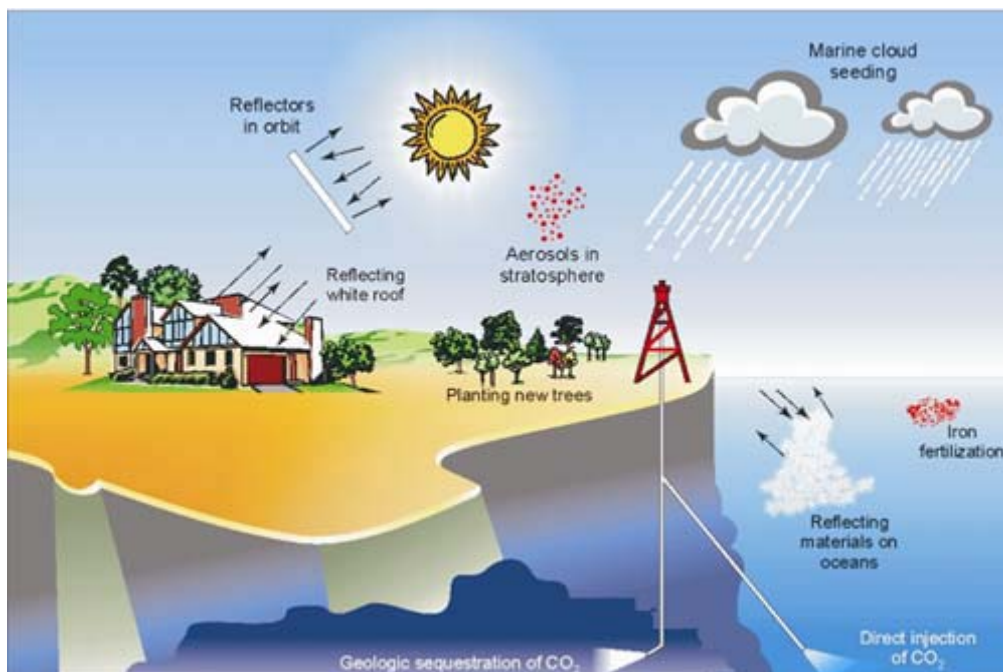


# The Debate on Geoengineering: Arguments, Risks and Consequences

(compiled by Florence Dafe, Scientific Secretariat NKGCF)



Schematic representation of various geoengineering proposals, adapted from Bala (2009)

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## 1. Introduction

The distinction between geoengineering and more conventional responses to the CO<sub>2</sub>-climate problem is fuzzy. Geoengineering has become a label for technologically overreaching proposals that have been omitted from serious consideration in climate assessments for a long time (Keith, 2001). Now, as it becomes more and more clear how costly the reduction of greenhouse gas emission will be (in monetary and non-monetary terms) and, consequently, how slow the progress in this area will be, some scholars argue that geoengineering schemes might be the better alternative, being a cheap technological quick-fix. However, there are a variety of reasons why geoengineering might be a bad idea, being neither cheap nor offering a quick solution to the problem of climate change.

This working paper starts by presenting some of the tools commonly considered as geoengineering and their associated risks. In a second step some major arguments for and against geoengineering in general by scholars from the relevant fields of social and natural sciences will be summarized.

## 2. Geoengineering in general and associated risks

### Geoengineering can be distinguished between

- 1) Measures attempting to remove greenhouse gases that are already in the atmosphere (not to be confused with CCS) and thus removing an important cause for climate change.
- 2) Measures attempting to mitigate the changes caused by enhanced levels of greenhouse gases in the atmosphere (mostly attempts to influence the short-wave radiation balance of Earth).

There are considerably more risks and uncertainties associated with 2) compared to 1), which simply tries to remove a governing cause for global change.

### Pro geoengineering

- No change in lifestyle necessary: Technical 'quick fix could be attractive to the public, as to politicians, as an alternative to fundamental changes in their lifestyles (Virgoe, 2008).
- Case of catastrophic climate change:
  - o The option may be needed as a hedge against unexpectedly harsh changes in climate (Barrett, 2007; Virgoe, 2008; Weitzman, 2007).
  - o Cicerone (2006) argues that, "As environmental problems grow, one can expect demand for geoengineering solutions to increase."
  - o Catastrophic climate change would likely unfold over a number of centuries, but avoiding it will require a technological revolution, and geoengineering might help to "buy time" to develop and diffuse these new technologies (Wigley, 2006).
- Engineering nature is nothing new: Morton (2007) reports that a few voices argue that it is too late for this thinking — that we are already engineering nature by exerting a vast influence over the nitrogen cycle, the carbon cycle, the radiative balance of the atmosphere and everything else. In this sense we live in an engineered world, and the question is simply how to engineer it better. In the scientific community this argument has achieved little traction. The key point, articulated by climate scientist David Keith from the University of Calgary in Canada, is that "making a mess is not the same as engineering."

