

Climate Engineering

A critical review of proposals, their scientific and political context, and possible impacts.

compiled for [*Scientists For Global Responsibility*](#), November 1996

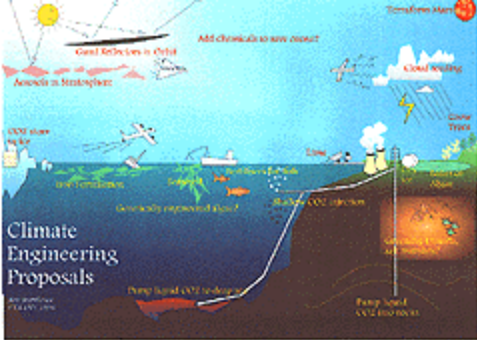
[Ben Matthews](#)

School of Environmental Sciences, UEA, Norwich NR47TJ
Fax 01603 507719, Tel (wk) 01603 593733,
email ben@chooseclimate.org

Abstract:

This review of climate engineering proposals aims to provide a comprehensive resource of up to date information and ideas for people concerned about the development of large-scale technical fixes to counter the problem of global warming. The proposals fall into three main categories: increasing the reflection of solar radiation back to space, enhancing natural sinks of carbon dioxide, and direct disposal of carbon dioxide captured at source. In addition, proposals involving weather modification, ozone chemistry and terraforming Mars are mentioned briefly. Direct disposal of carbon dioxide is included because it involves exploitation of "global commons" such as the deep ocean, and because it is often compared with schemes to increase natural sinks. Some of these proposals are realistic and thus a real cause for concern, whilst the reader may find amusement in reading some of the crazier schemes! All of these technical fixes are intended to tackle the symptom of the problem of fossil fuel consumption. The development of technology to encourage energy efficiency or renewable energy, on the other hand, which is intended to reduce that consumption, is much less controversial, and is not considered here.

Some academic research projects which may lead to climate engineering, such as fertilisation of the Southern Ocean with added Iron, have recently received much media attention. However, the media seems to be less aware of the much larger community of researchers who are employed by the fossil fuel and power industries to investigate similar proposals for enhancing CO₂ sinks. This review aims to clarify not only how each proposal might work or fail, but also who is promoting each idea. Sponsorship by the fossil fuel industry is closely linked to the bluffing game of international greenhouse politics, where excuses for doing nothing are always welcome. Hidden political values are concealed in cost-benefit analyses, in which a trade off can be made between climate engineering or climate warming damages, implying that consumption is already non-negotiable. The "just in case" argument for backing climate engineering research may become a self-fulfilling prophesy in this political context, but in the real world the choice



might then be between two potential catastrophes, for positive feedback processes make the climate system inherently surprising. I conclude by asking whether such research should continue, and how we might check its momentum in the future.

[Click here for a picture summarising climate engineering proposals \(beware 250KB!\)](#)

Contents

- [1. Introduction](#)
- [2. Climate Engineering Proposals](#)
 - [2.1 Weather engineering, cloud seeding, storm diversion](#)
 - [2.2 Reflection of incoming solar radiation](#)
 - 2.2.1 General Principle
 - 2.2.2 Sulphate aerosols or dust in the stratosphere
 - 2.2.3 Giant reflectors orbiting the earth
 - 2.2.4 Other ways to reflect solar radiation
 - [2.3 Removal of CO2 from the air by enhancing natural sinks](#)
 - 2.3.1 Ocean sink proposals: general principles
 - 2.3.2 Ocean fertilisation: general points
 - 2.3.3 Early proposals: seaweed
 - 2.3.4 Recent nitrate/phosphate fertilisation proposals
 - 2.3.5 Iron Fertilisation of the Oceans
 - 2.3.6 Other ocean-algae ideas
 - 2.3.7 Liming the Oceans
 - 2.3.8 Greening the deserts
 - 2.3.9 Planting Trees
 - [2.4 Direct disposal of anthropogenic CO2](#)
 - 2.4.1 Pumping liquid CO2 to the bottom of the ocean
 - 2.4.2 Storing CO2 under the rocks
 - 2.4.3 CO2 Storage as dry ice
 - 2.4.4 CO2 Fixation by in-situ lakes of algae
 - [2.5 Soaking up ozone destroying chemicals by adding more](#)
 - [2.6 And bringing Life to Mars](#)
- [3. Who sponsors Climate Engineering proposals?](#)
 - [3.1 Industrial sponsors and consultants](#)
 - [3.2 The International Energy Agency Greenhouse Gas R&D Programme](#)
 - [3.3 The Research Institute for Innovative Technology for the Earth](#)
 - [3.4 The Electric Power Research Institute](#)
- [4. Commentary on Impacts: Climate Science, Politics and Feedbacks](#)

- [4.1 History and Future](#)
- [4.2 Will climate engineering sponsorship distort the science of global change?](#)
- [4.3 The impact on climate politics](#)
 - 4.3.1 The Current Situation
 - 4.3.2 Cost Benefit Analysis: How much is life worth?
 - 4.3.3 Scientific or political solutions?
- [4.4 From proposal to reality](#)
 - 4.4.1 Who might carry out climate engineering?
 - 4.4.2 The momentum of research
 - 4.4.3 Feedbacks and surprises
- [4.5 Should Climate Engineering Research Continue?](#)
- [5. Where do we go from here?](#)
 - [5.1 Overview](#)
 - [5.2 Climate Convention CoP 3 in Kyoto and the IPCC](#)
 - [5.3 The Antarctic Treaty and International Law](#)
 - [5.4 Common Research Funding](#)
 - [5.5 Consensus Conferences](#)
 - [5.6 Consumer pressure and boycotts](#)
 - [5.7 Question Value Assumptions](#)
 - [5.8 Notes of Caution](#)

[References](#)

[Addresses and web pages](#)

[Acronyms](#)

[Acknowledgements](#)

Part 1. Introduction

Many of us like to think that our job plays some small role in the massive task of "saving the world". Myself, I was convinced long ago that global warming was the greatest potential threat to all life on earth, because we were entering unknown territory in a chaotic system dominated by little-known feedback processes. If positive feedbacks predominate in the "runaway greenhouse", this could spell the end of life on earth. On the other hand, I knew that for 4 billion years the Earth had remained comfortable for life, and this was largely due to negative feedback processes involving life itself. In particular, the beautiful little algae in the sea controlled the pump of CO₂ from the atmosphere to the ocean, and thus kept the world cool. And so I ended up working here in the laboratory, measuring CO₂ fluxes in and out of a tankful of such algae.

But in this university there are many others also motivated to "save the world", who find themselves instead studying development, social sciences or economics. And in a gathering of such people, they often grumble about how the "the World Bank (or similar

organisations) rule the world". On such occasions, I sometimes like to jut in and point out that really, if anything, it is the algae in the sea that rule the world. For, in the long term at least, it is they that have controlled the chemistry of the ocean, and thus of the atmosphere, and thus the global climate, and despite our pollution they continue to do this, so far little perturbed..

