

REVIEW

Geoengineering: could we or should we make it work?

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Schemes to modify large-scale environment systems or control climate have been proposed for over 50 years to (i) increase temperatures in high latitudes, (ii) increase precipitation, (iii) decrease sea ice, (iv) create irrigation opportunities, or (v) offset potential global warming by injecting iron in the oceans or sea-salt aerosol in the marine boundary layer or spreading dust in the stratosphere to reflect away an amount of solar energy equivalent to the amount of heat trapped by increased greenhouse gases from human activities. These and other proposed geoengineering schemes are briefly reviewed. Recent schemes to intentionally modify climate have been proposed as either cheaper methods to counteract inadvertent climatic modifications than conventional mitigation techniques such as carbon taxes or pollutant emissions regulations or as a counter to rising emissions as governments delay policy action. Whereas proponents argue cost-effectiveness or the need to be prepared if mitigation and adaptation policies are not strong enough or enacted quickly enough to avoid the worst widespread impacts, critics point to the uncertainty that (i) any geoengineering scheme would work as planned or (ii) that the many centuries of international political stability and cooperation needed for the continuous maintenance of such schemes to offset century-long inadvertent effects is socially feasible. Moreover, the potential exists for transboundary conflicts should negative climatic events occur during geoengineering activities.

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1. Historical perspective (modified after Schneider 1996)

In Homer's 'Odyssey', Ulysses is the frequent beneficiary (or victim) of deliberate weather modification schemes perpetuated by various gods and goddesses. In Shakespeare's 'The Tempest', a mortal (albeit a human with extraordinary magical powers) conjures up a tempest in order to strand on his mystical island a passing ship's crew with his enemies aboard. In literature and myth, only gods and magicians had access to controls over the elements. But in the twentieth century, serious proposals for the deliberate modification of weather and/or climate have come from engineers, futurists or those concerned with

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counteracting inadvertent climate modification from human activities. Some argue that it would be better or cheaper to counteract inadvertent human impacts on the climate with deliberate schemes rather than to tax polluting activities or to switch to alternative means of economic sustenance. So, while control of the elements has been in the human imagination and literature for millennia, it is only in the waning of the last millennium that humans have proposed serious techniques that might just do the job—or at least could modify the climate, even if all the basic ramifications are not now known, or even knowable.

In *ca* 1960¹, for example, authors N. Rusin and L. Flit from the former Soviet Union published a long essay entitled *Man versus climate*. In this essay the authors, displaying a traditional Russian geographical perspective, claim that ‘... the Arctic ice is a great disadvantage, as are the permanently frozen soil (permafrost), dust storms, dry winds, water shortages in the deserts, etc’. And, they go on, ‘... if we want to improve our planet and make it more suitable for life, we must alter its climate’. But this must not be for hostile purposes, they caution, as ‘almost all the huge programmes for changing nature, e.g. the reversal of the flow of northern rivers and the irrigation of Central Asian deserts, envisage improvements in the climate’ (Rusin & Flit 1960, p. 17). They recount earlier proposals for dazzling projects such as injecting tiny white particles suspended in space in the path of the solar radiation, to light up the night sky. M. Gorodsky and later V. Cherenkov put forward ‘... proposals to surround the Earth with a ring of such particles, similar to the ring around Saturn’ (in Rusin and Flit). The plan was to create a 12 per cent increase in solar radiation, such that high latitudes would ‘... become considerably warmer and the seasons would scarcely differ from one another’. And so it goes in this essay, detailing plans to divert rivers from the Arctic to the Russian wheat fields, or from the Mediterranean to irrigate areas in Asian USSR. One ambitious project is to create a ‘Siberian Sea’ with water taken from the Caspian Sea and Aral Sea areas. Of course, flowery rhetoric with images of blooming now-arid zones stands in stark contrast to the ecological disaster that surrounds the Aral Sea today; environmental degradation is associated with much less ambitious engineering projects (Glazovsky 1990). But the upbeat little pamphlet, written at the height of human technological hubris in the mid-twentieth century, certainly is filled with, if nothing else, entertaining geoengineering schemes.

Other sets of such schemes have also been part of geoengineering folklore and include damming the Straits of Gibraltar, the Gulf Stream, the Bering Straits, the Nile or creating a Mediterranean drain back into Central Africa where a ‘second Nile’ would refill Lake Chad, turning it into the ‘Chad Sea’ after the Straits of Gibraltar were dammed. However, the authors of such schemes do not emphasize the fact that the current Mediterranean produces a significant fraction of the salty water that sinks and becomes intermediate depth water in the North Atlantic, only to rise again in the high North Atlantic, in the Iceland–Norwegian Sea areas, making that part of the world’s oceans sufficiently salty that surface water sinks to the bottom at several degrees Celsius above freezing. In that process of sinking, approximately half the bottom waters of the world’s oceans are formed. The Gulf Stream’s surface water that flows into the higher latitudes of the northeastern North Atlantic and into Scandinavia allows northwestern

¹ The precise date of the Rusin & Flit paper is unknown.

Europe to enjoy a more moderate climate relative to that of, say, Hudson Bay. The latter, at the same latitude, does not have the benefit of the salty waters and the Gulf Stream's penetration high into the North Atlantic, which inhibits sea ice formation and contributes to a milder climate.

Other examples of attempts to modify the atmosphere, but for a different purpose, followed from the first use of the word 'geoengineering' of which I am aware. This term was informally coined in the early 1970s by Cesare Marchetti (and formally published by the invitation of the editor of *Climatic Change* in its inaugural issue as [Marchetti 1977](#)). Marchetti outlined his thesis:

The problem of CO₂ control in the atmosphere is tackled by proposing a kind of 'fuel cycle' for fossil fuels where CO₂ is partially or totally collected at certain transformation points and properly disposed of. CO₂ is disposed of by injection into suitable sinking thermohaline currents that carry and spread it into the deep ocean that has a very large equilibrium capacity. The Mediterranean undercurrent entering the Atlantic at Gibraltar has been identified as one such current; it would have sufficient capacity to deal with all CO₂ produced in Europe even in the year 2100.

([Marchetti 1977](#))

About the same time Russian climatologist Mikhail Budyko expanded on this theme of geoengineering, also for the purpose of counteracting inadvertent climate modification:

If we agree that it is theoretically possible to produce a noticeable change in the global climate by using a comparatively simple and economical method, it becomes incumbent on us to develop a plan for climate modification that will maintain existing climatic conditions, in spite of the tendency toward a temperature increase due to man's economic activity.

The possibility of using such a method for preventing natural climatic fluctuations leading to a decrease in the rate of the hydrological cycle in regions characterized by insufficient moisture is also of some interest.

([Budyko 1977](#), p. 244)

Fortunately, Budyko does go on to apply the appropriate caveat: 'The perfection of theories of climate is of great importance for solving these problems, since current simplified theories are inadequate to determine all the possible changes in weather conditions in different regions of the globe that may result from modifications of the aerosol layer of the stratosphere.' What Budyko proposed is a stratospheric particle layer to reflect away enough sunlight to counteract heat trapping from anthropogenic greenhouse warming. Obviously, he believed that deliberate climate modification would be premature before the consequences could be confidently precalculated.