### Contra geoengineering

- Unintended Side-effects/high risks  
The Fourth Assessment Report of the IPCC comments, “Geo-engineering options . . . remain largely speculative and unproven, and with the risk of unknown side effects.” IPCC (2007)
- Unexpected consequences:
  - o Scientists cannot possibly account for all of the complex climate interactions or predict all of the impacts of geoengineering (Robock, 2008).
  - o There are still the unknowns, such as the long-term effects of short-term experiments—stratospheric aerosols have an atmospheric lifetime of a couple years (Robock, 2008).
- Considering the geoengineering option requires the need for a decision-making mechanism which can assess risks and benefits under scientific uncertainty (Virgoe, 2008).
- There’s no going back: We don’t know how quickly scientists and engineers could shut down a geoengineering system - or stem its effects - in the event of excessive climate cooling from large volcanic eruptions or other causes. Once we put aerosols into the atmosphere, we cannot remove them (Robock, 2008).
- Human error. Complex mechanical systems never work perfectly. Should we stake the future of Earth on a such a complicated arrangement, built by the lowest bidder? (Robock, 2008)
- Problems of scale: If an experiment to control the Earth’s climate is conducted we will not be able to convincingly demonstrate that it actually works unless we have collected validation data for at least several decades towards the background of natural climate variability (Bengtsson, 2006).
- Increasing risks: Without eventual curbs on greenhouse gas emissions, the scale and duration of a geoengineering intervention will have to continue to grow, at increasing expense and risk of side-effects (Virgoe, 2008).
- Long term commitment: Mankind subscribes to the necessity to perform activities (e.g. shoot sulfur in the stratosphere) for long periods of time (millennia). There are parallels to the nuclear waste sequestration problem, where recent events show that there are difficulties with these commitments already after decades.
- Pressure for mitigation: Repeated assertions that society will not invest in mitigation—and thus geoengineering will be needed - seem premature: The potential for climate policy to be implemented will probably intensify as severe climate impacts occur and people become more aware of the short delay times to be equally well off associated with conventional mitigation. (Schneider, 2008)
- Excuse for doing nothing: Some Critics worry that merely talking about geoengineering, will take pressure off politicians to make serious efforts to mitigate emissions—its mere existence as an imagined option may thus assure its use. Thus, geoengineering could be used as an excuse to maintain the status quo by those are not willing to bear the costs of GHG reduction (Schneider, 2008)
- Assessment of this option as a sort of emergency brake in case climate change would distract the scientific mainstream from searching for sustainable approaches to diminishing economic dependence on fossil fuels (Brovkin et al., 2009).
- Costs and Complexity: If society ever deploys geoengineering it is likely that many interventions are deployed in tandem—one to focus on the central disease and others to fix the ancillary harms, for example, albedo modification along with active efforts to offset ecological side effects, ocean acidification, and other harms that the simple primary geoengineering system cannot rectify (Victor, 2008).
  - o As the number of interventions rises so will the cost and complexity. More complex systems will be harder to assess because they will involve so many different interactions.

- To date, none of the technical or economic assessments of geoengineering have examined this kind of complex multi-faceted geoengineering - what Victor (2008) calls 'cocktail geoengineering'.
- Pressure to resort to geoengineering: Many studies seem to conclude that society should invest in enough knowledge about geoengineering to put the option 'on the shelf' in case it is needed if a climate emergency appears. The shelf analogy is misplaced for two reasons. (Victor, 2008)
  - Matter of incentives: The brightest young minds and the most entrepreneurial organizations rarely mobilize themselves to put complex technologies on the shelf, especially when rival activities exude greater rewards.
  - It is impossible to assess the options—and thus put them on the shelf—without actually testing them at scale. Readying the option for use in an emergency probably requires actually using it, at least for test deployments.
- Less sun for solar power: Scientists estimate that as little as a 1.8 percent reduction in incoming solar radiation would compensate for a doubling of atmospheric carbon dioxide. Even this small reduction would significantly affect the radiation available for solar power systems as the response of different solar power systems to total available sunlight is not linear (Robock, 2008); For the estimate for reducing incoming solar radiation, see Govindasamy et al. (2003). For the response of solar power systems, see MacCracken, (2006).
- Whitening of the sky (but nice sunsets): Atmospheric aerosols close to the size of the wavelength of light produce a white, cloudy appearance to the sky. They also contribute to colourful sunsets, similar to those that occur after volcanic eruptions. Both the disappearance of blue skies and the appearance of red sunsets could have strong psychological impacts on humanity (Robock 2008).
- Ocean acidification, which constitutes an important global change (not affected by the type 2 measures).

## 2.1. Reactions of the ecosystem/climate and environmental impacts

- Geoengineering only addresses climate change. It has few impacts on other environmental goals (Virgoe, 2008)
- Continued ocean acidification and consequences for the ocean biosphere: If humans adopted geoengineering as a solution to global warming, with no restriction on continued carbon emissions, the ocean would continue to become more acidic, because about half of all excess carbon dioxide in the atmosphere is removed by ocean uptake. Continued acidification threatens the entire oceanic biological chain, from coral reefs right up to humans (Royal Society, 2005).
  - Polar waters, particularly those surrounding Antarctica, are expected to become under-saturated with respect to aragonite, making it difficult for organisms, such as pteropods to make aragonite and causing aragonite already formed to dissolve.
  - Many coral reefs, which already are in decline, may be pushed into nonexistence due to further ocean acidification (Doney, 2006).
- Response of the climate system:
  - Were a geoengineering effort to be shut off, the climate would respond very rapidly (Wigley, 2006).

