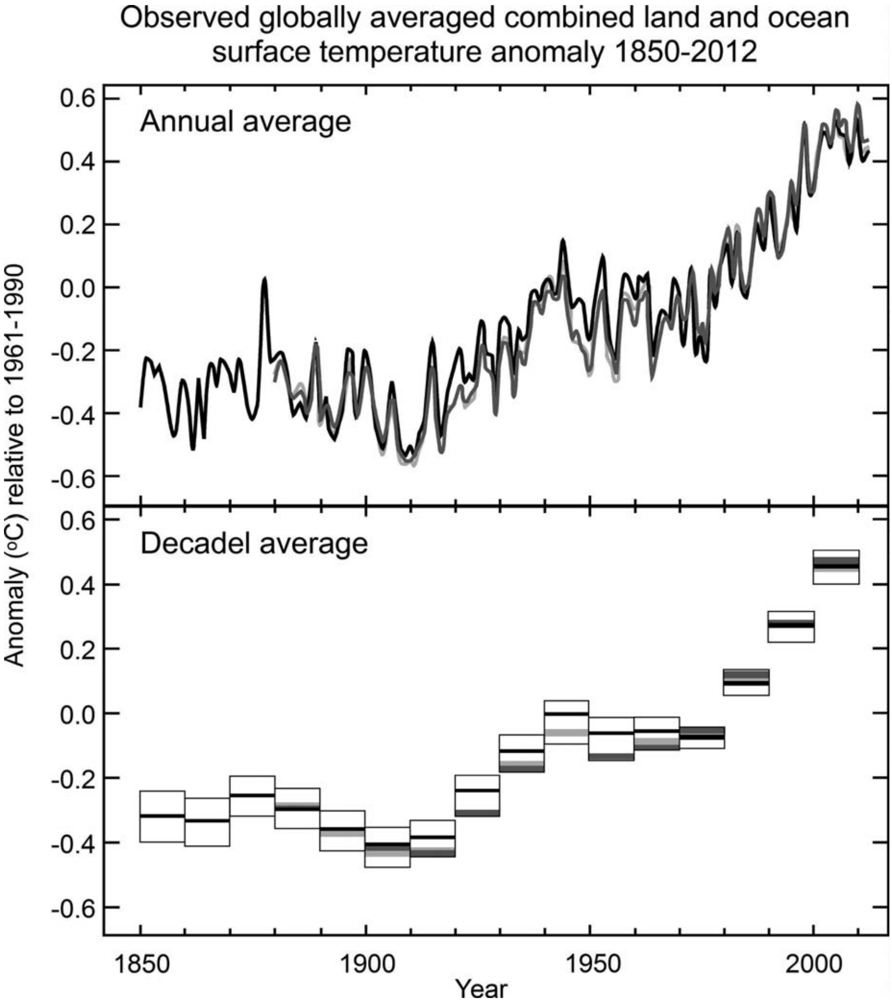

Figure 5 Observed globally averaged combined land and ocean surface temperature anomaly 1850–2012 (Data from the IPCC 2013).[9]

> *Over the last two decades, the Greenland and Antarctic ice sheets have been losing mass, glaciers have continued to shrink almost worldwide, and Arctic sea ice and Northern Hemisphere spring snow cover have continued to decrease in extent.*[9] *(p.7)*

This has been most noticeable in the Arctic where annual sea ice extent has shrunk considerably, especially in summer. The picture is less clear in Antarctica where some areas are seeing growth of ice extent where other areas are seeing a retreat. Permafrost temperatures have increased and in parts of the Russian European North reductions in permafrost thickness and extent have been observed since the 1970s.

> *The rate of sea level rise since the mid-nineteenth century has been larger than the mean rate during the previous two millennia. Over the period 1901–2010 global sea level rose by 0.19 (0.17–0.21) m.*[9] *(p.9)*

Ocean thermal expansion and glacier mass loss together explain about 75% of the observed global sea level rise since 1970. In the last interglacial, 129 000 to 116 000 BP (before present years), sea level was between 5 and 10 m above present levels.