However, I begin to wonder, whether maybe the others were right after all. For I can envisage, in the not too distant future, that economists could be telling us how we should control the algae in the sea, to control the climate as we want it, to find the most economically "efficient" response to global warming. They already produce global cost benefit analyses to tell us how much CO₂ we should put in the sky, to best suit humans with money and power. But if they are given the link to the algae, it may be my own colleagues here who took the initiative to make it possible. New experiments on the "Iron Fertilisation hypothesis" last summer proved particularly successful. The scientists' motivation is not to control the world's climate, but curiosity to find out what does control the growth of the algae, necessary to understand ice ages and predict future climate change. But the question is, once you have the key to such "climate engineering", is it not likely to be developed, and directed according to the interests of money and power? History shows us, how the exciting science of one decade, turns into the more dubious technology of the next. Nuclear physics and molecular genetics are examples. Is it possible that the science of climate feedbacks, biogeochemical cycles, or "geophysiology" could be heading the same way?

My colleagues would probably tell me, that my World Bank scenario is alarmist and unhelpful, that's not what the scientists are intending. Some say that our task is only to solve the scientific challenge, and it is always better to possess the key to the mystery. Yet not surprisingly, there was a lot of controversy here after the recent publication of the results of the Iron experiment (more detail later), particularly fuelled by reluctance on the part of certain prominent researchers to reject the idea that their research might lead eventually to a partial technical fix to global warming. A hostile editorial in *New Scientist* (vol 152 no 2051) led to mudslinging in the media, for instance Jonathon Porritt's newspaper article "Beware the Quick Fixes of Nutty Professors" in response to another article welcoming this wonderful cure which might give us the freedom to drive more cars. It seems people either hate the iron fertilisation "quick fix" or love it, in rough proportion to their love of consumption and faith in technological "progress". The controversy encapsulated deep divisions.

Following from that, I decided to see whether there were other realistic "climate engineering" proposals in the scientific literature. I found about a dozen different ideas. These are considered in detail in section 2 of this paper. Of course, we should expect that in any field, there will always be some crazy proposals, many of which will never receive enough resources to be tested. But then I noticed that most of the papers came not from academics in institutions which pursue the basic science of global change, but instead from engineers, chemists, and biotechnologists who seemed to be sponsored by the fossil fuel or power industries. Sponsorship of climate engineering research is considered in section 3. It seems that these schemes are not just being suggested, but are already being

pushed, as a cheaper alternative than reducing CO2 emissions. This made me much more concerned.

There are three reasons to be worried about this turn of events, and these are considered in section 4. First, the push to find such a technical fix, will distort the science of global change. Second, if there is a serious prospect of a technical fix, this will weaken people's resolve to take the responsible course of drastically reducing fossil fuel consumption. And third, most worrying but most distant in the future, there is prospect of these proposals becoming reality. For the global climate is a highly non-linear system determined by complex feedback processes, and we still have a poor understanding of how it works. Any attempt to deliberately tinker with this system, could backfire very badly. Most new experiments do not work the first time as expected. There are always unwanted side effects. But if we tinker with the whole world, we only get one chance.

So, I wondered, perhaps the time is ripe for concerned people to get together, to check the enthusiasm of the climate engineers, and provide a forum for consideration of the ethical issues and side effects? Possible approaches are considered in Section 5. This might be a new topic for organisations such as "Scientists for Global Responsibility", or for the more radical young scientists under the banner "new luddites", who have recently devised peaceful but innovative ways to question the "Optimism" of the scientific establishment, so far focussing on cars, genetic engineering, and specific events in science festivals. But it might seem strange for such "green" activists, to start questioning whether we should curtail some climate change research. And perhaps the proposals still seem so far fetched, that we would only make ourselves look silly, by taking them too seriously at the moment? I will postpone further judgement, and continue by outlining some of the proposals in more detail.

Note that US academics have coined the term "geoengineering" to describe this topic. However, both to me and to citation indices, this still tends to conjure up hard hats and oil rigs, belonging to more traditional applied geology. So for the moment, I will stick with "climate engineering". "Terraforming" is another term, but refers to other planets.

[Click here to continue to Part Two](#) : Climate Engineering proposals

(This HTML document has been split into four files to ease downloading)

[Here is the whole paper as one HTML file](#)

[Click here to return to the beginning of the paper](#)

[Return to Choose-Climate Home Page](#)

Part 2: Climate Engineering proposals

[[Click here for a picture summarising climate engineering proposals \(beware 250KB!\)](#)]

2.1 Weather Engineering - cloud seeding, storm diversion

Local short- term events such as rainfall and strong winds are really weather rather than climate phenomena, and as such cloud seeding and storm diversion could be excluded from this paper. However, I will mention them briefly, since attempts to modify weather far predate any climate engineering proposals, even if we ignore rain dances and sacrifices to the gods!

The vapour pressure exerted by a water droplet or ice crystal increases with curvature, and therefore very small droplets will evaporate even if the air is greatly supersaturated with respect to flat water surfaces. To form drops some kind of condensation nucleus is therefore needed (a charged ion or particle) to attract together the first water molecules. This is the principle behind cloud seeding. In-situ experiments were begun by Veraart in 1931, soon followed by Schaefer and Langmuir from General Electric in New York. Originally dry ice was dropped from planes through ice clouds. Later silver iodide crystals were released from ground burners, the crystals very effectively mimicing the structure of ice, creating 10¹⁵ nuclei per gram of AgI. During the 1940s and 50s the claims of the rainmakers raised many expectations, particularly in Texas, Mexico and Israel, although there was little rain to show for it. In the Blue Ridge Mountains (US) the technique was employed to prevent the formation of large hailstones which damage crops, until farmers the other side of the mountain filed a lawsuit claiming theft of their rain! Recently there has been a little more success at rainmaking in Mexico, and much research continues in Israel (e.g. Rangno 1995). However, success in Israel might not be so welcome elsewhere in the middle east! For several recent papers on rain seeding, see the journal of Applied Meteorology 35 no 9 (1996).

Diverting hurricanes might cause even more conflict than stealing another country's rain. It is theoretically possible by selective cloud seeding, given that a tropical storm derives its energy from the latent heat released as clouds are formed. There have also been proposals, backed by the US Electric Power Research Institute, to develop powerful ionising lasers to deliberately induce lightening in thunderstorms before they reach cities or power installations (Muir 1995). Potentially these might also divert storms.

However, such ideas have never been tried. Weather is too chaotic. If storms can be begun by the flap of a butterfly's wing, who would insure the scientist who might direct a hurricane the wrong way?