Anticipating the increasing calls for deliberate climate modification as a geoengineering countermeasure for the advent or prospect of inadvertent climate modification, William Kellogg and I raised a number of aspects of this issue that had only been hinted at by previous authors. After summarizing a whole host of such schemes, we concluded:

One could go on with such suggestions, some to cool and some to warm vast regions of the earth, some to change the patterns of rainfall, some to protect from damaging storms, and so forth. They could be used to improve the current climate (for some) or to offset a predicted deterioration of climate (for some), whether the deterioration was natural or man-induced ...

We believe that it would be dangerous to pursue any large-scale operational climate control schemes until we can predict their long-term effects on the weather patterns and the climate with some acceptable assurance. We cannot do so now, and it will be some time—if ever—before we can. To tamper with a system that determines the livelihood and life-styles of people the world over would be the height of irresponsibility if we could not adequately foresee the outcome. However, we recognize that this may not be the opinion of some, especially those who live in the affected regions where a prediction of climatic change could be a forecast of local disaster if the predicted change were not offset.

(Kellogg & Schneider 1974)

We went on to argue that some people could even consider use of climate modification as an overt or clandestine weapon against economic or political rivals, and that that prospect might require the need for an international treaty. We noted that the potential for disputes would be very high since any natural weather disaster occurring during the time that some group was conducting deliberate climate modification experiments could lead those affected by that disaster to make accusations that the climate modifiers were responsible for that event. Courts could be clogged with expert witnesses testifying on the one hand how the deliberate intervention could not possibly have caused some unusual hurricane or '300-year flood', followed by other witnesses (perhaps the same ones collecting double fees?) turning around and testifying for the other side that current knowledge is insufficient to rule out the possibility that a geoengineering scheme in one part of the world might very well have affected some extreme event on the other side of the world. We concluded, only partially tongue in cheek, that,

We have raised many more questions than we are even remotely capable of answering, but we do wish to offer one 'modest' proposal for 'no-fault climate disaster insurance.' If a large segment of the world thinks the benefits of a proposed climate modification scheme outweigh the risks, they should be willing to compensate those (possibly even a few of themselves) who lose their favored climate (as defined by past statistics), without much debate as to whether the losers were negatively affected by the scheme or by the natural course of the climate. After all, experts could argue both sides of cause and effect questions and would probably leave reasonable doubts in the public's mind ...

(Kellogg & Schneider 1974)

A number of people picked up the geoengineering issue on and off in the 20 years since. For example, Schelling (1983) pointed out that world economic development was not going to pay much attention to global warming prospects given the realpolitik of population and economic growth advocates within the political establishments in nearly all countries. Schelling concluded that should global warming prove to be as significant as some climatologists or ecologists feared plausible, then perhaps we should consider geoengineering as a cost-effective and politically acceptable alternative to energy taxes or fuel switching (which could spell the politically unpalatable demise of the coal industry, for example).

2. Geoengineering as part of global change cost/benefit analysis?

However, 20 years ago, with the significant increase in publicity attached to the problem of global warming, and in the wake of the intense heat waves, drought, fires and large hurricanes in North America in 1988 and 1989, concerns reached

the halls of the US Congress and many parliaments around the world. Legislators began examining serious proposals for energy taxes, fuel switching, demand-side management, lifestyle changes and other policies that directly affect some economic interests (e.g. Lashof & Tirpak 1990; Gaskins & Weyant 1993; IPCC 1995a). Then, as foreshadowed some decades earlier calls for geoengineering inevitably resurfaced after a relatively quiescent two decades.

The most ambitious attempt to justify and classify a range of geoengineering options was associated with a US National Research Council panel on the policy implications of global warming (NAS 1992). In particular, Robert Frosch, a member of that panel, worked assiduously to try to gather information on many proposed schemes, and then did a careful job of engineering analysis. Not only did he write down a range of geoengineering schemes and try to calculate their potential effectiveness for climate control, but also he did order of magnitude calculations of the relative costs of changing the Earth's temperature by geoengineering versus conventional means such as energy taxes (estimating how many dollars per ton carbon dioxide reduction the climate control scheme might be equivalent to). As a member of that panel, I can report that the very idea of including a chapter on geoengineering led to serious internal and external debates. Many participants (including myself) were worried that even the very thought that we could offset some aspects of inadvertent climate modification by deliberate climate modification schemes could be used as an excuse to maintain the *status quo* by those who would be negatively affected by controls on the human appetite to continue polluting and using the atmosphere as an unpriced sewer. Those who worried about climatic impacts often favoured market incentives to reduce emissions or regulations for cleaner alternative technologies. However, Frosch effectively countered that argument. Supposing, it was said, a currently envisioned low probability but high consequence outcome really started to unfold in the decades ahead (e.g. 5°C warming in the next century—which had already been characterized as having potential catastrophic implications for ecosystems; see Peters & Lovejoy 1992; Root & Schneider 1993). Let us also assume, it was argued, that by the second decade of the next century the next generation of scientific assessments such as IPCC (1995b, 2007a) converged on confidently forecasting that the Earth had become committed to climate change (and its consequences—IPCC 2007b) serious enough either to require a dramatic retrenchment from our fossil fuel-based economy (which would be politically difficult to accept in a world increasingly dependent on carbon fuels, especially coal) or to endure potentially catastrophic climatic changes. Under such a scenario, we would simply have to practice geoengineering as the 'least evil', it was argued.

3. Geoengineering revisited in the twenty-first century

Recently, Crutzen (2006) reignited the geoengineering debate in a special topic issue of *Climatic Change*. His arguments were based on exasperation with the capacity of society to mitigate the 'right way', and thus to prevent 'dangerous anthropogenic interference with the climate system' (as it was put by the United Nations Framework Convention on Climate Change signed by over 190 countries). Thus, geoengineering may be the only remaining solution, Crutzen lamented. A lively debate followed in that special issue, mirrored in many media

accounts, since Crutzen, a Nobel Laureate in chemistry, generated a great deal of public interest for this debate considering his credentials as one of the pioneers in discovering ozone depletion and as an advocate for mitigation rules to protect the ozone layer.

The most recent incarnation of the geoengineering debate—and some other novel solutions—is this Theme Issue of *Phil. Trans. R. Soc. A*. I will briefly summarize the logic for geoengineering and alternative energy schemes outlined in various contributions in this issue and discuss some general aspects after that.

Anderson & Bows (2008) begin by emphasizing the difficult current situation with respect to mitigation action relative to mitigation need:

It is increasingly unlikely that an early and explicit global climate change agreement or collective ad hoc national mitigation policies will deliver the urgent and dramatic reversal in emission trends necessary for stabilization at 450 ppmv CO_{2e}. Similarly, the mainstream climate change agenda is far removed from the rates of mitigation necessary to stabilize at 550 ppmv CO_{2e}. Given the reluctance, at virtually all levels, to openly engage with the unprecedented scale of both current emissions and their associated growth rates, even an optimistic interpretation of the current framing of climate change implies that stabilization much below 650 ppmv CO_{2e} is improbable.