> *The atmospheric concentrations of carbon dioxide (CO_2), methane, and nitrous oxide have increased to levels unprecedented in at least the last 800 000 years. CO_2 concentrations have increased by 40% since pre-industrial times, primarily from fossil fuel emissions and secondly from net land use change emissions. The ocean has absorbed about 30% of the emitted anthropogenic carbon dioxide, causing ocean acidification.*[9] *(p.9)*

Figure 6 shows that the total emissions of carbon dioxide and the global mean surface temperature response are approximately linearly related. In order to limit global warming to less than 2 °C it is shown that anthropogenic emissions from all sources must not exceed approximately 1 trillion

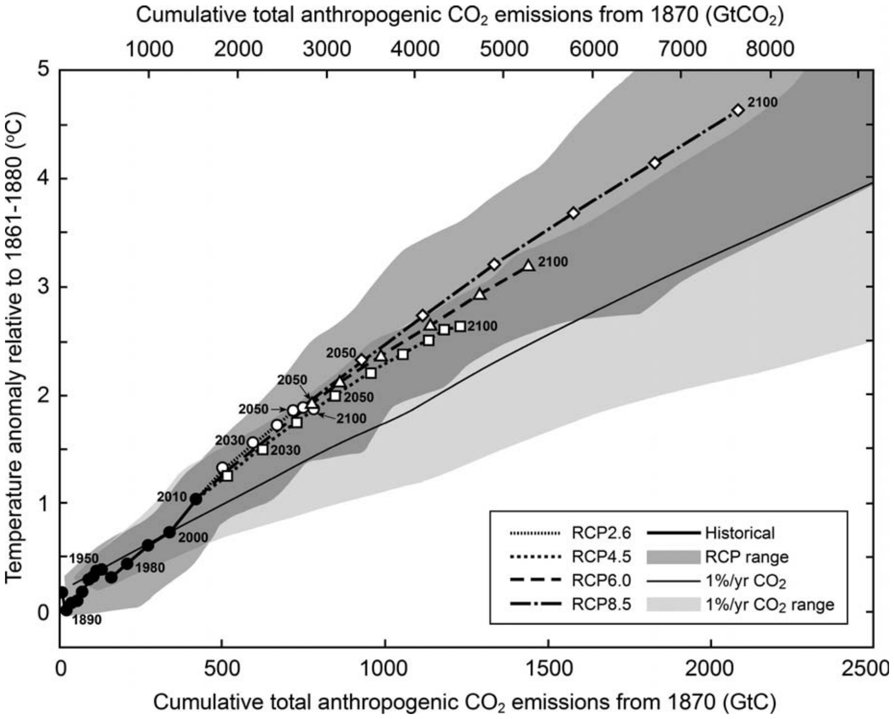

Figure 6 Cumulative total anthropogenic CO_2 emissions from 1870 (http://www.climatechange2013.org/images/figures/WGI_AR5_FigSPM-10.jpg).

tonnes of carbon. Emissions are continuing to rise despite the recent global recession and we are already halfway towards this target. The carbon dioxide that is already in the climate system will continue to raise temperatures even if the world runs on carbon-free energy.

> *A large fraction of anthropogenic climate change resulting from CO_2 emissions is irreversible on a multi-century to millennial time scale, except in the case of a large net removal of CO_2 from the atmosphere for a sustained period. Surface temperatures will remain approximately constant at elevated levels for many centuries after a complete cessation of net anthropogenic CO_2 emissions. Due to the long time scales of heat transfer from the ocean surface to depth, ocean warming will continue for centuries. Depending on the scenario, about 15 to 40% of emitted CO_2 will remain in the atmosphere longer than 1000 years.*[9] *(p.26)*
>
> *There are many approaches and pathways to a sustainable and resilient future. However, limits to resilience are faced when thresholds or tipping points associated with social and/or natural systems are exceeded, posing severe challenges for adaptation.*[10] *(p.20)*

Clearly we need new solutions to global warming since carbon dioxide induced warming will continue for centuries even if there is a complete cessation of all emissions. This increase in energy to the climate system will increase the severity of extreme events leading to unprecedented heat waves, floods, droughts, storms and subsequent landslides, tsunamis and coastal erosion. These have knock on impacts on humans *via* agriculture, food security, forestry, health, infrastructure, tourism, transport and water supply that may cause a host of global problems including increased poverty, reduced security, increased migration and possibly a breakdown of society as we know it. Could geoengineering of the climate system provide this new solution?