2.2 Climate engineering proposals involving reflection of incoming solar radiation

2.2.1 General Principle:

The temperature at the Earth's surface adjusts (slowly) such that the energy from incoming solar radiation (sunlight- uv and visible) is balanced by terrestrial radiation

(infra red) emitted from the Earth. When greenhouse gases reflect back some of that terrestrial radiation, the surface warms and emits more radiation, until the amount escaping the atmosphere balances the sunlight as before. For a review of radiative forcing, see IPCC 1996 (g) It has been suggested, that to offset the warming effect of the predicted rise in greenhouse gases in the atmosphere, we could instead reduce the incoming solar radiation, by intercepting about 1% of sunlight. To some extent this happens anyway. Sulphate aerosol pollution is produced as a by-product of burning fossil fuel, and this aerosol reflects sunlight both directly, and by seeding the condensation of tiny cloud droplets. In industrial areas principally around 45 degrees north, (central Europe, northern China and India, northern USA), this more than offsets current greenhouse warming as shown clearly by the latest data (Santer et al. 1996). However, this is a local and short lived effect, because the aerosols are rapidly removed from the troposphere as acid rain. Would-be climate engineers desire a longer-lasting effect. Two principle methods have been proposed: giant reflectors in space, and stratospheric dust or aerosols. It has been pointed out by Schneider (1996) that such schemes could never offset global greenhouse warming without creating large regional climate changes, even if the aerosols were much more evenly distributed in the stratosphere than in the troposphere. Terrestrial and solar radiation never balance locally, since the atmosphere and oceans shift a large amount of heat between regions, and cloud cover also varies. A climate engineering "fix" based on reflecting solar radiation would cool most strongly different regions from those where there was most greenhouse warming.

2.2.2 Sulphate aerosols or Dust in the stratosphere.

Aerosols or dust in the stratosphere survive much longer than in the troposphere, and are already known to cool the planet, as observed following large volcanic eruptions. In the early 1990s, dust from mount Pinatubo checked global warming, and the observed cooling effect matched well with the most recent model predictions.

It has been suggested that we could deliberately inject either sulphate aerosols or dust into the stratosphere. For a recent review refer to Dickinson (1996). The idea is first credited to the Soviet scientist Budyko (1974) and developed by many others since, mainly in the US, even reaching a US government report (National Academy of Sciences 1992). Originally rockets or rifle shells would have carried the dust, but Penner (1984) suggested that it could be done more easily by a slight modification of commercial jet fuel, and this would be very cheap. In a policy statement to an International Energy Workshop in San Diego in 1992, he presented the dust idea as a "Low-cost no regrets" option for mitigating greenhouse warming, showing that it would cost just 0.1 cents (using coal dust) to cool the planet to compensate for one tonne of Carbon as CO₂ in the atmosphere, or 1 cent if SiH₄ was used to make inert SiO₂ dust (Penner 1993). However, he first attempts to rubbish the whole global warming scenario, and clearly doesn't intend that we carry this out unless, by some strange chance, all those scientists in IPCC happen to be right and we really do find we have a problem. Then, "for intolerable warming, low-cost planetary albedo augmentation may become the method of choice some decades in the future".

Besides being cheap, the aerosol fix is also promoted as "reversible", i.e. you can easily stop if it doesn't work, and within a few years the dust would fall out. On the other hand, most greenhouse gases have a much longer lifetime so if they are to be offset with stratospheric aerosols, we would have to rely on the ability of future generations to keep flying those planes, to keep repairing the shield or be faced with sudden warming.

Even if we are content to pass on that burden, we would also be cutting the amount of sunlight reaching plants on the surface, and presumably also changing its spectral composition. Perhaps the plants would take up less CO₂? And do we really want to live under a constant haze in the sky to keep us cool? Do a few scientists and policymakers have the right to impose this on all other life on the planet?

Another obvious objection is that the injected particles might provide a very efficient surface for ozone destruction, as polar stratospheric clouds already do every spring. It seems the engineers have not yet looked at this in any detail.

2.2.3 Giant Reflectors orbiting the earth

This idea is very simple, to put gigantic foil sheets up in orbit around the earth, again to reflect sunlight. They would periodically cast a shadow, intercepting incoming light about 1% of the time, and would be assembled in space because such things couldn't be launched from down here.

Such proposals, it seems, have kept many physicists amused, and the orbits of the various parasols, mirrors and "solar sails" are spelled out in some details in Fogg's "Terraforming" book (Fogg 1995, pp 173-182). None seem very realistic yet, and they certainly wouldn't come cheap, but I guess the idea might be being promoted by those who fell by the wayside with the demise of the US Star Wars (Strategic Defence Initiative) programme. Recalling how so much money was spent on this, whose only result was to distract from the task of nuclear disarmament, I wouldn't be so surprised if they try to persuade another US president to take a personal fancy to such ideas. After all, it's more glamorous than some other fixes, for example, growing seaweed (below)! And politically much simpler to explain to an electorate than resisting the car-culture.

2.2.4 Other ways to reflect solar radiation

Solar radiation might also be deliberately reflected locally by altering the surface "albedo". There have even been rumours recently about "painting the deserts white", although I have not traced their source.

The effect of such schemes would probably be small compared to natural feedbacks which change in albedo in response to climate change. For instance, the northward movement of forests and reduction in snow cover in Siberia and Canada would be expected to cause increased absorption of sunlight. On the other hand simple climate models suggest that cloud cover is expected to increase, but these models do not yet take

into account seeding by sulphate aerosols. The latter may be partially provided by marine algae, and thus would be influenced by ocean fertilisation schemes (see below)

2.3 Climate engineering proposals involving removal of CO₂ from the air by enhancing natural sinks

2.3.1 Ocean sink proposals: general principles

Nobody denies that the deep ocean has an enormous capacity to store carbon dioxide. This is principally due to the high alkalinity of seawater, such that for every 100 molecules of CO₂ stored in it, roughly 98 of these are found as bicarbonate ions, 1 has been converted further to a carbonate ion, and only one remains as CO₂.

(for chemists: $\text{CO}_2 + \text{H}_2\text{O} \rightleftharpoons \text{HCO}_3^- + \text{H}^+ \rightleftharpoons \text{CO}_3^{2-} + 2\text{H}^+$)

Thus a little CO₂ in air (at 1 atmosphere pressure) can be in equilibrium with about 100 times more "total CO₂" in the equivalent volume of seawater.

The problem is that most of the ocean water is not in contact with the atmosphere. Transfer of CO₂ between the surface ocean and the deep ocean is slow, and occurs by two main processes: subduction of cold salty waters, particularly in the North Atlantic, and the biological "pump" whereby organic particles sink below the mixed surface layer. Only a small fraction of these particles eventually reach the sediment, the longest-term sink of carbon, but on the timescale of a thousand years or so removal to the deep water itself is sufficient. If this happened faster, the pulse of CO₂ in the atmosphere from fossil fuel burning would be much smaller, and thus the greenhouse warming less dramatic, although the long-term equilibrium climate change would be unaffected.

So climate engineers want to get CO₂ into the deep ocean faster. There are various proposals: CO₂ could be pumped there directly, soaked up by changing the alkalinity of the water, or absorbed into an enhanced biological pump by "fertilisation" of the ocean with nutrients. For a general review of enhancing ocean CO₂ sinks, see DeBaar (1992),

Surface seawater is also typically supersaturated with respect to calcium carbonate, and it might be expected that precipitation of this solid (directly, or into shells or corals etc.) would be a good way to remove CO₂ from the system. Paradoxically, it actually does the opposite, by decreasing the alkalinity. While ocean chemists have long understood this, it seems that some engineering consultants have yet to work it out, proposing, for example, to increase the growth of calcareous seaweeds. Governments who prefer to trust such private consultants may be wasting their money.