The analysis presented within this paper suggests that the rhetoric of 2°C is subverting a meaningful, open and empirically informed dialogue on climate change. While it may be argued that 2°C provides a reasonable guide to the appropriate scale of mitigation, it is a dangerously misleading basis for informing the adaptation agenda. In the absence of an almost immediate step change in mitigation (away from the current trend of 3% annual emission growth), adaptation would be much better guided by stabilization at 650 ppmv CO_{2e} (i.e. approx. 4°C).

(Anderson & Bows 2008)

To help accelerate the reduction of CO₂ emissions, given the reluctance for fuel switching, Breeze (2008) joins with those who have extended the Marchetti suggestion for deep oceanic sequestration of CO₂ to deep terrestrial sequestration underground:

To achieve a reduction in carbon emissions from coal-fired plants, however, it will be necessary to develop and introduce carbon capture and sequestration technologies. Given adequate investment, these technologies should be capable of commercial development by *ca* 2020 ... Two things are required. The first is investment, primarily from Western governments, to develop the technologies for carbon capture and storage to a state where they can be deployed economically on a wide scale. The second is the introduction of global carbon emission limits, with cost penalties for emitting carbon that are sufficiently stringent to persuade generators across the globe to build plants based on these technologies.

(Breeze 2008)

But, carbon capture and sequestration for coal-fuelled power plants would not do much for transportation systems dependent on liquid fuels. To address this knotty problem, Zeman & Keith (2008) call for a switch of conventional fuels to ‘carbon neutral hydrocarbons’ (CNHCs), as the ‘viable alternative to hydrogen or conventional biofuels and warrant a comparable level of research effort and support’. They call for both direct and indirect methods of producing such CNHCs, using biomass and air capture with chemical plants at massive scales. After an extensive set of preliminary engineering–economic analyses of possibilities, they conclude somewhat optimistically that:

... CNHCs may be a cost-effective way to introduce hydrogen into the transportation infrastructure in a gradual manner. The continued use of liquid hydrocarbon fuels will minimize the disruptions and delays caused by requiring a different transportation infrastructure. It is far from evident, however, that any of these solutions, including electric vehicles, will be the method of choice. The lack of a clear technological 'winner' warrants equal attention and funding on all potential solutions.

(Zeman & Keith 2008)

In this paper is a ringing endorsement of inducing technological change with investments in unconventional alternatives to jump start the mitigation process in transportation sectors.

Although not represented in this issue, to counter the emissions of such distributed sources of carbon dioxide as moving vehicles, Klaus Lackner has proposed using wind-scrubbing devices. Comparing the process to the way trees remove CO₂ from the air, he described a tower design on the scale of a small-town water tower that could take up the CO₂ emissions of 15 000 cars. Lackner posited that it would take 250 000 such towers worldwide to take out as much carbon dioxide as the world is currently putting into the atmosphere. Lackner said: 'The way to get carbon dioxide out of the atmosphere is akin to how a tree does it. It puts surfaces up, the leaves, over which the CO₂ flows and as the air flows the CO₂ is being absorbed. Once you have absorbed that on a surface which is let us say wetted with a liquid you can collect that liquid and then remove the CO₂ from that liquid.' This could then be disposed of underground or used in manufacturing processes (Public Radio International 2007).

Massachusetts Institute of Technology engineer Howard Herzog has questioned whether Lackner's design would hold together on the proposed scale and cautions that more research is needed on the technology. Hertzog also said that more energy could be expended in keeping the slats coated in absorbent and disposing of it, than would be saved possibly producing more CO₂ than would be removed (Beal 2007). As with other technological innovations, companies are forming and producing prototypes, and Lackner has joined forces with Allen and Burt Wright and the late Gary Comer in Global Research Technologies, which has created a working model of a machine in which air moves through panels of hanging fabric coated with a proprietary material that captures the CO₂. Then the doors close, and the fabric strips are sprayed with a sodium carbonate solution that binds the CO₂ and becomes sodium bicarbonate. The water is drained off and an electro dialysis process strips CO₂ from the sodium bicarbonate. With the firm's electricity supplied by the coal-fired plants of Tucson Electric Power, the process produces as much carbon dioxide as it strips from the air (as Herzog cautioned), but the Wrights and Lackner are encouraged, foreseeing more efficient machines powered with renewable energy. Once these are in place, they believe that their technology can significantly start reducing the amount of carbon dioxide in the atmosphere. A machine the size of a 40 foot shipping container, according to Allen Wright, can remove a ton of CO₂ a day.

Lackner said that the process could not only offset but also reduce the amount of CO₂ in the global atmosphere, with an investment of \$1.6 trillion. 'It's a big scale, so big it's unimaginable', said Wright. 'But we as a species constantly build big things. If the Great Wall of China were an air collector, it would remove 8 billion tons a year' (Beal 2007). Wright estimated that 50 million shipping container-sized devices would handle the problem.

In addition to questions about whether such technologies are actually sufficiently scaleable and the availability of non-carbon-producing energy sources for the scrubbers, any real deployment also depends on the proof that CO₂ can be successfully stored and development of a carbon offset market that will pay for the machines along with public and private investment in the portfolio of solutions, which includes CO₂ capture and sequestration.

Returning to the articles in this issue, so far the authors I have mentioned are not really talking about geoengineering—despite Marchetti's coining of that term in the context of oceanic disposal of smoke stack-removed CO₂—but rather about alternative ways to mitigate that are unconventional and need a big R,D&D boost. At this point, several authors of subsequent articles move towards real geoengineering—manipulations of stocks and flows of components of the Earth's biogeochemical processes to alter the radiative balance of the atmosphere. We can begin this departure with the suggestions of Lampitt *et al.* (2008) for modifications to oceanic processes to create sequestration of carbon:

The oceans sequester carbon from the atmosphere partly as a result of biological productivity. Over much of the ocean surface, this productivity is limited by essential nutrients and we discuss whether it is likely that sequestration can be enhanced by supplying limiting nutrients. Various methods of supply have been suggested and we discuss the efficacy of each and the potential side effects that may develop as a result. Our conclusion is that these methods have the potential to enhance sequestration but that the current level of knowledge from the observations and modelling carried out to date does not provide a sound foundation on which to make clear predictions or recommendations.

(Lampitt *et al.* 2008)

Moreover, they conclude:

There is at present a clear and urgent need for tightly focused research into the effects of ocean fertilization. The critical areas of research will involve large-scale field experiments (100×100 km) tightly coupled to high-resolution three-dimensional computational models with embedded biogeochemistry. This is required for each of the four classes of fertilization schemes that have been proposed. Until completed satisfactorily, it is impossible to provide a rational judgment about whether the schemes proposed are (i) likely to be effective and (ii) likely to cause unacceptable side effects. Once this research has been carried out, it will be the responsibility of the science community to perform appropriate cost-benefit-risk analyses in order to inform policy. At the same time, discussions between the commercial, regulatory and scientific communities must take place so that the principles and practices of verification can be established.