- We have only insufficient knowledge of the climate system and lack resources to model it accurately enough: Present climate models are highly parameterized and the processes regulating the interaction of clouds, aerosols and radiation through the depth of the atmosphere are highly tuned. Aerosols are not well mixed and interact with clouds in a complex way, where many questions are still open as we lack detailed empirical data. The role of clouds in regulating the climate under changed forcing conditions is not yet known with sufficient details. Recent model experiments indicate that the Earth's climate system is exposed to considerable internal variations, which essentially are of chaotic nature (Bengtsson, 2006).

## 2.2. Economics of geoengineering

### Pro geoengineering

- Costs: Advocates casually claim that it would not be too expensive to implement geoengineering solutions (Ricke et al., 2008)
  - Even a single country might be able to undertake geoengineering (Moreno and Smulders, 2007).
  - While the marginal cost of any abatement technology increases exponentially, geoengineering cost is independent of the amount of mitigation that has to be done. There are high up-front costs, but the marginal cost are essentially zero, which gives a decreasing average cost of abatement (Moreno and Smulders, 2007).
  - Calculation of costs: Analogues with natural events, such as volcanoes, make it possible to calculate the scale of effort that would be needed to offset crudely some of the effects of some climate warming. It is already possible to test some geoengineering methods at very low cost and without undue risk of irreversible effects on the planet (Victor, 2008).
  - Likely innovation will probably lower costs of deployment (Victor, 2008).
- Incentive Problems (Barrett, 2007): It may be impossible for countries to keep a commitment to abstain from experimenting with geoengineering.
  - Supplying the global public good of averting global climate change by means of reducing emissions is vulnerable to free riding: Too few countries are likely to participate in such an effort, those that do participate are likely to reduce their emissions by too little, and even their efforts may be overwhelmed by trade leakage.
  - Geoengineering constitutes a large project: By means of this technology, a single country, acting alone, can offset its own emissions—and those of every other country. By contrast, mitigating climate change by reducing emissions requires unprecedented international cooperation and very substantial costs.
  - Because of its low cost compared to emissions reduction, the incentives for it to be tried are very strong.
  - The incentives for countries to reduce emissions on a substantial scale are too weak, and the incentives for them to develop geoengineering are too strong, for commitment to be a realistic prospect. These two incentives combined are so powerful that many countries may be prepared to develop and deploy geoengineering unilaterally.

- Any country that had an incentive to join a coalition of countries in financing a geoengineering project initially would have at least as strong an incentive to continue with it later— unless in the meantime, previous efforts at reducing emissions succeeded in lowering atmospheric concentrations. The reason is that were a geoengineering effort to be shut off, the climate would respond very rapidly
- Carbon fuels as precondition for development: Some states might realize that carbon fuels are of particular importance to their development, wealth, or power – these could be developing nations or those with oil or coal resources (Davies, 2009; Victor, 2008).

### **Contra geoengineering**

- Costs and Cost assessment:
  - There have been no definitive cost studies, and estimates of large-scale government projects are almost always too low (Robock, 2008).
  - Victor (2008): It is especially difficult to assess the cost of geoengineering schemes because humans have never tried to deploy such systems on a planetary scale
  - Angel (2006) estimates that his scheme to launch reflective disks into orbit would cost “a few trillion dollars”, Nicholas Stern’s calculation of the cost of climate change as a percentage of global GDP (roughly \$9 trillion) is in the same ballpark; Angel’s estimate is also orders of magnitude greater than current global investment in renewable energy technology.
  - If society ever deploys geoengineering it is likely that many interventions are deployed in tandem—one to focus on the central disease and others to fix the ancillary harms (‘cocktail geoengineering’). As the number of interventions rises so will the cost and complexity. More complex systems will be harder to assess because they will involve so many different interactions (Victor, 2008).
- Incentive problems:
  - “Moral hazard” problem: Critics of geoengineering proposals have observed that the mere possibility of a technical “quick fix” to global warming risks reducing the incentive to take painful measures to reduce emissions of greenhouse gases (Bengtsson, 2006).
  - Promise to use geoengineering only temporarily lacks credibility: The argument that geoengineering might play in “buying time” for a policy needed to stabilize concentrations doesn’t work as in this case there is a commitment problem: If geoengineering should prove benign, the incentive to reduce atmospheric concentrations would be muted (Barrett, 2007).
- Risk assessment: When trying to assess the consequences of possible failures of geoengineering, the difficulties in even assigning probability measures to such failures amplify the reasons for a risk-adverse agent to avoid such risks (Weitzman, 2007).

## **2.3. Aspects of Law, Governance and Politics**

### **Pro geoengineering (research)**

- Failure to acknowledge the possibility of geoengineering will mean that countries will be unrestrained should the day come when they would want to experiment with this technology (Barrett, 2007).