Another related effect of the seawater carbonate chemistry is often ignored by the engineers, as pointed out by Orr and Sarmiento (1992). For every ten units of CO₂ you remove from the surface ocean, about 9 are replaced from the vast pool of bicarbonate ions in the water, and only about 1 would be replaced from the atmosphere. So if, for instance, seaweed was used as a fuel, the main effect would be to shift CO₂ temporarily from the ocean to the atmosphere. It may be better than burning fossil fuel, but is not an efficient way to solve the problem!

2.3.2 Ocean fertilisation: general points

The principle nutrients limiting the growth of ocean algae are nitrate, phosphate, and in some places, iron (more on this below). To some extent we are already increasing the nutrient supply to coastal waters, through agricultural and sewage runoff. However, further from shore the nitrate and phosphate are supplied mainly by upwelling of deep water. Over much of the ocean, where warm surface water rests stably above cold deep water, the nutrient supply is poor and little grows.

So there have been many proposals to grow more algae by augmenting the nutrient supply. Not only might this enhance the biological carbon pump, but it might also provide a fuel or even food for fish.

On the other hand, our ability to predict the many feedbacks intrinsic to marine ecology is still very poor (for a summary see IPCC 1996 (e)). For instance, the important role of bacteria in recycling nutrients is just beginning to be uncovered. Plankton may also produce other gases which affect climate: notably nitrous oxide and methane which are much more potent greenhouse gases than CO₂, dimethyl sulphide which oxidises to form sulphate aerosols which seed clouds (see above), and also smaller quantities of hydrocarbons and halocarbons which affect atmospheric chemistry.

At least in surface waters you could easily measure some effects of a perturbation. However, once the surplus algae sank deeper, there is little consensus as to their fate. One concern is that the extra supply of organic carbon could use up all the oxygen in parts of the deep ocean. This might lead to the production of a lot of methane, or nitrous oxide. Fuhrman and Capone (1991) review some of these concerns.

Furthermore, there has been little consideration of the effect on any life in the sea bigger than algae. As a general rule, biodiversity in the sea decreases in highly productive algal blooms. And suppose we really could predict the effect on all the plankton, krill, fish, whales: how then would this help us make a decision whether to go ahead or not?

In any case, the science is very far from making such predictions. Consider, for example, the failure of the scientific management of fish stocks, or the poor understanding of toxic algal blooms. Marine ecology is a complex non-linear system that behave chaotically, with many surprises in store.

2.3.3 Early proposals: Seaweed.

Seaweed dominated the early ocean-algae climate engineering proposals. The idea was to set up kelp farms, eventually covering tens of thousands of square kilometres of the open ocean, originally with the intention of producing methane. In the 1970s \$20million of research was funded by the (then) American Gas Association, only to find that it would cost them 6 times more than the energy they would gain. The vast cost comes from the need to supply nitrate and phosphate to the surface ocean. Either you can add man-made chemicals, in amounts well exceeding the total world production of fertiliser, or use a lot

of energy to pump up nutrient rich water from the sea floor. It has also been pointed out (Orr and Sarmiento 1992) that such water is usually supersaturated in CO₂, which would then be released to the atmosphere...

Nevertheless, in the heat of the greenhouse effect and with Carbon taxes/credits in sight, the seaweed idea has been revived, mainly by the US Electric Power Research Institute. They say it would cost about \$200/tonne C sequestered. Engineers have devised grand schemes with diagrams showing the tracks of supertankers moving about the farms harvesting the seaweed. A more sensible review can be found in Ritschard (1992).

I have not yet found any mention of the potential effect on marine ecology. After all, it's not something we would expect electricity companies to investigate.

2.3.4 Recent nitrate/phosphate fertilisation proposals

Both the European Community and the Japanese have recently supported research investigating coastal fertilisation to increase both the biological carbon sink, and the supply of fish. Such projects have received much scorn from academic marine biologists, who say they are simplistic and may do far more harm than good, for instance encouraging jellyfish, anoxia or toxic algal blooms. (see Mackenzie 1996). Nevertheless they have found support due to commercial backing. Norsk Hydro (one of the world's biggest manufacturer of fertilisers, incidentally) wishes to add nitrate and phosphate to the Norwegian sea and is already experimenting in fjords. Meanwhile Mitsubishi is funding a similar proposal off Japan, claiming it might not only capture carbon dioxide, but also produce a lot of sardines (Matuo et al 1995)!

Others are more ambitious still. Jones (1996) calculates the nitrogen needed to soak up the entire projected anthropogenic global CO₂ emissions. He also claims to get 260 kilos of fish per tonne of nitrogen...

2.3.5 Iron Fertilisation of the Oceans

Of all climate engineering proposals, fertilisation of the Southern Ocean with iron has raised the most controversy. Perhaps this is because experiments designed to investigate whether iron is the key limiting nutrient are already underway and well publicised, with four papers appearing in one recent issue of nature (vol 383 no 6600), remarkable for any topic.

The idea has been around for about 7 years, and is credited to John Martin who first developed the clean laboratory techniques to measure how little iron there was dissolved in open seawater. The concentration is low because it falls out as a precipitate from alkaline seawater, so the only supply to the open ocean is atmospheric dust. This led him to suggest that iron might be the limiting nutrient, which would explain an old puzzle: Why, in the Southern Ocean and the Equatorial Pacific, is the algal growth much less than would be expected from the supply of nitrate and phosphate? If iron was the answer, as suggested by bottle incubations of the algae in these waters, it might also be a

feedback controlling ice ages. Atmospheric dust increases during glacial periods. This dust could fertilise the Southern Ocean and the algae would soak up enough CO₂ to reduce the greenhouse effect, enhancing the ice age.

This led to his famous quote at a conference, "give me half a tanker of Iron, and I'll give you an ice age". It was a joke. But once this idea was out, for the "biggest manipulation of nature ever attempted by man", it seemed inevitable that scientists would want to try it out, albeit on a small scale. The proposal briefly caught the attention of the US media, with portrayals of irresponsible mad scientists in white coats about to take over the world. It was feared especially that the possibility of a technofix to global warming would weaken resolve to reduce CO₂ emissions. To calm the uproar the scientists adopted a resolution, including "The American Society of Limnology and Oceanography urges all governments to regard the role of iron in marine productivity as an area for further research and not to consider iron fertilisation as a policy option that significantly changes the need to reduce emissions of CO₂". The story is summarised by Chisholm and Morel (1991) in the preface to a special issue of *Limnology and Oceanography* (36 no 8) on the topic.

However, the scientists were determined to continue research, on the grounds that we need to understand ice ages in order to predict future climate. Plans were hatched for the "first real experiment in oceanography" (i.e. you tinker with the ocean rather than just observe it), adding iron to a 80km² patch of the Pacific Ocean west of the Galapagos Islands. This was possible due to a new method using the gas sulphur hexafluoride to trace the patch. During the first experiment in 1993, the algae grew well but there seemed to be little effect on the CO₂ (Watson et al 1994). In the summer of 1995 the experiment was repeated with multiple iron additions and was much more "successful". In particular, there was a large decrease in CO₂ in the water (Cooper et al 1996) and the algae also produced a lot of Dimethyl Sulphide (Turner et al 1996) which might seed clouds over the ocean (see above) and thus have an additional cooling effect. The DMS cooling is very hard to quantify but might be considerably greater than the reduction in CO₂ greenhouse warming.