4 What is Geoengineering?

4.1 Introduction

Many different geoengineering definitions exist, and it is interesting to observe the solidification of the word's meaning through time. See Box 1 which provides the *Oxford English Dictionary* reference for geoengineering.[11] It can be seen that since approximately the 1980s, a reasonably consistent idea of geoengineering has settled in the English language. The influential 2009 Royal Society report on geoengineering succinctly defines geoengineering as "the deliberate large-scale intervention in the Earth's climate system, in order to moderate global warming" and this definition is used henceforth.[12] There is currently a debate about whether the term 'geoengineering' should be replaced with 'climate engineering' since it offers clearer labelling. However, there is little evidence at present that geoengineering is being usurped by climate engineering, within the British media at least.

Box 1 OED definition of geoengineering.[11]

The Oxford English Dictionary documents changes in the meaning and use of words throughout history.

Geoengineering, noun.

Definition – The application of large-scale engineering methods to modify rock formations or other features of the natural environment; (in later use esp.) the modification of the global environment or the climate in order to counter or ameliorate climate change.

1962 *New Mexican (Santa Fe, New Mexico)* 16 Feb. 9/3. The 30 graduate geologists currently employed by the department, either as materials testers or as central research laboratory workers handling geoengineering assignments.

1969 *Sci. News* **95** 159/1. Teller... urged that Australia act as a proving ground for nuclear geoengineering.

1976 C. Marchetti, *Geoengineering & CO_2 Probl.* p. iii. Geoengineering... is a kind of 'system synthesis' where solutions to global problems are attempted from a global view.

1983 T. Hoyle, *Last Gasp* iv. 51. The Russians are keen to find out everything they can about what affects the climate because of their grandiose geoengineering schemes.

1994 *Guardian* 17 Mar. 94. The market can supply appropriate geoengineering—for example, companies launching mirrors into space to deflect sunlight.

2007 *Nature* 10 May 115/2. Geoengineering... explores in what circumstances aspects of the climate system might be deliberately modified to limit the worst eventualities of climate change.

Geoengineering is distinct from climate change mitigation and adaptation. Mitigation involves strategies to reduce anthropogenic emissions of greenhouse gases, for example through the transition to a low carbon economy. Adaptation aims to increase resilience towards the effects of climate change, for example by improving flood defences and providing protection against climate dependent disease. Geoengineering is not a new idea and it has its origins in weather modification studies.[13] A good history of geoengineering, as opposed to weather modification, is provided by the review of Keith.[14]

Geoengineering schemes can be divided into two main categories, namely: Carbon Dioxide Removal (CDR) and Solar Radiation Management (SRM), and the subsequent chapters in this book provide specific details about various CDR and SRM schemes: Chapters 2 and 3 – carbon sequestration (CDR); Chapter 4 – artificial trees (CDR); Chapter 5 – increased surface albedo; Chapter 6 – brighter clouds (SRM); Chapter 7 – stratospheric aerosol (SRM); and Chapter 8 – space based solutions (SRM).

Geoengineering schemes typically aim to reduce climate change impacts through use of analogues of processes already present in the Earth system. For example stratospheric particle injection (see Chapter 7) mimics the effect of large volcanic eruptions; these eruptions can inject megatonnes of particle material into the stratosphere leading to an increased global albedo and planetary cooling. The last eruption to have a major effect on climate was Mt Pinatubo in the Philippines in 1991 which reduced global surface temperatures by ~0.5 °C for a 1–2 years.[15] The geoengineering analogue to volcanic activity is anthropogenic particle injection into the stratosphere *via* a non-volcanic route such as an aeroplane or pipe delivery system.[16]