(Lampitt *et al.* 2008)

The next generation of iron fertilization of the oceans is dealt with in greater depth by Smetacek & Naqvi (2008), who explain the process:

Iron fertilization of the open ocean, by both natural and artificial means, has been in the limelight ever since John Martin formulated the 'iron hypothesis' (Martin 1990). It postulates that adding iron to nutrient-rich but low productive ocean regions, by dust in the past and artificial fertilization in the future, would stimulate phytoplankton blooms, which would drawdown significant amounts of atmospheric carbon dioxide (CO₂) and, by mass sinking, sequester the carbon for long time scales in the deep ocean and sediments. The hypothesis was welcomed by biogeochemists and palaeoceanographers as a plausible mechanism to explain the lower glacial atmospheric CO₂ levels that coincided with higher dust deposition rates compared with the interglacials. Plankton ecologists on the other hand were sceptical that the trace nutrient iron could limit phytoplankton growth to the same extent as light and the macronutrients nitrate and phosphorus. Unfortunately, the spectre of

wanton commercialization of OIF put the scientific community as a whole on its guard. ... We argue that such experiments, if carried out at appropriate scales and localities, will not only show whether the technique will work, but will also reveal a wealth of insights on the structure and functioning of pelagic ecosystems in general and the krill-based Southern Ocean ecosystem, in particular.

(Smetacek & Naqvi 2008)

The comment about putting the community 'on its guard' proved prescient, as current international negotiations concerning governance of the oceanic commons by the Intergovernmental Oceanographic Commission are seriously considering banning all commercial oceanic manipulations that look like geoengineering, and allowing only research experiments (see: http://ioc-unesco.org/index.php?option=com_oe&task=viewEventAgenda&eventID=187).

Another geoengineering scheme to manipulate the atmosphere–ocean interface is proposed by Salter *et al.* (2008):

Wind-driven spray vessels will sail back and forth perpendicular to the local prevailing wind and release micron-sized drops of seawater into the turbulent boundary layer beneath marine stratocumulus clouds. The combination of wind and vessel movements will treat a large area of sky. When residues left after drop evaporation reach cloud level they will provide many new cloud condensation nuclei giving more but smaller drops and so will increase the cloud albedo to reflect solar energy back out to space. If the possible power increase of 3.7 W m^{-2} from double pre-industrial CO_2 is divided by the 24-hour solar input of 340 W m^{-2} , a global albedo increase of only 1.1 per cent will produce a sufficient offset. The method is *not* intended to make new clouds. It will just make existing clouds whiter.

(Salter *et al.* 2008)

The latter proposals for marine cloud albedo enhancement are elaborated on by modelling of the marine aerosol injections to enhance cloud albedo by Latham *et al.* (2008):

Analytical calculations, cloud modelling and (particularly) GCM computations suggest that, if outstanding questions are satisfactorily resolved, the controllable, globally averaged negative forcing resulting from deployment of this scheme might be sufficient to balance the positive forcing associated with a doubling of CO_2 concentration. This statement is supported quantitatively by recent observational evidence from three disparate sources. We conclude that this technique could thus be adequate to hold the Earth's temperature constant for many decades.

More work—especially assessments of possible meteorological and climatological ramifications—is required on several components of the scheme, which possesses the advantages that (i) it is ecologically benign—the only raw materials being wind and seawater, (ii) the degree of cooling could be controlled, and (iii) if unforeseen adverse effects occur, the system could be immediately switched off, with the forcing returning to normal within a few days (although the response would take a much longer time).

(Latham *et al.* 2008)

The authors go on to say:

In addition to requiring further work on technological issues concerning the cloud albedo enhancement scheme (Salter *et al.* 2008), we need to address some limitations in our understanding of important meteorological aspects, and also make a detailed assessment of possibly adverse ramifications of the deployment of the technique, for which there would be no justification unless these effects were found to be acceptable.

(Latham *et al.* 2008)

The most ambitious and large-scale set of schemes are very similar to the Budyko stratospheric aerosol suggestions, but with much more precision and regional focus. Caldeira & Wood (2008) propose reducing incoming solar radiation (insolation) with injected aerosols that have been tested with current generations of climate models:

We perform numerical simulations of the atmosphere, sea ice, and upper ocean to examine possible effects of diminishing incoming solar radiation, insolation, on the climate system. We simulate both global and Arctic climate engineering in idealized scenarios in which insolation is diminished above the top of the atmosphere. We consider the Arctic scenarios because climate change is manifesting most strongly there. Our results indicate that, while such simple insolation modulation is unlikely to perfectly reverse the effects of greenhouse gas warming, over a broad range of measures considering both temperature and water, an engineered high CO₂ climate can be made much more similar to the low CO₂ climate than would be a high CO₂ climate in the absence of such engineering.

(Caldeira & Wood 2008)

Why do this grand scale environmental manipulation scheme? They offer the standard answer:

As desirable and affordable as reductions in emissions of greenhouse gases may be, they are not yet being achieved at the scale required. Emissions of CO₂ into the atmosphere are increasing more rapidly than foreseen in any of the IPCC marker scenarios (Raupauch *et al.* 2007) with each release of CO₂ producing a warming that persists for many centuries (Matthews & Caldeira 2008).

(Caldeira & Wood 2008)

After proposing very specific suggestions for insolation reductions, Caldeira and Wood suggest that, while not perfect offsets to CO₂ increases, stratospheric dust injections carefully designed could eliminate much of the warming that would otherwise occur with business-as-usual emissions. But, like the other authors, caveats abound:

Nobody claims that such climate engineering would be perfect or is devoid of risks. Furthermore, it is clear that such climate engineering will not reverse all adverse effects of carbon dioxide emission; for example, climate engineering will not reverse the acidifying effect of carbon dioxide on the oceans (Caldeira & Wickett 2003).

(Caldeira & Wood 2008)

Reflecting Kellogg and Schneider's tongue in cheek 'no fault climate disaster insurance', they wisely warn that: 'Of course, it would be strongly preferable to obtain international consensus and cooperation before deployment and operation of any climate engineering system.' Then, inexplicably in my view, they go on to suggest that geoengineering could, nevertheless, be easily done unilaterally—precisely what Kellogg and I warned was very risky to international security owing to the likely perception of negative effects in some places at some times. This is the way Caldeira and Wood put it:

However, unlike CO₂ emissions reduction, the success of climate engineering does not depend fundamentally on such consensus and cooperation. Putting aside the question of whether or not such a course of action would be wise, a climate engineering scheme could be deployed and operated unilaterally by a single actor, perhaps at remarkably low economic expense.

(Caldeira & Wood 2008)

Fortunately, their ultimate paragraph returns to more circumspect reasoning:

Modelling of climate engineering is in its infancy. However, continued growth in CO₂ emissions and atmospheric CO₂ concentrations, combined with preliminary numerical simulations such as those presented here, constitute a *prima facie* case for exploring climate engineering options—and associated costs, risks and benefits—in greater detail.