As it happens, models predict that the same amount of CO₂ would have been soaked up anyway, once this surface water of the equatorial Pacific, which doesn't mix well with deep water, moved to a region of higher iron supply and nitrate became limiting. This is not true, however, around Antarctica, where surface water is subducted down and the carbon removed from contact with the atmosphere. The key test would be to repeat the experiment in the Southern Ocean. The UK team, my colleagues here in UEA, are looking for funds to carry this out.

Prof Andy Watson does not rule out the possibility that this could one day lead to a climate engineering fix. "We are interested in the possibility that something as relatively simple as this could be used." But his model predicts that even a continuous widespread iron fertilisation could only reduce atmospheric CO₂ by 60ppm by 2100, a tenth of that needed to offset "Business-As-Usual" fossil fuel emissions. Peng and Broecker (1991) predicted a similar limitation.

On the other hand, one country (eg Australia) or even a multinational corporation might like to claim this 60ppm for their own credit, in a future world of carbon emission taxes or quotas (This is considered more in section 4.4.1). Iron Fertilisation is cheap, perhaps as low as 5\$ per tonne of Carbon fixed, compared to \$200 for many other proposed sinks. You need to add iron continuously, but not much. Aeroplanes could deliver dust, or rusting tankers or discarded oil rigs could produce it in situ. A more sophisticated approach might employ purpose-designed slow-release floating granules.

The prospect of the ecology of the Southern Ocean being traded off against national or corporate carbon emissions quotas in some crazy Cost-Benefit Analysis raises many ethical questions to which I will return later. But even putting that aside, the scientists are far from being able to predict the effect on that ecology, as already noted in the general points on ocean fertilisation (above).

It has been also suggested, that iron fertilisation could alter the dynamics of the Southern Ocean to increase the natural flux of Iron-rich water from depths to the surface, resulting in a runaway iron fertilisation. This physical feedback might be initiated by a decrease in sunlight penetration through the algae. So it is quite possible, that we could underestimate the feedbacks and go too far, creating another ice age after all...

It is not surprising that iron fertilisation has raised so much controversy. Of all climate engineering proposals, it is perhaps the easiest and cheapest to carry out, very elegant, and yet it carries the most unpredictable consequences. It also involves the pristine ocean around Antarctica, the part of the world least affected by our pollution so far. Experiments have already been "successful", and the organisers need to publicise the results to help secure more funding, for they have so far avoided commercial sponsorship and rely on research council funds. Perhaps because it is investigated openly by independent ocean scientists, the idea retains more credibility than it would if backed by industry. Some claim that we should push ahead with research, to ensure the results are open for the world to judge, before any commercial venture can get established. There is already an international race among oceanographers to get the money for the next experiment. But the Southern Ocean belongs to none of us, perhaps more rightly to whales, krill, penguins, algae, all life on earth. Respect for this seems to have been lost in the race to be first with clever science. On this kind of problem. Suppose they could design some new algae, that pumped CO₂ as efficiently as possible out of the surface ocean, was resistant to iron deficiency, or produced loads of dimethyl sulphide. They could then give them some special advantage over other species. Just release a few cells to the sea, sit back and watch the planet cool. But then how to stop it?

Genes are already identified for characteristics suitable for capturing CO₂ from power station flue gases in lakes of algae (more below). Presumably it's not so far from there to modifying typical marine algae. The Japanese fund "Research Initiatives for Innovative Technology for the Earth" (RITE 1994, see also below) already sponsors projects entitled "Gene Manipulation Reinforcement of the Carbon Fixation Capability of Photosynthetic Organisms", "Creation of Iron Deficiency-resistant Plants", and "Biological elimination of atmospheric CO₂ by enhanced pump activities and the SuperRuBisCO". The last of

these sounds particularly alarming, it's also worryingly close to my own field of work, regarding air-sea CO₂ exchange and the physiological response of algae to low CO₂, which I had thought was so harmless... I notice they have already identified the gene for this response (Fukuzawa 1995). Perhaps we can only hope, that over 4 billion years, all the successful kinds of marine algae have already evolved.

2.3.7 Liming the oceans.

Dissolving lime in the oceans is the opposite chemical process to the coccolith formation mentioned just above. Indeed, it has even been shown that you can combine coccolith cultures, waste concrete and seawater to fix atmospheric CO₂ (Takano and Matsunaga 1995)!

That works in the laboratory. But H Kheshgi of the Exxon Research and Engineering Company (Kheshgi, 1994) was more ambitious: He proposed increasing the alkalinity of the ocean surface mixed layer, by adding lime (CaO) in situ. The lime dissolves quickly, and would reduce the CO₂ in the water locally, pulling it in from the air. But to get this lime, you have to heat limestone (CaCO₃) with coal in kilns, driving off CO₂. This produces almost as much CO₂ as the seawater would take up (80%), except that you have it conveniently in one place, and perhaps it might be possible to store it compressed out of the way (see below). The whole process seems extremely inefficient. Soda ash (Na₂CO₃) could be used instead, but there isn't enough of it available.

To soak up as much CO₂ as we currently add to the atmosphere each year, you would need to start with about 30 billion tonnes of limestone, about ten times the rate it is currently mined. Imagine the scale of superquarries that would be dug for this purpose, they would dwarf those for roadbuilding, already facing intense opposition. On the other hand, once fully mixed into the ocean, the long term change would be almost negligible. But the lime could never be added evenly across the ocean surface, it would have to be added at a few localised points. There, it would surely have a dramatic effect on marine ecology. Or it might just reprecipitate (perhaps with the help of some coccolithophores...) before dispersing enough to affect much CO₂.

2.3.8 Greening the Deserts

People have always dreamed of greening the world's deserts. Their potential as a CO₂ sink as well as a food source has revived interest in such grand schemes. One such proposal from the Japan Gas Association and RITE (Ozawa et al 1995) includes generation of clouds by evapotranspiration from coastal mangroves and lagoons, and artificial mountains to promote rainfall, along with underground dams and new cities. They even provide an "artists impression" of this new landscape.

A slightly less ambitious scheme was proposed by Glenn (1992) at the US Electric Power Research Institute, using halophytes. These are plants, usually found in salt marshes, that thrive in saline conditions. The idea is that, perhaps with a bit of genetic engineering, they could be adapted to desert lands irrigated with seawater, or lake/river water that has

become too salty for any other purpose. Glenn estimated that world-wide there are 130million hectares of suitable land, and that this could sequester about 0.7 billion tonnes Carbon annually, at a cost of about \$200/tonne. It is suggested that some of the crop could be ploughed back into the "soil", the rest could be buried dry. He also recommends a particular oilseed crop, that is edible, tasty, nutritious, and could also be a fuel. The main problem is that you need a lot of excess irrigation to leach out the salts that would otherwise build up. Presumably you also leach out nutrients at the same time, so where do you replace them from? This question is not addressed.