CDR technologies aim to reduce climate change by removing greenhouse gases from the atmosphere. The greenhouse gas of choice is typically CO_2 because its high concentration makes extraction easier. Different CDR techniques use biological, chemical or physical approaches to remove CO_2 from the atmosphere. CDR is likely to be slow, compared to SRM, because of the huge amounts of CO_2 that need to be removed. The *IPCC 5th Assessment Report* (AR5) evaluates that CDR techniques would need to be deployed at large scale for over a century to be able to significantly decrease CO_2 concentrations.[9]

SRM schemes decrease the effects of climate change by reducing the amount of energy within the Earth system by reflecting a proportion of solar radiation back to space. It is expected that SRM techniques, if technologically feasible, would be able to quickly decrease average global temperatures over the timescale of a decade or so. Unlike CDR, SRM does not remove greenhouse gases from the atmosphere and, as such, can only be viewed as a temporary solution to climate change, albeit one which might be used to buy time whilst civilization transfers to a low carbon economy, or successfully integrates CDR schemes to counterbalance fossil fuel burning. Another obvious downside of SRM is that it only counteracts the radiative effects of greenhouse gas emissions; it does not counteract the non-radiative effects such as the partitioning of excess atmospheric CO_2 into the oceans. Hence ocean acidification would still occur under SRM scenarios and itself represents a serious environmental threat.

Another potential issue with SRM geoengineering is the termination problem. Since SRM could rapidly decrease the Earth's temperature, if it is turned off the restoration of climate to its non-geoengineered state would also be fast. Rapid rises in temperature are much more stressful for ecosystems and human infrastructure to cope with than slow changes. If SRM techniques were found to be causing unplanned and deleterious effects the termination problem would then cause a dilemma: rapidly switch off SRM and risk stressing various systems, or gently ramp down SRM thus prolonging the unwanted side effects. CDR techniques are not as susceptible to termination risks because of their slower timescale of action.

The relative ranking of different geoengineering proposals is difficult because of the multiple assessment criteria. It is not clear at present what the best metrics are with which to assess geoengineering proposals. The influential Royal Society report uses four main technical criteria through which to rank the different technologies: effectiveness, timeliness, safety and affordability.[12] The report highlights that no single technology, identified to date, scores highly in all four sections. Moreover there are also non-technological criteria which should be used to assess the different technologies; these are much more difficult to rank quantitatively and include: public attitudes, social acceptability, political feasibility and legality. The complexity further increases with many of the ranking criteria liable to change over time.[12]

It should be noted that, if used, geoengineering does not have to be employed to completely remedy all of anthropogenic climate change. It might be more usefully utilized as part of a toolbox of technologies and policies with which to stabilize climate change.[17]

4.2 Are there Parallels to Climate Change and Geoengineering?

Myriad environmental risks and problems have been created since civilization entered into the Anthropocene – the human-dominated geological epoch that overtook the Holocene.[18] In fact it is likely that geologists of the future will use these anthropogenic changes to exemplify the Anthropocene. In addition to anthropogenic climate change, these environmental problems and risks include but are not limited to: stratospheric ozone depletion; biodiversity loss; overfishing; changes in the phosphorus and nitrogen cycles; and chemical pollution including nuclear waste and persistent organic pollutants.[19] Many of these environmental pollutant problems can be understood in the context of a tragedy of the commons analysis,[5] in which a common resource (*e.g.* the atmosphere and oceans) is overused to individual advantage but to the group's disadvantage.

Global problems of pollution typically arise because of the persistence of pollutants and the limited ability of natural systems to absorb anthropogenic stressors. If the lifetime of a pollutant is sufficiently long then the pollutant can be transported globally. For atmospheric pollutants, a lifetime greater than a couple of years will lead to global ubiquity and persistence. The atmospheric lifetime of CO_2 is difficult to define exactly due to multiple location dependent loss processes, such as uptake by the oceans and biosphere, but it is approximately on the timescale of fifty to a hundred years. This makes CO_2 a cross national boundary pollutant, and defines a molecule of CO_2 released in one specific country as dangerous as a molecule released in any other country. The cross boundary nature of CO_2 can be viewed as a benefit for CDR approaches to geoengineering. If the significant removal of the long lived CO_2 gas can be achieved, then the technology can be deployed anywhere worldwide to reduce the global burden of atmospheric CO_2.