(Caldeira & Wood 2008)

Others who have not contributed to this issue have put forth other broad-scale geoengineering approaches. In an article published in 2006 in *Proceedings of the National Academy of Sciences of the United States of America*, Roger Angel, reflecting the kinds of schemes proposed 30 years earlier in Rusin and Flit, described the concept of blocking 1.8 per cent of the solar flux with a space sunshade orbited near the inner Lagrange point (L1), in-line between the Earth and the Sun. Building on the work of Early (1989), Angel's transparent sunshade would be used to deflect the sunlight, rather than to absorb it to minimize the shift in balance out from L1 caused by radiation pressure (Angel 2006). The plan involves launching a constellation of trillions of small free-flying spacecraft far above Earth into an orbit aligned with the Sun, called the L1 orbit. This constellation of spacecraft would form a long, cylindrical cloud approximately half the Earth's diameter, and approximately 10 times longer. Approximately 10 per cent of the sunlight passing through the 60 000 mile length of the cloud, pointing lengthwise between the Earth and the Sun would be diverted away from the Earth, which would uniformly reduce sunlight over the planet by approximately 2 per cent. According to Angel, this would be enough to balance the heating of a doubling of atmospheric carbon dioxide in Earth's atmosphere. Angel says, 'The concept builds on existing technologies. It seems feasible that it could be developed and deployed in about 25 years at a cost of a few trillion dollars. With care, the solar shade should last about 50 years. So the average cost is about \$100 billion a year, or about two-tenths of 1 per cent of the global domestic product.' However, he does add the standard caveats for all such Buck Rogers-like schemes: 'The sunshade is no substitute for developing renewable energy, the only permanent solution. A similar massive level of technological innovation and financial investment could ensure that' (EurekaAlert 2006).

Another set of extremely large-scale proposals that have been championed by Martin Hoffert and others and have gained interest is the construction of a space-based solar power system. Hoffert *et al.* (2002) posited this idea among others as ways to not only reduce energy consumption but also to provide non-carbon-emitting forms of energy and thus help stop the increase in the carbon dioxide-induced component of climate change, which is an energy problem in their view. They describe the space-based Solar System as follows:

Space solar power (SSP) exploits the unique attributes of space to power Earth (Glaser 1968; Glaser *et al.* 1997). Solar flux is ~ 8 times higher in space than the long-term surface average on spinning, cloudy Earth. If theoretical microwave transmission efficiencies (50 to 60%) can be realized, 75 to 100 W_e could be available at Earth's surface per m² of PV array in space, $\leq 1/4$ the area of surface PV arrays of comparable power. In the 1970s, the National Aeronautics and Space Administration (NASA) and the U.S. Department of Energy (DOE) studied an SSP design with a PV array the size of Manhattan in geostationary orbit [(GEO) 35,800 km above the equator] that beamed power to a 10-km by 13-km surface rectenna with 5 GW_e output. [10 TW equivalent (3.3 TW_e) requires 660 SSP units.] Other architectures, smaller satellites,

and newer technologies were explored in the NASA 'Fresh Look Study' (Mankins 1997). Alternative locations are 200- to 10,000-km altitude satellite constellations (Hoffert & Potter 1997), the Moon (Criswell 2002a; Criswell 2002b), and the Earth-Sun L2 Lagrange exterior point [one of five libration points corotating with the Earth-Sun system (Landis 1997).

(Hoffert *et al.* 2002)

Interviewed by the American Public Broadcasting Station in 2000, Hoffert said:

In my opinion, such a business could eventually evolve into one in which you could sell either bits of information or kilowatt-hours, using essentially compatible components: the same kinds of antennas in orbit and similar kinds of antennas on the ground. Of course, it has to be studied, but I think that the levels of microwave power, in terms of the objective health effects, will be below those that occupational health and safety regulations say are dangerous to humans.

Until now, it's been very interesting and exciting for us to explore the solar system and to find out how the universe works with the Hubble telescope, but for the enormous investments we've put into space, we haven't gotten very much return as a society. There are energy resources available in space, and it's possible to exploit them. So that could become a frontier that could also play a very big role in human energy consumption on the Earth.

He goes on to say that 'a 50- to 100-year time scale is not too long for that to happen in, when you consider what happened in the last 100 years'.

Finally in this Theme Issue of *Phil. Trans. R. Soc. A*, geophysicist Lovelock (2008), the co-inventor of the Gaia hypothesis about planetary homeostasis, weighs in on the subject with a perspective from his long years of experience:

The gaps that exist in knowledge about the state of the ocean, the cryosphere and even the clouds and aerosols of the atmosphere make prediction unreal. The response of the biosphere to climate and compositional change is even less well understood; most of all, we are ignorant about the Earth as a self-regulating system and only just beginning to recognize that many separate but connected subsystems exist that can exert positive and negative feedback on a global scale.

(Lovelock 2008)

Nevertheless, even Lovelock cannot resist putting a dog of his own into this enticing geoengineering show:

Lovelock and Rapley (2007) suggested the use of a system of large pipes held vertically in the ocean surface to draw up cooler nutrient-rich water from just below the thermocline. The intention was to cool the surface directly, to encourage algal blooms that would serve to pump down CO₂ and also to emit gases such as DMS, volatile amines and isoprene (Nightingale & Liss 2003), which encourage cloud and aerosol formation. The pipes envisaged would be about 100 m in length and 10 m in diameter and held vertically in the surface waters and equipped with a one-way valve. Surface waves of average height 1 m would mix in 4.2 tons of cooler water per second.

Our intention was to stimulate interest and discussion in physiological techniques that would use the Earth system's energy and nutrient resources to reverse global heating. We do not know if the proposed scheme would help restore the climate, but the idea of improving surface waters by mixing cooler nutrient-rich water from below has a long history; indeed, it is at present used by the US firm Atmocean Inc. to improve the quality of ocean pastures.

(Lovelock 2008)

Nevertheless, his early cautionary emphasis soon returns with an apt metaphor in a section labelled ‘Planetary Medicine’:

What are the planetary health risks of geoengineering intervention? Nothing we do is likely to sterilise the Earth but the consequences of planetary scale intervention could hugely affect humans. Putative geoengineers are in a similar position to that of physicians before the 1940s.

(Lovelock 2008)

In a later section entitled ‘Ethics’ Lovelock reiterates his opening theme:

Before we start geoengineering we have to raise the following question: are we sufficiently talented to take on what might become the onerous permanent task of keeping the Earth in homeostasis? Consider what might happen if we start by using a stratospheric aerosol to ameliorate global heating; even if it succeeds it would not be long before we faced the additional problem of ocean acidification. This would need another medicine, and so on.

We could find ourselves enslaved in a Kafka-like world from which there is no escape.

(Lovelock 2008)

4. Personal reflections

I am sympathetic to those who expressed the concern that the very knowledge of the potential of geoengineering to offset some inadvertent global change disturbances could provide ammunition to those who wished to ‘solve’ the side effects of indefinite expansionary consumption and population trends with a dubious technological fix rather than a fundamental change in the political acceptability of the fossil fuel-based growth paradigm. Nevertheless, I, too, share the concern of others that should the middle to high end of the current range of estimates of possible inadvertent climatic alterations actually begin to occur, we would indeed face a very serious need for drastic, unpopular action to change consumption patterns in a short time—a politically dubious prospect. Thus I, somewhat reluctantly, voted with the majority of the NAS panellists in 1991 who agreed to allow a carefully worded chapter on the geoengineering options to remain in the report—provided it had enough explicit caveats that the committee could not possibly be interpreted as advocating near-term use of such schemes, only a study of their climatic, ecological, social and economic implications. For example, in the report of the mitigation panel of the NAS committee, it was noted that ‘it is important to recognize that we are at present involved in a large project of inadvertent ‘geoengineering’ by altering atmospheric chemistry, and it does not seem inappropriate to inquire if there are countermeasures that might be implemented to address the adverse impacts... Our current inadvertent project in ‘geoengineering’ involves great uncertainty and great risk. Engineered countermeasures need to be evaluated but should not be implemented without broad understanding of the direct effects and the potential side effects, the ethical issues, and the risks’ (NAS 1992, p. 433).