Some other obvious points seem to have been overlooked. If you make the desert wet (or even just grow trees on it), it becomes darker, thus absorbing considerably more sunlight and warming the planet. There would also be very high evaporation, and water vapour itself is a greenhouse gas. On the other hand, if more clouds formed as a result, they reflect sunlight. We should also recall, that rice paddy fields are a very large source of methane, and these salt marshes might be likewise.

However, this idea may get further support. For instance, if transferable carbon taxes/credits are introduced, the oil producing states, most of which are in desert regions, might like to gain some carbon credit. Will they try to green the oilfields?

2.3.9 Planting trees

There are plenty of good reasons to plant trees, and carbon storage is but one of them. A review of the issues can be found in Marland (1992). I will not dwell long on this topic, partly because it is too vast and already well known. Although reforestation might be considered climate engineering, it takes place within national boundaries rather than exploiting the "global commons", and also it can hardly be considered a new unknown technology! Trees can be planted by people locally and they know what to expect as a result.

However, there are a few common misconceptions. For instance, mature forest does not take up carbon, only young forest is a net sink. As the forest matures, it approaches equilibrium where growth equals decay. So this is only a long term solution, if you continually harvest the wood and then store it somehow. It has also been suggested that we fertilise existing forests to maximise carbon uptake, this would likewise provide only a temporary sink.

On the other hand, some grasslands or peat bogs in particular, can be a permanent sink for carbon, as more accumulates on top each year. Recent reports suggest that this carbon sink may be equal or greater in magnitude than the world's trees. Also, if a peat bog is dried out by planting trees, the previously anaerobic peat becomes accessible to soil micrororganisms, which release it as CO₂, or worse, as methane. So it is not always wise, from a climate perspective, to put trees where there were none recently before.

2.4 Proposals involving direct disposal of anthropogenic CO₂

2.4.1 Pumping liquid CO₂ into the bottom of the ocean.

Judging from the number of papers, I guess that far more research money has been poured into this topic than all of the others here put together. It attracts funding because a company could dispose of just its own CO₂, and thereby avoid taxes or emissions quotas. I'm not sure whether this strictly counts as "climate engineering". However, it is usually placed in comparison with the other proposals here, and discussed in the same journals. The deep ocean is also a "global commons" rather than the property of the company, and as such we all have a right to be concerned with its use. And this topic raises many of the same ethical and scientific dilemmas, as do the proposals above.

For general reviews see DeBaar (1992), Ormerod (1994), Kheshgi (1994b), Reimer (1996). For more detail see the conference proceedings in "Energy Conversion and Management" (1992,1993,1995,1996).

A lot of technology has been developed, to separate CO₂ from stack gases, on the assumption that this is the key to the pollution problem. But burning fossil fuel produces so much CO₂, that really the major problem is where to put it afterwards. As mentioned above, the deep ocean has an enormous capacity, and is the natural medium-term sink for carbon. Note that the best long-term sink is not in seawater, but fixed by photosynthesis back into the oil and coal from which it came. Unfortunately these take millions of years to form.

The gas would first have to be liquefied, and then pumped down pipelines (for which the technology doesn't exist yet) to below 1500m depth (for environmental reasons -see below). It would then mix with seawater, forming a very acidic plume which would spread out across the sea floor.

Originally it was thought 3000m was necessary, because above this height the pressure is insufficient to keep the CO₂ as a liquid. However, various groups then claimed shallow injection was possible (e.g. Drange and Haugan 1992) because, so long as you could get enough CO₂ to dissolve before the bubbles rose to the air, then the resulting dense CO₂ solution in seawater would sink naturally. They looked for sites where ocean currents already descended continental slopes.

A complicating factor is that when concentrated CO₂ and water are mixed, they react to form solid compounds known as clathrates. In trial experiments, the clathrates blocked the end of the CO₂ pipe. A lot of research then followed on this topic. Indeed, it has been proposed that the clathrates may be useful, because they sink rapidly, so this helps to solve the depth problem. The Japanese are particularly keen on the idea of deliberate clathrate formation.

I have read some amusing paragraphs from these engineers, tagged on at the end of the papers to show some environmental concern. They are worried primarily about the fish being confused by all these rising bubbles and falling clathrate particles, perhaps trying to eat them, perhaps becoming psychologically disturbed! We are assured that they are

looking into this problem, but it would only be confined to a small local area around the end of the pipe. Well, maybe so. But there are far more worrying implications, both to the regional and global environment.

CO₂ is an acidic gas, and the liquid CO₂/seawater mixture would be highly acidic. It could therefore kill most marine life, perhaps over a large area of the sea floor. Usually the chemistry of the benthic environment changes very little, so even a small perturbation may have disastrous effects (for pH tolerance see IEA 1996). Perhaps the engineers view the deep sea as worthless mud with a few worms in it. However, marine ecologists have recently estimated that there are so many different species of benthic organisms, that the biodiversity is comparable to the tropical rainforests. We just don't know much about it yet. Again, does this give us a right to destroy such life to satisfy our thirst for burning oil?

Finally a few of these questions are being considered, for instance in a paper from MIT (Auerbach et al 1996) or at an International Energy Agency Workshop on environmental impacts (IEA 1996). The marine biologists came up with some fairly restrictive criteria, such as "no species should be driven to extinction" and "no significant destruction of ecological processes at basin scales", for which there must be no acidic strata which could form a barrier to migration. To be sure of that, and to protect diversity of shelf slopes, CO₂ should be released below 1500m. On the other hand, a pure "CO₂ lake" sitting on the sea bed (it's denser than water) would be disastrous for life in the sediment.

Harrison et al (1995) also raise an additional concern: they suggest that the high concentration of CO₂ in the seawater would reduce its capacity to hold other gases, particularly oxygen, and therefore the bottom water might become anoxic. Methane could then form, although they assert it wouldn't rise to the sea surface.

But how can we be sure that the CO₂-rich water will not return to the surface? Deep ocean currents do change over time, sometimes suddenly, rarely predictably, depending on finely balanced physics. Or instead of upwelling slowly to the surface, the CO₂-rich water might become unstable while the CO₂ is still concentrated, rising suddenly as plumes of gas. Methane does this occasionally from the sea bed, indeed, there is a theory that this may account for the mysterious loss of ships in the "Bermuda triangle", which would sink in the froth. And only last year, we may recall the natural disaster of lake Nyos in Cameroon, where a plume of CO₂ that suddenly bubbled up from the bottom, asphyxiated all humans and animals within a few miles of the lake. This CO₂ had been accumulating from quiet volcanic activity in the rocks, but so far nobody can explain why it suddenly destabilised when it did. Pumping liquid CO₂ to the bottom of the sea, could lead to similar disasters; until we understand what triggers them, we cannot deny the possibility.

If that CO₂ that we had stored over several decades, suddenly came back up and into the atmosphere in just a year or two, the effect on the global climate could be catastrophic. For a sudden pulse of CO₂ could cause enough warming, to trigger climate feedback

processes that lead to a runaway greenhouse effect. It would have been much better to have put the CO₂ into the atmosphere, year by year as it was produced.