It is perhaps useful to investigate whether there are contemporary or historic parallels to climate change and geoengineering. The identification of the Antarctic ozone hole and the subsequent phase-out of ozone destroying chemicals is often cited as the paradigm of the success of environmental science. Furthermore it is also often used as evidence that anthropogenic climate change can be fully understood and rectified.

The Antarctic ozone hole was first identified in the 1985 and it was soon understood that the release of halogen containing species, in the form of refrigerants and propellants, was leading to stratospheric ozone depletion especially in the polar regions.[20] Once the cause and effect of the ozone hole had been largely understood, then international treaties, starting with the *Montreal Protocol on Substances that Deplete the Ozone Layer* (1987), rapidly started to reduce the concentration of ozone destroying substances in the stratosphere. A mitigation approach to the ozone hole problem was successfully instigated and carried out. Geoengineering or adaptation type approaches were not used or required. Due to these efforts, the ozone hole is now expected to completely recover by approximately the year 2065.

So now that the scientific understanding of climate change is maturing and attribution of anthropogenic emissions to the warming of the climate system is explicit,[9] could a similar strategy to that used with the ozone hole problem be followed? The major difference between the ozone hole and climate change is the transferability of the responsible pollutant. The global economy was not reliant on ozone depleting refrigerants and propellants and hence the mitigation approach was relatively straight forward. For the ozone hole problem, it was somewhat simple to find replacement refrigerants and propellants which possessed much lower ozone depleting potentials. By contrast CO_2, the main greenhouse gas, has no substitute, and if we continue to burn hydrocarbons then CO_2 will result. At present the global economy and its infrastructure are reliant on burning hydrocarbons.

Whilst climate change has clear parallels with other environmental problems, including the ozone hole, it is the largest environmental problem that the human race has so far encountered. It is global in scope and the chief greenhouse gases responsible cannot be substituted for less harmful chemical species. As such it is probably the most difficult, as well as the largest, environmental problem encountered.

4.3 Scientific Respectability of Geoengineering

The IPCC has for the first time described geoengineering in its most recent fifth assessment report.[9] Whilst the report uses rather bland language, the inclusion of geoengineering within this document constitutes a coming of age moment for the science of geoengineering which in many eyes has previously looked like nothing more than crank science.

A milestone for the acceptance of geoengineering into the global scientific discourse on climate change occurred upon publication of an editorial by Paul Crutzen, who was jointly awarded the Nobel Prize in Chemistry in 1995 for his work in atmospheric science.[21] Within this editorial the SRM technique of stratospheric injection of aerosols was evaluated and it stated "… although by far not the best solution, the usefulness of artificially enhancing earth's albedo and thereby cooling climate by adding sunlight reflecting aerosol in the stratosphere might be explored and debated…". This cautious justification of geoengineering research by one of the luminaries of environmental science helped to give legitimacy to the nascent field of geoengineering.

More recently, another prominent and highly respected scientist providing further cautious justification of research has been Lord Rees of Ludlow who has filled several of the top scientific positions within UK science including: presidency of the Royal Society, Astronomer Royal, and Master of Trinity College, Cambridge. ‘‘Most nations now recognize the need to shift to a low-carbon economy, and nothing should divert us from the main priority of reducing greenhouse gas emissions. But if such reductions achieve too little too late, there will surely be pressure to consider a plan ‘B’ – to seek ways to counteract the climatic effects of greenhouse gas emissions by ‘geoengineering’.’’[12]

The greater visibility of geoengineering science, in part helped by the respectability given by such examples, combined with the bleak outlook on climate change has led to an explosion in research output on geoengineering (see Figure 7). This output has been spread over a wide range of disciplines including the physical and social sciences, and engineering.