It seems that this issue a decade and a half later than the NAS report has, in virtually every paper, echoed the warnings that have been implicit in all responsible essays on geoengineering since Budyko in the mid-1970s.

In the context of one geoengineering proposal, the deliberate use of augmented stratospheric aerosols as a seemingly inexpensive advertent attempt to offset a few watts per square metre of inadvertent global-scale heating from anthropogenic greenhouse gases, it is likely that stratospheric dust cooling could not possibly be a perfect regional balance to greenhouse warming owing to the very patchy nature of the greenhouse forcing itself (see Schneider 1996). That is, aerosols injected in the stratosphere would, owing to high winds and a lifetime measured in years, become relatively uniformly distributed in zonal bands over the hemisphere. This means that they would reflect sunlight back to space relatively uniformly around latitude zones. Their reflection of sunlight would also vary with latitude because the amount of incoming sunlight and its relative angle to the Earth changes with latitude and season. This fairly uniform, zonally averaged rejection of sunlight would be balancing a relatively non-uniform trapping of heat associated with greenhouse gases owing to the patchy nature of cloudiness (Schneider 1994) in the lower atmosphere (to say nothing of the very patchy nature of soot and sulphate aerosols in the lower atmosphere).

Thus, 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 CO₂ 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. This also suggests the need to create a hierarchy of anthropogenic climate forcing indicators, of which global average radiative forcing is but the simplest aggregate modulus.

Govindasamy & Caldeira (2000) tested this concern with a climate model and argued that although perfect offsets are not possible at regional scales, zonal injections of aerosols make a CO₂-doubled world that has aerosol geoengineering compensations look much more like an undisturbed greenhouse effect world. However, let me remind the reader that it is well established that climate models do not represent regional climatic patterns as well as they simulate continental to hemispheric scale projections (IPCC 2007a).

I will not argue that regional climatic anomalies arising from some aerosol geoengineering offset scheme would necessarily be worse than an unabated 3–6°C warming before 2100—a range that implies a very high likelihood for dangerous anthropogenic interference with the climate system (IPCC 2007b). Rather, I simply wish to reiterate why the strong caveats, which suggest that it is premature to contemplate implementing any geoengineering schemes in the near future, are stated by all responsible people who have addressed the geoengineering question. Such caveats must be repeated at the front, middle and conclusion sections of all discussions of this topic, as they indeed are in this issue as well.

5. Who would reliably manage geoengineering projects for the world community over a century or two?

Indeed, as noted by all responsible authors who have addressed this problem, much is technically uncertain and geoengineering could be a ‘cure worse than the disease’ (Schneider & Mesirov 1976), given our current level of ignorance of both

advertent and inadvertent climate modifications. But, there is also the potential for human conflict associated with the fact that deliberate intervention in the climate system could, as noted more than 30 years ago, coincide with seriously damaging climatic events that may or may not have been connected to the modification scheme and likely could not conclusively be shown to be connected to or disconnected from that modification. This potential for conflicts poses serious social and political obstacles to would-be climate controllers, regardless of how technically or cost effective the engineering schemes may eventually turn out to be. Of course, this has to be traded off against the potential for conflicts from the uneven distribution of climate impacts from unabated emissions that will drive global warming.

Fortunately, the seemingly staggering costs—trillions of dollars—of mitigation that substitutes non-carbon-emitting sources for conventional fossil fuel-burning devices represent a mere year or so delay in being some 500 per cent richer a century from now with 450 ppm CO₂ with stringent climate mitigation versus a potentially dangerous 900 ppm concentration if there are no significant mitigation policies deployed (see Azar & Schneider 2002). Thus, repeated assertions that society *will not* invest in mitigation—and thus geoengineering *will* be needed—seem as premature as arguing for near-term deployment of still-untested geoengineering schemes. Moreover, 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.

Institutions currently do not exist with the firm authority to assess or enforce responsible use of the global commons (Nanda & Moore 1983; Choucri 1994). There are some partially successful examples (e.g. the Montreal Protocol and its extensions to control ozone-depleting substances, the nuclear non-proliferation treaty or the atmospheric nuclear test ban treaty) of nation states willing to cede some national sovereignty to international authorities for the global good. However, it would require a significant increase in ‘global-mindedness’ on the part of all nations to set up institutions to attempt to control climate and to compensate any potential losers should the interventions possibly backfire—or even be perceived to have gone awry. Moreover, such an institution would need the resources, skills and authority to inject continuously, and monitor over a century or two, measured amounts of dust in the stratosphere, iron in the oceans or sea-salt aerosols into clouds in order to counteract the inadvertent enhanced heat trapping effects of long-lived constituents such as CO₂.

I, for one, am highly dubious about the likelihood of a sufficient and sustainable degree of global-scale international cooperation needed to assure a high probability that world climate control and compensation authorities (e.g. see Schneider & Mesriow 1976) could be maintained without interruption by wars or ideological disputes for the next two centuries. Just imagine if we needed to do all this in 1900 and then the rest of twentieth century history unfolded as it actually did! Would climate control have been rationally maintained, or would gaps and rapid transient reactions have been the experience?

In Schneider (1996), I proposed the following health metaphor as apt: it is better to cure heroin addiction by paced medical care that weans the victim slowly and surely from drug addiction than by massive substitution of methadone or some other ‘more benign’ or lower cost narcotic. For me, a more rapid implementation of

energy-efficient technologies, alternative, less polluting agricultural or energy production systems (e.g. [Johansson *et al.* 1993](#)), better population planning, wildlife habitat protection (particularly for threatened ecosystems) and commodity pricing that reflects not simply the traditional costs of labour, production, marketing and distribution but also the potential 'external' costs from a modified environment (e.g. [NAS 1992](#); [IPCC 2007c](#)) are the kinds of lasting measures that can cure 'addiction' to polluting practices without risking the potential side effects of geoengineering—planetary methadone in my metaphor. Rather than pin our hopes on the gamble that geoengineering will prove to be inexpensive, benign and administratively sustainable over centuries—none of which can remotely be assured now—in my value system, I—and most of the authors of this issue as well—would prefer to start to lower the human impact on the Earth through more conventional means.

However, critics have asked, is it not one's reluctance to embrace manipulations of nature at a large scale ignoring the potential consequences of 'geosocial engineering' implicit in changing the culture away from its fossil fuel-based growth and development habits? Do we not know comparably little about the social consequence of carbon taxes, such critics suggest, and are not the potential human consequences of manipulating the world's economy potentially worse than the politics or environmental implications of geoengineering? In [Schneider \(1996\)](#), I had several responses to these legitimate concerns. First, although in principle these are empirically determinable comparisons between the relative consequences of 'geo' versus 'social' engineering, in practice both are sufficiently unprecedented on the scales being considered here that estimates of impacts will remain highly uncertain and subjective for some time to come. Moreover, values will dominate the trade-off: for example, risk aversion versus risk proneness or the precautionary principle for protecting nature versus the unfettered capacity of enterprising individuals, firms or nations to act to improve their economic conditions.