It also takes a lot of energy to pump anything down to such a pressure under the ocean, and you have to burn a lot more fossil fuel to make this extra energy, so this process is extremely inefficient. There seems to be some disagreement in the literature as to exactly how much more energy is needed, but it is at least 30-40% extra. Part of the confusion arises because both CO₂ "capture" from flue gases (essentially an entropy problem) and CO₂ "disposal" (transport, pressurising) cost energy, but where one stops and the other begins is arbitrary. Also, the costs are much higher for conventional power stations than for new ones purpose-designed for CO₂ capture. The overview by Ormerod (1994) helps to clarify this. The IEA (Riener 1996) asserts that capture is considerably more costly than disposal.

Not only is all this expensive to the consumer, but in the long term it also makes the problem worse, because to get that extra energy you have to burn more fossil fuel... So you end up disposing more CO₂ (eg 40%) into the deep ocean than you would have put into the atmosphere if it had gone up in smoke as at present. Over hundreds of years through ocean circulation and diffusion, the CO₂, including that "extra" CO₂, will find its way back into equilibrium with the atmosphere. The graphs by Kheshgi (1994b) illustrate this problem well. Effectively this is putting an extra burden on future generations in order to avoid a problem now. This is an issue of intergenerational equity, which wouldn't usually be noticed in any cost-benefit analyses because the future is so rapidly discounted.

Bacastow and Dewey (1996) also point out that as the global climate warms and CO₂ increases in the atmosphere, the deep ocean's buffering capacity for CO₂ uptake decreases, and so deep ocean disposal becomes a less favourable option.

Despite all these technical and environmental problems, each year there are more papers on this topic. They want to conduct a small scale experiment soon, so there will be another IEA workshop to plan this and choose a site. It is proposed that the trace gas sulphur hexafluoride, which is a greenhouse gas 25000 times more potent than CO₂, will be released alongside the CO₂, to track the fate of the dense high-CO₂ water (VanScoy 1996). A five year experiment in a fjord (a relatively closed system) has also been proposed to investigate the effect on benthic biology.

After all, the sponsors will want a return for their money. These include British Coal, the Dutch government, the US Electric Power Research Institute and Department of Energy, Statoil, Exxon, Norsk Hydro, the Japanese Electric Power Research Institute, Tokyo Electric Power Company, Mitsubishi, and the Japanese Ministry of International Trade and Industry through NEDO and RITE (more later).

2.4.2 Storing CO₂ under the rocks

Although the ocean is a much bigger sink, some CO₂ might be stored more easily and reliably (?) underground, in aquifers or depleted oil and gas wells. Indeed, such projects are already underway, both in Texas and below the North Sea from a Norwegian platform.

This CO₂ currently being pumped back underground was not captured from power station flue gas: without carbon emission taxes or quotas this process is still too expensive for large-scale operation. It comes from under the rocks in the first place, mixed with the oil and gas deposits. Gas from the Sleipner Vest gas field off Norway contains 9.5% CO₂, most of which has to be separated from the methane before it can be sold. The recent introduction of a carbon tax (180\$/t C) in Norway encouraged Statoil to set up an installation to pump the CO₂ (about one million tonnes a year) into a sandstone aquifer 1000m under the platform (see IPCC 1996 (b) and European Chemical News 1996). This is seen as a pilot project, perhaps leading eventually to the burial of up to 1/3 of all Europe's CO₂ emissions. The paper by Haugen and Eider (1996) outlines the large-scale European proposals, whilst Pearce J.M. et al (1996) consider the lessons which can be learnt from the Texan "enhanced oil recovery" schemes. In such schemes the CO₂ is pumped into an oil well such that its pressure forces out more oil, preferably without the CO₂ and oil becoming mixed together, though this is not always straightforward.

To bury 1/3 of Europe's CO₂ emissions clearly requires much more than separation of the CO₂ initially mixed with natural gas. Yet to separate CO₂ from the flue gases of conventional power stations is very expensive and inefficient. Statoil envisages instead a "hydrogen" economy whereby the fuel is converted into CO₂ and H₂ rather than being oxidised completely in combustion (Kaarstad 1995). The hydrogen (note it's highly explosive!) would be used to power transport, whilst the CO₂ could be buried.

Perhaps the greatest danger with these schemes is that the pressurised CO₂ would not stay in the aquifers under the rocks. If CO₂ stored for several decades suddenly reemerged as a sudden pulse to the atmosphere, the resulting sudden greenhouse warming could be catastrophic. On the other hand, perhaps the rocks are slightly more secure than the deep ocean, for which the same applies?

Liquefying the CO₂ and pumping it down also requires a lot of energy so the process is once again inefficient, requiring considerably more CO₂ to be produced in the first place, as above for ocean storage.

Another concern is that the CO₂ could contaminate groundwater in nearby aquifers, making it acidic and unsuitable for many purposes.

Even if these concerns could be met, it is unlikely that enough suitable storage locations are available to remove a large fraction of world CO₂ emissions. However, there is now a very wide range of figures describing the available capacity, depending upon how secure you want the CO₂ to be. Some such figures are given in an IEA report (1996b page 18), and are of the order of 200Gt Carbon, compared to 750Gt in today's atmosphere. Note

that not much of this capacity will be conveniently situated near the sources of the CO₂. The largest site, for instance, may be below Indonesia.

2.4.3 CO₂ storage as dry ice

One amusing idea, is to store the CO₂ on site as giant insulated balls of dry ice. W Seifritz from Stuttgart has been looking into this (Seifritz 1993): he reckons 400m diameter spheres would be the easiest to keep cool. One such sphere would store enough for 6.4 GigaWatt-years of electricity production, although about 25% of that energy would have to be expended on freezing the CO₂ in the first place. These giant golf balls would be designed to leak slowly, rather than being kept cold for ever. That way, Seifritz argues, we can delay the release of CO₂ to the atmosphere, to emerge gradually over 800 years, and slowly find its own way into the ocean. By this time he expects the fossil fuel will have run out and we will have had to find more renewable sources of energy anyway. Will people in 800 years time thank him for this kind consideration?!

Rather than maintaining giant golf balls, Honjou and San (1995) propose shipping the CO₂ to Antarctica in tankers, and then storing it within the ice sheet. They suggest that by storing the CO₂ in certain locations in midwinter, it should be possible to get it to -78C without extra cooling. It would then be insulated in caves in the ice. This is clearly a ludicrous proposition, for the stored CO₂ would be a certain time-bomb if global warming did begin to melt, or even warm, the antarctic ice sheet...

Dry ice has also been proposed as an alternative method of deep ocean disposal. Murray et al (1996) suggest that "torpedos" of dry ice (heavier than water) could be dropped from the sea surface and would penetrate the sediment far enough that most of the CO₂ would react with porewater and be trapped as a solid, thus minimising the impact on the ocean water itself.