4.4 *The Arguments for and against Geoengineering Research*

Geoengineering *via* CDR techniques is far less controversial than SRM techniques and as such there is little opposition to research and development of CDR techniques. Conversely there has been loud and fierce

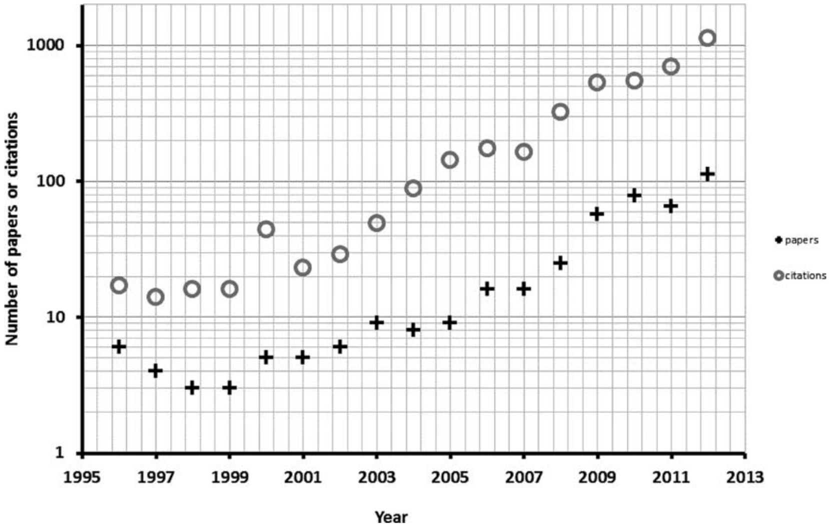

Figure 7 Geoengineering research output.
(Data compiled from the search returns to the subject query ‘geoengineering’ within Scopus, an abstract and citation database of peer-reviewed literature; www.elsevier.com/online-tools/scopus).

opposition to the research and development of SRM techniques. Most SRM research has been justified by framing it in the context of future proofing society against unbearable climate change. The argument is as follows: mitigation by reducing global greenhouse emissions is the best way to solve climate change because it keeps the planet closer to its natural state. However, in the last decades there has been little progress on reducing emissions and in fact our emissions are increasing. For example our CO_2 emissions are rising by the equivalent of approximately 2 ppmv per year at present (see Figures 2 and 3). Therefore there are justified concerns and wide spread pessimism about our ability to curb emissions in the short term (*ca.* 100 years). This generates real worries that civilization might not be able to mitigate CO_2 in time, hence geoengineering might be required. This argument frames geoengineering as the lesser of two evils when compared to dangerous climate change, and it follows that if there is the possibility that we will need geoengineering in the future, then we should prepare for that possibility now.

There are clearly different levels of environmental risk associated with the three major strands of geoscientific research: modelling, laboratory and field studies. Desk studies that use computer models to predict the outcomes of geoengineering offer zero risk to the environment. Likewise laboratory studies offer virtually no risk to the environment since they do not interact with world external to the laboratory. Field trials are more problematic and could interact with biogeochemical cycles if their scale was large enough. Common sense should dictate that if and when field trials are attempted, they would start at sufficiently small scales so their environmental effect would be localised in time and space, and negligible over wider temporal and spatial regions. If initial small scale trials were successful then increasingly larger and longer trials would be implemented with the increased risk of environmental harm.

The future proofing rationale for geoengineering research has many opponents both individual and institutional. The arguments raised against geoengineering research are numerous, and will not be fully explored here, but they can broadly be classified as technical, moral or political in standpoint.

From the technical standpoint, a major worry about geoengineering research is: how can you test and validate the various geoengineering schemes? The Earth is a highly complex non-linear system with numerous feedbacks which are not fully understood. Whilst various geoengineering schemes could be simulated within computer models and laboratory tests, at some stage field trials would be required. Validation would require field trials of sufficient size to generate a response in the Earth's climate so a clear cause and effect could be observed. This would necessitate large field trials.