- Political Economy Perspective: With today's technologies, achieving a deep cut in emissions will require costly investment for uncertain benefits that accrue mainly in the distant future - attributes that tend not to be rewarding for politicians (Victor, 2008).
- Overcoming problems of cooperation:
  - o The politics of mitigating emissions are additionally difficult because deep cuts in emissions are possible only with the cooperation of many nations with diverging preferences (Victor, 2008).
  - o Geoengineering, by contrast, offers prompt benefits with seemingly small costs—attributes that greatly simplify the problem of collective action (Schelling, 1996).
  - o A geoengineering intervention may only require action by one party or implementing agency; a single implementing agency might also be preferable to a plurality of actors, which would present a coordination problem. In the case of the more technically difficult proposals, the capacity to conduct the intervention is anyway likely to be confined to a very limited number of actors (Virgoe, 2008).
  - o Unlike collective efforts to control emissions, which are plagued by the constant threat of defection, the incentives to sustain cooperation are much stronger once geoengineering has begun, because failure to keep a geoengineering mask in place will lead to rapid climate change. (Victor, 2008)
  - o Once geoengineering has begun, even those who are hostile to the idea will reluctantly find they must support continued action (Victor 2008).
- Overseeing research: An active geoengineering research programme that is highly transparent and engages a wide range of countries would socialize a community of responsible geoengineers (Victor, 2008).

### **Contra geoengineering**

- Geoengineering as a concept is not ruled out by existing legal instruments (for an overview see Virgoe, 2008, Davies, 2009 or Bodansky, 1996)
- Conflicts with current treaties: The terms of ENMOD explicitly prohibit “military or any other hostile use of environmental modification techniques having widespread, long-lasting or severe effects as the means of destruction, damage, or injury to any other State Party.” Any geoengineering scheme that adversely affects regional climate, for example, producing warming or drought, would therefore violate ENMOD (Robock, 2008).
- Undermining emissions mitigation: If humans perceive an easy technological fix to global warming that allows for “business as usual,” a change of consumption patterns and energy infrastructure will be even more difficult. This is the oldest and most persistent argument against geoengineering (Cicerone, 2006).
- Military use of the technology: The United States has a long history of trying to modify weather for military purposes. Eighty-five countries, including the United States, have signed the U.N. Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques (ENMOD), but could techniques developed to control global climate forever be limited to peaceful uses? (Robock 2008)
- Commercial control of technology: Who would end up controlling geoengineering systems? Governments? Private companies holding patents on proprietary technology? And whose benefit would they have at heart? These systems might value shareholder profits over the public good. (Robock, 2008)
- Huge regulatory task:

- The regulatory task in geoengineering requires the setting of norms that restrain all potential geoengineers as well as principles to govern the trade-offs that geoengineers will face as they decide which cocktails of geoengineering systems to deploy. (Victor, 2008)
- Control of the thermostat: How would the world agree on the optimal climate? What if Russia wants it a couple of degrees warmer, and India a couple of degrees cooler? Should global climate be reset to preindustrial temperature or kept constant at today's reading? If we proceed with geoengineering, will we provoke future climate wars? (Robock, 2008)
- Barrett (2007) sees as major regulatory questions: Who is to decide whether geoengineering should be deployed? What about countries that have different attitudes towards risk, or that object to the idea of deliberately altering the climate whatever the benefits may be? Should a country be allowed to do so unilaterally? Could it be prevented from doing so?
- Distribution of costs and benefits: Changes or improvements on a global scale may not have uniform effects and certain areas or communities may suffer far more than other groups, or suffer where others are benefitting (Davies, 2009).
  - The distribution of side-effects - between countries, and between groups - could raise questions of compensation, as well as political and legal issues of liability, which will need to be addressed by a governance regime (Virgoe, 2008).
  - Reversing established gains: Almost any change disadvantages some, and combating climate change may result in gains being taken away from areas for whom a degree or two of temperature rise, or changes in weather patterns, were beneficial (Davies, 2009).
  - Side-effects of local climate management: Such local management will become ever more attractive, quite independently of what occurs on a global scale, but it is unlikely that effects can be entirely sealed within a jurisdiction. Yet measuring and establishing causation and liability are likely to be difficult. There is a need for agreement on the kind of measures that are tolerable (Davies, 2009).
- Need for durable governance regime:
  - Most Geoengineering Techniques would require continuing input or require monitoring pointing to the need for a durable governance regime (Virgoe, 2008).
  - The potential for conflicts poses serious social and political obstacles (Schneider, 2008).
  - MacCracken (2006) argues that "it seems rather unlikely that a global coalition of nations could be kept together to sustain such a diversion of resources" over such a long time-frame.

## 2.4. Moral and ethical consequences

### Pro geoengineering

- Barrett (2007): The world's poorest countries are especially vulnerable to climate change, and yet they are likely to be the least able to develop and deploy a geoengineering effort. Should the more capable states be required to do so for them?