Second, I do not plead guilty to the charge of nature-centric bias by ignoring the cultural consequences of emissions policies. One who worries more about potential side effects of geoengineering countermeasures to inadvertent modification of nature than about side effects of manipulating the world's energy economy via, say, carbon taxes is simply recognizing that it was humans, not nature, that began the spiral of difficulties in the first place by indulging in inadvertent modifications of the environment. Rather, the bias is on the anthropocentrists, since they ignore that searching for solutions to human disturbances to nature that do not raise yet additional risks for coupled human natural systems ([Liu *et al.* 2007](#)) is a way of balancing anthropocentric and nature-centric values. Carbon taxes are simply one possible way to internalize into human economics the potential external damages (or 'externalities') of our activities.

To be sure, flexibility is essential for any policy to be both effective and fair, plus it needs to be capable of being reversed if unforeseen negative outcomes materialize. But, since human systems have already disturbed nature in the first place, it seems to me that the risks of countering inadvertent human impacts on nature should next be borne by humans, not an already besieged nature.

Nevertheless, I do (somewhat reluctantly) agree that study of geoengineering potential is clearly needed, given our growing inadvertent impacts on the planet (negative impacts that are already being borne unfairly in vulnerable places such

as Bangladesh and sub-Saharan Africa—and even the Gulf Coast of the USA). But, I must conclude with a caveat: I would prefer to get slowly unhooked from our economic dependence on massive increases in carbon fuels than to try to cover the potential side effects of business-as-usual development with decades of sulphuric acid injections into the atmosphere or iron into the oceans or aerosols into the marine boundary layer, to say nothing of Buck Rogers schemes in space.

But, deep Earth sequestration and alternative non-carbon-emitting fuels—also discussed in this issue—clearly do not suffer from the side effects of geoengineering schemes, or the who-controls-the-climate problems, and are obvious candidates for rapid learning-by-doing efforts.

In short, my personal prescription for climate policies can be summarized in five sequenced steps.

- (i) Adaptation is essential now to assist those who will likely be harmed by ‘in the pipeline’ climate change. Actions that simultaneously enhance ‘sustainable development’ would seem the most attractive options.
- (ii) Performance standards required of buildings, appliances, machines and vehicles to wring the maximum potential for cost-effective engineering energy efficiency need to be mandatory and widespread.
- (iii) A ‘learning-by-doing feeding frenzy’ needs to emerge, where we set up public–private partnerships to fashion incentives to help us ‘invent our way out’ of the problem of high-emitting technological and social systems.
- (iv) A shadow price on carbon has to be established to ensure that the full costs of any energy production or end use system is part of the price of doing business. Cap and trade and carbon taxes are the prime examples of such schemes to internalize external risks from business-as-usual emissions, but these schemes must recognize the special problems they may pose for certain groups: poor people and coal miners or SUV workers. So, in addition to internalizing these externalities to protect the environmental commons, we need to consider side payments or other compensation schemes to be fair to the losers of the mitigation policies and to provide a transition for them to a softer economic landing, so to speak.
- (v) Finally, my last policy category in the sequence is to consider deploying geoengineering schemes. However, as has been said by all in this issue, and as I fully agree, R&D is needed and should be an early part of the climate policy investment sequencing, even if deployment is the last resort.

References

- American Public Broadcasting System 2000 Beyond fossil fuels: an interview with Professor Martin Hoffert by Jon Palfreman in the series, *What’s up with the weather*, a production of *Nova & Frontline*. See <http://www.pbs.org/wgbh/warming/beyond/>.
- Anderson, K. & Bows, A. 2008 Reframing the climate change challenge in light of post-2000 emission trends. *Phil. Trans. R. Soc. A* **366**, 3863–3882. (doi:10.1098/rsta.2008.0138)
- Angel, R. 2006 Feasibility of cooling the Earth with a cloud of small spacecraft near the inner Lagrange point (L1). *Proc. Natl Acad. Sci. USA* **103**, 17 184–17 189. (doi:10.1073/pnas.0608163103)

- Azur, C. & Schneider, S. H. 2002 Are the economic costs of stabilizing the atmosphere prohibitive? *Ecol. Econ.* **42**, 73–80. (doi:10.1016/S0921-8009(02)00042-3)
- Beal, T. 2007 Tucson firm has plan for towers to suck up CO₂. *Arizona Daily Star*, 25 November 2007. See <http://www.azstarnet.com/metro/213272>.
- Breeze, P. 2008 Coping with carbon: a near-term strategy to limit carbon dioxide emissions from power stations. *Phil. Trans. R. Soc. A* **366**, 3891–3900. (doi:10.1098/rsta.2008.0113)
- Budyko, M. I. 1977 *Climatic changes*. (Transl. Izmeniia Klimata, Gidrometeoizdat, Leningrad, 1974, p. 244.) Washington, DC: American Geophysical Union.
- Caldeira, K. & Wickett, M. E. 2003 Anthropogenic carbon and ocean pH. *Nature* **425**, 365. (doi:10.1038/425365a)
- Caldeira, K. & Wood, L. 2008 Global and Arctic climate engineering: numerical model studies. *Phil. Trans. R. Soc. A* **366**, 4039–4056. (doi:10.1098/rsta.2008.0132)
- Choucri, N. (ed.) 1994 *Global accord: environmental challenges and international responses*. Cambridge, MA: The MIT Press.
- Criswell, D. R. 2002a In *Innovative solutions to CO₂ stabilization* (ed. R. Watts), pp. 345–410. New York, NY: Cambridge University Press.
- Criswell, D. R. 2002b Solar power via the moon. *Ind. Physicist* **8**, 12–15.
- Crutzen, P. J. 2006 Albedo enhancement by stratospheric sulfur injections: a contribution to resolve a policy dilemma? *Climatic Change* **77**, 211–220. (doi:10.1007/s10584-006-9101-y)
- Early, J. T. 1989 Space-based solar screen to offset the greenhouse effect. *J. Br. Interplanet Soc.* **42**, 567–569.
- EurekaAlert 2006 Space sunshade might be feasible in global warming emergency. AAAS, 3 November 2006. See http://www.eurekaalert.org/pub_releases/2006-11/uoa-ssm110306.php.
- Gaskins, D. & Weyant, J. 1993 EMF-12: model comparisons of the costs of reducing CO₂ emissions. *Am. Econ. Rev.* **83**, 318–323.
- Glaser, P. E. 1968 Power from the sun: its future. *Science* **162**, 857–861. (doi:10.1126/science.162.3856.857)
- Glaser, P. E., Davidson, F. P. & Csigi, K. I. (eds) 1997 *Solar power satellites*. New York, NY: Wiley-Praxis.
- Glazovsky, N. F. 1990 *The Aral crisis: the origin and possible way out*. Moscow, Russia: Naulca.
- Govindasamy, B. & Caldeira, K. 2000 Geoengineering Earth's radiation balance to mitigate CO₂-induced climate change. *Geophys. Res. Lett.* **27**, 2141–2144. (doi:10.1029/1999GL006086)
- Hoffert, M. I. & Potter, S. E. 1997 Energy supply. In *Engineering response to global climate change* (ed. R. G. Watts), pp. 205–259. Boca Raton, FL: Lewis.
- Hoffert, M. I. *et al.* 2002 Advanced technology paths to global climate stability: energy for a greenhouse planet. *Science* **298**, 981–987. (doi:10.1126/science.1072357)
- Intergovernmental Panel on Climate Change 1995a In *Climate change 1995: economic and social dimensions of climate change—contribution of Working Group III to the Second Assessment Report of the Intergovernmental Panel on Climate Change* (eds J. P. Bruce, H. Lee & E. F. Haites). Cambridge, UK: Cambridge University Press.
- Intergovernmental Panel on Climate Change 1995b In *Climate change 1995: the science of climate change—contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change* (eds J. T. Houghton, L. G. Meira Filho, B. A. Callender, N. Harris, A. Kattenberg & K. Maskell). Cambridge, UK: Cambridge University Press.
- Intergovernmental Panel on Climate Change 2007a In *Climate change 2007: the physical science basis—contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (eds S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor & H. L. Miller). Cambridge, UK: Cambridge University Press.
- Intergovernmental Panel on Climate Change 2007b In *Climate change 2007: impacts, adaptation, and vulnerability—contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (eds M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden & C. E. Hanson). Cambridge, UK: Cambridge University Press.