Geoengineering would require huge infrastructure and with that infrastructure there would be the possibility of human error. Recently there have been two large examples of large negative impacts of human error on the environment: the Deepwater Horizon oil spill (2010) and the Fukushima

Daiichi nuclear disaster (2011). All technical validations come with a level of uncertainty. What level of uncertainty would be acceptable for geoengineering? There is also the worry of unanticipated consequences of geoengineering – the so called 'unknown' unknowns. What is the likelihood of these being foreseen prior to a major scale geoengineering attempt? The precautionary principle might seem to argue strongly against geoengineering.

From the political standpoint, there is a suspicion that geoengineering will encourage political inertia with respect to CO_2 mitigation. A situation of moral hazard could be generated in which geoengineering provides a political get out clause for the more costly option of mitigation. Hence if geoengineering technologies are developed and are ready to be deployed, then there is less chance that mitigation will occur in a significant and timely fashion. Whilst geoengineering research is in its youth and so far its research costs have been minor, is geoengineering the correct big project for governments to put their money into? Would geoengineering research remove money from the mitigation research effort? The long lifetime of greenhouse gases and the climate change problem in general, makes legislation difficult due to the time inconsistency between the timescale of government (years to decades) and the timescale of climate change (decades to centuries).

The governance of geoengineering is another problem. Who would own the technology? And who would fund the process? It seems likely that if geoengineering is to happen then the UN would have to be the ultimate responsible authority. At present, there are no specific UN based regulations against geoengineering. However, several existing frameworks are thought to have relevance to some types of geoengineering, for example: *The Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter* (1972) might be applied to iron fertilization of the oceans, and *The Environmental Modification Convention* (1978) could potentially be applied more widely to geoengineering schemes in general. In common with the effects of climate change. the effects of geoengineering are likely to be unevenly distributed globally. There will be winners and losers, so how is equity ensured amongst the nations? Would compensation be required for the losers? Geoengineering would need a final goal – a climatic endpoint. Who sets this goal? Different countries and regions will clearly have different views on what constitutes a desirable outcome. Moreover is it possible that some countries would regard global warming to be a positive outcome, for example, in polar regions? Geoengineering is likely to be cheap compared to the transfer of the world to a low carbon economy, at least in the near future. Therefore it will be financially possible for large countries and companies. How do we avoid unilateralism?

Geoengineering offers moral questions as well. Such as: is geoengineering hubristic (see Chapter 9)? Does this technology represent a step too far in our control of the Earth system? By even talking about geoengineering, do we normalize the concept or provide it with premature credibility? Does the mere presence of geoengineering research represent a slippery slope towards the ultimate use of geoengineering? This is the atomic bomb argument – that once a technology has been developed it is unlikely that it will not be utilized.

5 Summary and Conclusions

The atmosphere is the most valuable resource on the planet and as such every effort needs to be made to protect it. Unfortunately the rise in greenhouse gases since the industrial revolution, and the intimately linked change in climate, is proving to be the most difficult environmental problem. Even though the strongest scientific evidence tells us that the anthropogenic releases of greenhouse gases are responsible for climate change, there has been little success in emissions reduction. The reasons behind this failure are complex but the outcome is not; the regions of the Earth inhabited by humans are on average getting hotter.

Since mitigation efforts against climate change are failing, the arguments for the possibility of geoengineering become louder. Geoengineering is a contentious issue which evokes strong reactions within all levels of society. SRM technologies are more controversial than CDR technologies since they do not solve the root cause of the problem, however, they potentially offer a more rapidly deployed solution. At present no geoengineering technology is fit for purpose or ready for deployment. However, geoengineering research is rapidly increasing with hundreds, if not thousands, of scientists and engineers working on the topic worldwide. As such, geoengineering research has now likely passed through its infancy, and conclusions are being reached about the efficacy, benefits and disadvantages of the different proposals. It seems increasingly likely that geoengineering technologies could be developed that will reduce the effects of climate change. These benefits need to be carefully weighed against the detriments. A true assessment of geoengineering cannot be achieved until we better understand the environmental, technological, economic and governance issues, associated through its use. Thus this book sets out our present knowledge of this subject, as well as the areas where understanding is currently lacking.

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