### Contra geoengineering

- Questions of moral authority: Ongoing global warming is the result of inadvertent climate modification. Now that humans are aware of their effect on climate, do they have a moral right to continue emitting greenhouse gases? Similarly, since scientists know that stratospheric aerosol

injection, for example, might impact the ecosphere, do humans have a right to plow ahead regardless? There's no global agency to require an environmental impact statement for geoengineering. So, how should humans judge how much climate control they may try? (Robock, 2008)

- There are issues of procedural justice involved—who decides and who controls (see Aspects of law, governance and politics). But such concerns don't get much traction when everyone benefits. (Bunzl, 2008)
- Unequal distribution of costs and benefits: Changes or improvements on a global scale may not have uniform effects and certain areas or communities may suffer far more than other groups, or suffer where others are benefitting (Davies, 2009).
- Intergenerational Equity
  - o Substituting aerosol geoengineering for greenhouse gas emission abatement might fail an ethical test regarding intergenerational justice. Substituting aerosol geoengineering for greenhouse gas emissions abatements constitutes a conscious risk transfer to future generations. (Goes et al., 2009)
  - o As failure of geoengineering might result in abrupt climate change coming generations would have to live with the danger of this "Sword of Damocles" scenario, the abruptness of which has no precedent in the geologic history of climate (Brovkin et al., 2009).

### 3. Specific geoengineering tools and associated risks

#### 3.1. Schemes involving blocking or reflecting incoming solar radiation

Warming due to anthropogenic greenhouse gases can be countered by deploying systems in the stratosphere or in space that scatter sunlight away from the planet. The idea behind this is to reduce the solar radiation that reaches the surface of the earth by an amount that balances the reduction in outgoing longwave radiation due to increase in atmospheric CO<sub>2</sub>.

Stratospheric scatters are much cheaper but entail risks to stratospheric chemistry whereas space-based systems offer an expensive but 'clean' alteration of the solar 'constant'.

##### 3.1.1. Geoengineering tool: Injecting sulphate aerosols into the stratosphere as a means to block sunlight and cool earth

Crutzen (2006), for instance, points out that sulphate aerosols can act to cool the climate immediately; reducing emissions, in contrast, takes decades or generations. Crutzen argues that in the case of abrupt or catastrophic climate change, aerosols could provide a prompt cooling response in a way that emissions control simply could not.

Some scholars consider the 1991 eruption of Mount Pinatubo on the Philippine island of Luzon as a natural analogue to the geoengineered injection of sulphate aerosols and thus as a case for using this geoengineering-tool: The eruption of Mount Pinatubo injected 20 megatons of sulfur dioxide gas into the stratosphere, produced a sulfate aerosol cloud that is said to have caused global cooling for a couple of years without adverse effects.

### Pro sulphate aerosol injections

Volcanic eruptions as an analogue for sulphate aerosol injections?

- Researchers at the National Centre for Atmospheric Research showed in 2007 that the Pinatubo eruption caused large hydrological responses, including reduced precipitation, soil moisture, and river flow in many regions (Trenberth and Dai, 2007).
- Scientists have also seen volcanic eruptions in the tropics produce changes in atmospheric circulation, causing winter warming over continents in the Northern Hemisphere, as well as eruptions at high latitudes weaken the Asian and African monsoons, causing reduced precipitation (Robock, 2000; Oman et al., 2005, 2006).

### Contra

- Reduced precipitation: At the fall 2007 American Geophysical Union meeting, researchers presented preliminary findings from several different climate models that simulated geoengineering schemes and found that they reduced precipitation over wide regions, condemning hundreds of millions of people to drought (Robock, 2008).
  - o A study on geoengineering using a fully coupled atmosphere and model found that both tropical and arctic SO<sub>2</sub> injection would disrupt the Asian and African summer monsoons, reducing precipitation essential for the food supply for billions of people (Robock et al., 2008)
- Ozone depletion: Aerosol particles in the stratosphere serve as surfaces for chemical reactions that destroy ozone in the same way that water and nitric acid aerosols in polar stratospheric clouds produce the seasonal Antarctic ozone hole. For the next four decades or so, when the concentration of anthropogenic ozone-depleting substances will still be large enough in the stratosphere to produce this effect, additional aerosols from geoengineering would destroy even more ozone and increase damaging ultraviolet flux to Earth's surface (Solomon, 1999; Govindasamy and Caldeira, 2000).
- Effects on plants: Sunlight scatters as it passes through stratospheric aerosols, reducing direct solar radiation and increasing diffuse radiation, with important biological consequences.
  - o Some studies, including one that measured this effect in trees following the Mount Pinatubo eruption, suggest that diffuse radiation allows plant canopies to photosynthesize more efficiently, thus increasing their capacity as a carbon sink (Gu et al., 2002; Gu et al., 2003).
  - o At the same time, inserting aerosols or reflective disks into the atmosphere would reduce the total sunlight to reach Earth's surface. Scientists need to assess the impacts on crops and natural vegetation of reductions in total, diffuse, and direct solar radiation (Robock, 2008).
- Effects of cirrus clouds: As aerosol particles injected into the stratosphere fall to Earth, they may seed cirrus cloud formations in the troposphere. Cirrus clouds affect Earth's radiative balance of incoming and outgoing heat, although the amplitude and even direction of the effects are not well understood (Mohnen, 1990; Sassen et al., 1993).
- Environmental impacts of implementation: Any system that could inject aerosols into the stratosphere, i.e., commercial jetliners with sulfur mixed into their fuel, 16-inch naval rifles firing 1-ton shells of dust vertically into the air, or hoses suspended from stratospheric balloons, would cause enormous environmental damage (Robock, 2008).
- Regional temperature anomalies: Even if we somehow could manage to engineer our stratospheric aerosol injections to exactly balance on a hemispheric (or global) basis the amount of hemispherically (or globally) averaged heat trapped by human-contributed greenhouse gases such as CO<sub>2</sub> and methane, we would still be left with some regions heated to excess and others to