- Intergovernmental Panel on Climate Change 2007c In *Climate Change 2007: Mitigation of Climate Change—Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (eds B. Metz, O. Davidson, P. Bosch, R. Dave & L. Meyer). Cambridge, UK: Cambridge University Press.
- Johansson, T. B., Kelly, H., Reddy, A. K. N. & Williams, R. H. (eds) 1993 *Renewable energy: sources for fuels and electricity*. Washington, DC: Island Press.
- Kellogg, W. W. & Schneider, S. H. 1974 Climate stabilization: for better or for worse? *Science* **186**, 1163–1172. (doi:10.1126/science.186.4170.1163)
- Lampitt, R. S. *et al.* 2008 Ocean fertilization: a potential means of geoengineering? *Phil. Trans. R. Soc. A* **366**, 3919–3945. (doi:10.1098/rsta.2008.0139)
- Landis, G. A. 1997 *Proc. of Solar Power Satellite '97 Conf., 24–28 August 1997, Montreal, Canada*, pp. 327–328. Ottawa, Canada: Canadian Aeronautics and Space Institute.
- Lashof, A. & Tirpak, D. A. (eds) 1990 *Policy options for stabilizing global climate*. Report to Congress: Executive Summary. U.S. Environmental Protection Agency, Office of Policy, Planning and Evaluation. PM-221.
- Latham, J., Rasch, P., Chen, C.-C. J., Kettles, L., Gadian, A., Gettelman, A., Morrison, H., Bower, K. & Choulaton, T. 2008 Global temperature stabilization via controlled albedo enhancement of low-level maritime clouds. *Phil. Trans. R. Soc. A* **366**, 3969–3987. (doi:10.1098/rsta.2008.0137)
- Liu, J. *et al.* 2007 Complexity of coupled human and natural systems. *Science* **317**, 1513–1516. (doi:10.1126/science.1144004)
- Lovelock, J. 2008 A geophysicologist's thoughts on geoengineering. *Phil. Trans. R. Soc. A* **366**, 3883–3890. (doi:10.1098/rsta.2008.0135)
- Lovelock, J. & Rapley, C. R. 2007 Ocean pipes could help the Earth to cure itself. *Nature* **449**, 403. (doi:10.1038/449403a)
- Mankins, J. 1997 The space solar power. *Aerosp. Am.* **35**, 30–36.
- Marchetti, C. 1977 On geoengineering and the CO₂ problem. *Climatic Change* **1**, 59–68. (doi:10.1007/BF00162777)
- Martin, J. H. 1990 Glacial-interglacial CO₂ change: the iron hypothesis. *Paleoceanography* **5**, 1–13. (doi:10.1029/PA005i001p00001)
- Matthews, H. D. & Caldeira, K. 2008 Stabilizing climate requires near-zero emissions. *Geophys. Res. Lett.* **35**, L04705. (doi:10.1029/2007GL032388)
- Nanda, V. P. & Moore, P. T. 1983 Global management of the environment: regional and multilateral initiatives. In *World climate change: the role of international law and institutions* (ed. V. P. Nanda), pp. 93–123. Boulder, CO: Westview Press.
- National Academy of Sciences 1992 *Policy implications of greenhouse warming: mitigation, adaptation, and the science base*. Panel on Policy Implications of Greenhouse Warming, Committee on Science, Engineering, and Public Policy, pp. 433–464. Washington, DC: National Academy Press.
- Nightingale, P. D. & Liss, P. S. 2003 Gases in seawater. *Treatise Geochem.* **6**, 49–81.
- Peters, R. L. & Lovejoy, T. E. 1992 *Global warming and biological diversity*, p. 386. New Haven, CT: Yale University Press.
- Public Radio International 2007 Climate contest. In *Living on Earth* series with Steve Curwood Feb. 16, 2007. Klaus Lackner interview by Emily Taylor. See <http://www.loe.org/shows/shows.htm?programID=07-P13-00007#feature2>.
- Raupach, M. R., Marland, G., Ciais, P., Le Quere, C., Canadell, J. G., Klepper, G. & Field, C. B. 2007 Global and regional drivers of accelerating CO₂ emissions. *Proc. Natl Acad. Sci. USA* **104**, 10 288–10 293. (doi:10.1073/pnas.0700609104)
- Root, T. L. & Schneider, S. H. 1993 Can large-scale climatic models be linked with multiscale ecological studies? *Conserv. Biol.* **7**, 256–270. (doi:10.1046/j.1523-1739.1993.07020256.x)
- Rusin, N. & Flit, L. ca 1960 *Man versus climate*. (Transl. by Dorian Rottenberg). Moscow, Russia: Peace Publishers.

- Salter, S., Sortino, G. & Latham, J. 2008 Sea-going hardware for the cloud albedo method of reversing global warming. *Phil. Trans. R. Soc. A* **366**, 3989–4006. (doi:10.1098/rsta.2008.0136)
- Schelling, T. C. 1983 Climate change: implications for welfare and policy. In *Changing Climate*, pp. 442–482. Washington, DC: National Research Council.
- Schneider, S. H. 1994 Detecting climatic change signals: Are there any ‘fingerprints’? *Science* **263**, 341–347. (doi:10.1126/science.263.5145.341)
- Schneider, S. H. 1996 Geoengineering: Could—or should—we do it? *Climatic Change* **33**, 291–302. (doi:10.1007/BF00142577)
- Schneider, S. H. & Mesirov, L. E. 1976 *The genesis strategy: climate and global survival*, p. 419. New York, NY: Plenum Publishing Corp.
- Smetacek, V. & Naqvi, S. W. A. 2008 The next generation of iron fertilization experiments in the Southern Ocean. *Phil. Trans. R. Soc. A* **366**, 3947–3967. (doi:10.1098/rsta.2008.0144)
- Zeman, F. S. & Keith, D. W. 2008 Carbon neutral hydrocarbons. *Phil. Trans. R. Soc. A* **366**, 3901–3918. (doi:10.1098/rsta.2008.0143)