deficit. This would inevitably give rise to regional temperature anomalies and induce other regional climatic anomalies that could very well lead to greater than zero net global climate change even if the hemispheric average of radiative forcing for all human activities were somehow reduced to zero (Schneider, 2008).

- Long-term commitment: Because of the millennial persistence of the fossil fuel CO<sub>2</sub> in the atmosphere, high levels of stratospheric aerosol loading would have to continue for thousands of years until CO<sub>2</sub> was removed from the atmosphere (Brovkin et al., 2009; Bengtsson, 2006).
- Rapid warming if deployment stops: A technological, societal, or political crisis could halt a project of stratospheric aerosol injection in mid- deployment. Such an abrupt shift would result in rapid climate warming, which would produce much more stress on society and ecosystems than gradual global warming.
  - o Warming rates up to 20 times greater than present-day rates; Carbon sinks would weaken, potentially leading to unprecedented global temperature increases of 2-4°C per decade (more than ten times the current rate of temperature change) (Matthews and Caldeira, 2007).
  - o Using a coupled climate-carbon cycle model of intermediate complexity Brovkin et al. (2009) find that a termination of stratospheric aerosol loading results in abrupt global warming of up to 5°C within several decades.
- Possible failure of an economic cost-benefit test: A failure to sustain the aerosol forcing would lead to dramatic and abrupt climatic changes. The monetary damages due to this failure can dominate the cost-benefit analysis because the monetary damages of climate change are expected to increase with the rate of change (Goes et al., 2009).

### 3.1.2. Geoengineering tool: space-based sun shields

Instead of sulphur and dust, it has been also proposed to launch reflecting, small balloons or mirrors, or to add highly reflective nanoparticles of materials other than sulphur. These reflectors would be placed at a high enough altitude so that they do not interfere with air traffic. They would also avoid the risk for disrupting chemical processes in the stratosphere. However, the cost estimate is about 20 times as much as the distribution of dust in the stratosphere (NAS, 1992).

#### Contra space-based sunshields

- Costs: Most of the proposed space technologies have estimated costs that are much higher than those of stratospheric or tropospheric programmes.
  - o The cost estimate is about 20 times as much as the distribution of dust in the stratosphere, making these schemes economically unviable (NAS, 1992).
- Feasibility:
  - o University of Arizona astronomer Roger P. Angel has proposed putting a fleet of 2-foot-wide reflective disks in a stable orbit between Earth and the sun that would bend sunlight away from Earth. But to get the needed trillions of disks into space, engineers would need 20 electromagnetic launchers to fire missiles with stacks of 800,000 disks every five minutes for twenty years (Angel, 2006).
  - o The large number of reflectors and the trash problem posed by their fall make the system unattractive (Bala, 2009).
  - o Who would want to live nearby this site?
  - o Cost issues

- Lack of knowledge: Lack of knowledge about atmospheric effects of the resulting sound and gravity waves
  - o Scheme would itself inevitably lead to climate change, due to the different temporal and spatial forcing of increased CO<sub>2</sub> compared to reduced solar radiation (Lunt et al., 2008).
  - o A study on geoengineering using a fully coupled atmosphere model found significant cooling of the tropics, warming of high latitudes and related sea-ice reduction, a reduction in intensity of the hydrological cycle, reduced ENSO variability, and an increase in Atlantic overturning when the climate was geoengineered via sunshade scheme (Lunt et al., 2008).

### **3.1.3. Geoengineering tool: Add more clouds in the lower part of the atmosphere (the troposphere)**

The albedo can also be increased by increasing the quantity and reflectivity of lower cloud layers (Latham, 2002; Latham et al., 2008).

Most proposals suggest that this be done by increasing the abundance and reflectivity of the low-altitude stratocumulus clouds that naturally cover about 30% of the Earth's surface.

For instance it is suggested to spray seawater hundreds of meters into the air to seed the formation of stratocumulus clouds over the subtropical ocean (John Latham of the Nation Center for Atmospheric Research proposed that salt from seawater could be effectively used as CCN, a material that has the advantage of not (currently) being considered a pollutant).

Approximately 4% increase in cloud cover would be sufficient to offset CO<sub>2</sub> doubling. About 30% increase in CCN over the oceans would be necessary to increase the fraction of cloudiness or albedo of marine stratocumulus by 4%. This can be achieved by seeding the marine, low clouds with H<sub>2</sub>SO<sub>4</sub> CCN, from a fleet of ships or by building power plants out in the ocean.

#### **Contra an increasing cloud cover**

- Acid rain: A 1992 NAS report (NAS Panel on Policy Implications of Greenhouse Warming) considered a theoretical system that would use sulfuric acid as cloud condensation nuclei (CCN). Such an approach would have massive environmental impacts in the form of acid rain.
- Global changes in the distributions and magnitudes of ocean currents, temperature, rainfall and wind would result: Even if it were possible to seed clouds relatively evenly over the Earth's oceans, effects on the distributions and magnitudes of ocean currents could not be eliminated. Also, the technique would still alter the land–ocean temperature contrast, since the radiative forcing produced would be only over the oceans. In addition, if we would be attempting to neutralize the warming effect of vertically distributed greenhouse gases with a surface-based cooling effect, this could have consequences such as changes in static stability, which would need careful evaluation (Latham, 2008).

### 3.2. Geoengineering schemes aiming to remove carbon dioxide from the atmosphere, through natural or mechanical means.

Schemes typically remove atmospheric CO<sub>2</sub> and sequester it into terrestrial vegetation, ocean, or into deep geologic formations.

#### 3.2.1. Geoengineering tool: Ocean fertilization

Fertilizing the 'biological pump' may enhance the flux of carbon into the oceans that maintains the disequilibrium in CO<sub>2</sub> concentration between the atmosphere and the deep ocean.

While the use of nitrogen and phosphorus has been proposed, iron fertilization is the salient possibility because the ratio of iron addition to carbon fixation is very large (the Fe:C ratio is ~1:104 whereas for N:C it is ~1:6) (Keith, 2001). Thus, most approaches focus on dumping iron dust into the open ocean (OIF: Ocean Iron Fertilization) to trigger algal blooms.

Lovelock and Rapley (2007) propose another method: They suggest to use free-floating or tethered vertical pipes to increase the mixing of nutrient-rich waters below the thermocline with the relatively barren waters at the ocean surface. Water pumped up pipes — say, 100 to 200 metres long, 10 metres in diameter and with a one-way flap valve at the lower end for pumping by wave movement — would fertilize algae in the surface waters and encourage them to bloom. This would pump down carbon dioxide and produce dimethyl sulphide, the precursor of nuclei that form sunlight-reflecting clouds.

If it could be made to work, one advantage of the ocean fertilization approach is that it removes CO<sub>2</sub> from the atmosphere and thus more directly compensates for the buildup of anthropogenic CO<sub>2</sub>, imposing fewer environmental externalities than strategies that rely on the more imperfect method of increasing planetary albedo.

#### Contra ocean fertilisation

- Upwelling of carbon: Jorge Sarmiento, Director of Atmospheric and Oceanic Sciences Program at Princeton, argues that any such modification is likely to lead to upwelling of carbon from the deep ocean in other locations, and that it would likely be impossible to directly determine whether the strategy was causing more or less CO<sub>2</sub> to be sequestered in the ocean (Ricke et al. 2008).
- Unintended biogeochemical and ecological impacts:
  - o We do not understand the intended and unintended biogeochemical and ecological impacts. Environmental perturbations from OIF are nonlocal and are spread over a large area by ocean circulation, which makes long-term verification and assessment very difficult (Buesseler et al., 2008).
  - o Generation of other climate-relevant gases (greenhouse/cloud forming): Fluxes are potentially large particularly if the anticipated decrease in oxygen concentration is sufficient to generate larger quantities of methane and nitrous oxide. The interactions are complex and not well constrained with potentially a number of both positive and negative feedbacks (Lampitt et al. 2008).
  - o Eutrophication (a detrimental response of an ecosystem to excess macronutrients) and anoxia: The degree to which eutrophication might occur in artificially fertilized areas of the open ocean is debatable on account of differences in circulation patterns, nutrient supply mechanisms and biological communities compared with coastal seas (Lampitt et al. 2008).

- Modification of ocean pH: The effects of fertilization are likely to be to reduce the current trend of decreasing pH in the euphotic zone although in deeper water the increased POC supply would tend to lower pH although to only a small degree. Changes might impact on biological functions, including calcification, reproduction and physiology (Lampitt et al. 2008).
  - Modification of global macronutrient balance: Any attempt to fertilize the ocean with nutrients to stimulate production and hence carbon sequestration will inevitably result in a redistribution of nutrients on a global scale. Some areas may subsequently experience a decrease in nutrient supply leading to a reduction of biological productivity and possibly a reduction in economic activities such as fisheries (Lampitt et al. 2008).
  - Change to pelagic ecosystem structure: A probable consequence is a change to the structure and function of the biological communities especially in the euphotic zone. These changes may affect fisheries directly or indirectly or they may alter the details of the export process such as by modifying the characteristics of the settling particles produced by the euphotic zone communities (Lampitt et al. 2008).
  - Literature on the physiology of deep-living animals indicates that the marine ecosystem is highly susceptible to oceanic CO<sub>2</sub> and pH excursions likely to accompany direct injection of CO<sub>2</sub> into the deep-sea. (Seibel et al., 2001).
- Potential of iron fertilization:
- The cooperative project Lohafex of the AWI has dampened hopes on the potential of the Southern Ocean to sequester significant amounts of carbon dioxide (CO<sub>2</sub>) (AWI, 2009)
    - Iron addition stimulated growth of the planktonic algae (phytoplankton), which doubled their biomass by taking up CO<sub>2</sub> from the water. However, the increasing grazing pressure of small crustacean zooplankton (copepods) prevented further growth of the phytoplankton bloom. As a result, only a modest amount of carbon sank out of the surface layer by the end of the experiment.
    - The transfer of CO<sub>2</sub> from the atmosphere to the ocean to compensate the deficit caused by the LOHAFEX bloom was minor compared to earlier ocean iron fertilization experiments.
    - The larger blooms stimulated by earlier experiments were due to a group of algae known as diatoms. These unicellular algae are protected against grazers by shells made of glass (silica) and are known to sink to great depths after blooming. Diatoms could not grow in the Lohafex experiment because previous, natural blooms had already extracted all the silicic acid.
    - Since the silicic acid content in the northern half of the Southern Ocean is low, iron fertilization in this vast region will not result in removal of significant amounts of CO<sub>2</sub> from the atmosphere.
  - Modeling studies have addressed sequestration more directly and have suggested that OIF in areas of persistent high nutrients would be unlikely to sequester more than several hundred million tons of carbon per year. Thus, OIF could make only a partial contribution to mitigation of global CO<sub>2</sub> increases (Buesseler et al., 2008).
  - Regional variations: “Ecosystem response and carbon export seem to vary very substantially from region to region (Schiermeier, 2009; Pollard et al. 2009).
    - During the CROZEX experiment in 2004 and 2005, scientists observed the impact of natural iron fertilization on algal growth and carbon export near the Crozet Islands.

- The team found that, relative to one unit of added iron, the amount of carbon sequestered to 200 metres' depth, where it will stay for a couple of decades, was almost 80 times smaller than the amount that scientists had determined during a similar study in the nearby Kerguelen region and also smaller than lab experiments had suggested

### 3.2.2. Geoengineering tool: Enhancing terrestrial sinks

The large natural carbon fluxes between atmosphere and terrestrial biosphere provide a powerful lever for manipulating atmospheric CO<sub>2</sub> (Rosenberg et al., 1998).

A great diversity of methods have been proposed to exploit this leverage including

- reforestation and sequestration in agricultural soils via 'zero-till' methods
- genetic modification of crops to increase biotic carbon uptake
- carbon capture and storage techniques such as those proposed to outfit coal plants;

Enhancement of terrestrial sinks has been seen as green and low-tech in sharp contrast with geoengineering. Yet, if implemented at the scale required to capture a significant fraction of emissions, terrestrial sequestration would resemble planetary-scale environmental engineering and may well entail high-tech methods such as genetic modification of crops (Keith, 2001). The divergent treatment of terrestrial and oceanic sinks illustrates the inconsistencies that pervade discussion of planetary engineering (Keith, 2001).

#### Problems associated with the enhancement of terrestrial sinks

- Effects of latitude: A modelling study has shown that only tropical afforestation has the potential to mitigate climate warming, when both the climate and carbon cycle effects of forests are into account. New forests in the tropics, in addition to causing cooling through sequestering CO<sub>2</sub>, lead to increased evapotranspiration and cloudiness, which reduces the surface solar radiation and causes cooling. Afforestation projects in the mid-latitudes offer marginal benefits and high latitude boreal forests will actually accelerate global warming, because such projects in the seasonally snow-covered mid and high-latitude regions would decrease the surface albedo and enhance surface absorption of solar radiation. In these regions, the warming caused by this albedo effect is greater than the cooling that would result from the sequestration of CO<sub>2</sub> in the new forests (Bala et al., 2007).

#### Ambiguous Case: CCS

We may use fossil energy without emissions of CO<sub>2</sub> by first capturing the carbon content of fossil fuels while generating carbon-free energy products such as electricity and hydrogen and then sequestering the resulting CO<sub>2</sub> in geological formations or in the ocean.

It is unclear whether carbon capture and sequestration is rightly classified as geoengineering. It is certainly an end-of-pipe technical fix, but one Keith (2001) argues that injection into geological reservoirs resembles conventional pollution-mitigation technologies more closely than it resembles geoengineering, because it limits emission of CO<sub>2</sub> to the biosphere rather than compensating for emissions after they occur.

Unintended consequences of CCS: The complex interactions between pressurized fluids and porous rock and their evolution on time scales are not well understood but are a prerequisite for safe CO<sub>2</sub> sequestration: As rock formations were not designed by nature as storage vaults more research to

understand, predict and monitor the performance of rock formations used as storage sites is needed. CO<sub>2</sub> can dissolve in and change the acidity and density of ambient fluids and the increased pressure from the injection can induce a flow in a wide region around the injection side (De Paolo and Orr, 2008).

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