2.4.4 CO₂ fixation by in-situ lakes of algae

The most seriously considered idea, for on-site treatment of waste CO₂, brings us back to the algae again, but this time they would be in vast artificial lakes, covering tens of square kilometres for a medium-sized power station. It's really a form of solar power, which is why you need a large surface area, and uses photosynthesis to convert the CO₂ back into organic carbon. This might eventually be recycled as a fuel, chemical feedstock, or even food. They would be very strange algae, thriving on warm CO₂-rich stack gases bubbling through the acidic water. Various attempts are being made to culture and genetically engineer algae specifically for this purpose. They also need to be tolerant of sulphate, nitrate and other pollution from the fossil fuel combustion. It is reckoned that such frothing pea-soup reservoirs, would be four time more efficient than a tropical rainforest, at capturing solar energy. Maybe, but I know which I'd prefer to have outside my door!

There are many papers on this topic in the IEA conference proceedings (e.g. Brown 1996). Many of these are from projects sponsored by RITE.

2.5 Soaking up ozone-destroying chemicals, by adding more.

This proposal is not directly concerned with global warming, more with damage from the increased UV flux passing through holes in the ozone layer. On the other hand, stratospheric ozone destruction is intimately linked to climate change, both because ozone is a greenhouse gas, and because surface warming results in stratospheric cooling and therefore more polar stratospheric clouds which provide the surface for ozone-destroying chemistry.

The destruction of ozone is catalysed by free radicals of chlorine or nitrogen oxides, derived mainly from CFCs or aircraft exhaust respectively. The suggestion was (see Baum 1994), to add ethane or propane to the stratosphere to soak up the chlorine radicals, forming hydrochloric acid. About 50,000 tonnes would be needed in the Antarctic stratosphere each spring. However, to predict exactly what will happen, you have to solve simultaneously about 150 equations describing chemical reactions. Some simplifications have to be made, yet it isn't intuitive, which reactions will matter. Ralph Cicerone, who came up with this idea, found later that introducing a couple of new reactions, previously thought unimportant, changed the balance substantially. Now he is not so enthusiastic about the proposal. Perhaps we should be relieved!

2.6 And bringing life to Mars?

Despite the discovery this summer of what are claimed to be fossil bacteria from a Martian meteorite, it is generally accepted that the surface of Mars today is not hospitable. James Lovelock first noted that the chemistry of Mars' atmosphere, unlike our own, was in chemical equilibrium, and thus told his colleagues in NASA that the planet must be dead before any probe was sent there (the story is told in "The Ages of Gaia", Lovelock 1988). Lovelock went on to propose suggestions for bringing Mars to life, by first creating CFCs using energy from nuclear reactors, and by the resultant greenhouse effect melting the icecaps which contain water and frozen CO₂. More subtle manipulation would follow, and eventually seeding by algae and bacteria.

Lovelock did not expect that his proposal would be taken seriously, but many academics were inspired to develop it further, and even to extend the idea to other planets. Martyn Fogg's book on "Terraforming" (Fogg 1994) spells out the various proposals in meticulous detail, for example explaining equations describing the physics of parasols in space or even of shifting planet's orbits. There is also a substantive chapter on engineering the climate on earth. Fogg also notes various ethical concerns about terraforming, but these are somewhat lost in the overall mood of technological optimism.

Whether or not we feel we have the right to take over another planet, we would almost certainly make blunders. Consider, for instance, the escape of hydrogen. Mars' gravity is less than Earth's and its atmosphere thin and with little oxygen. Sunlight can split water molecules, and in such conditions the light hydrogen could easily be lost to space. After melting the oceans, we could then lose them forever. Or what if the nuclear explosions

made the planet too radioactive for any advanced life to survive? Or if there still survives the remains of life from long ago, which we unwittingly destroy?

In any case, it's a long way off yet, and most people would say, that we have far more important things to worry about down here on Earth.

Part 3: Who sponsors climate engineering proposals?

3.1. Industrial sponsors and consultants

The funders of research are usually indicated either at the beginning or end of a paper. Before reading such small print I had the impression that climate engineering was primarily the domain of a few eccentric academics. It is no longer so. Such professors may receive most publicity, but I was concerned to find most climate engineering research is now funded by industry, particularly those with a vested interest in continued high consumption of fossil fuels. In addition to direct sponsorship, there are many projects funded by government supported institutes set up for industrial research and development.

The table below is given only for purposes of illustration: there are many more sponsors involved and each is likely to back a range of proposals.

Sponsor	Example proposal
Statoil	CO2 storage in aquifers
Norsk Hydro	Ocean Fertilisation, CO2 disposal
Exxon	Liming the Ocean
British Coal	CO2 capture and disposal
Mitsubishi	Ocean Fertilisation to grow fish
Hitachi	CO2 fixation (through RITE)
Japan Gas Association	Greening Deserts
Japan Central Research Institute of Electric Power Industry	CO2 capture, ocean fertilisation
American Gas Association	Seaweed
RWE and DMT (Germany)	Sponsors of IEA
International Energy Agency	Overviews of many projects, see below
US Electric Power Research Institute	Many projects, see below
Research Institute for Innovative Technology for the Earth	Many projects, see below

I have not included here the many private engineering consultancies which have been hired to investigate proposals. Sometimes it is clear that they have little experience in global biogeochemistry, and make blatant errors or just discover what is already textbook knowledge to academics. However, it seems that certain governments trust such consultancies more than their own universities or research labs...

I also observed that most of the independent academics who submit papers describing direct climate engineering applications come from departments or institutes specialising not in environmental or earth sciences, ecology, meteorology or oceanography, but rather in chemical engineering, biotechnology, or industrial technology.

3.2 The IEA Greenhouse Gas R&D Programme

In 1991 the International Energy Agency set up a Greenhouse Gas Research and Development Programme, for the purpose of collating and directing research into technical responses to climate change. The programme has its headquarters in Cheltenham, UK, on a site provided by British Coal which also has research labs there dedicated to CO₂ disposal. The IEA programme is funded mostly by governments, although these are encouraged to invite participation from industries within their country, and there are three direct industrial sponsors: RWT and DMT of Germany, and EPRI (below). The programme's income in 1995 was £721,000. This funds little detailed research directly, acting more to bring people together and summarise their results, most notably by setting up a series of conferences on CO₂ capture and disposal (the proceedings are published in various issues of Energy Conversion and Management). There is also a series of workshops underway on ocean storage of CO₂, expected to lead soon to the design of a small scale experiment.

Recently, it was decided to broaden the remit to include other greenhouse gases, for instance reducing methane emissions from natural gas flaring and leakage: generally this is a cheaper way to prevent the same greenhouse warming. Many publications are available from the programme, whose address and [web page](#) are given with the references

3.3 The Research Institute of Innovative Technology for the Earth (RITE)

RITE was set up in 1990 by the Japanese Ministry for International Trade and Industry (MITI), through the New Energy Development Organisation (NEDO). It is run from its own laboratory in Kyoto's Kansai Science City, and had 486 employees in 1995. There are three headquarters labs, for global systems analysis, for plant physiology, microbiology and genetics, and for chemical CO₂ fixation and catalysis. Additionally RITE supports international joint projects for which it publicly invites proposals. The total budget in 1995 was 60m US\$, and 500m US\$ was earmarked for the first 10-year projects. It should be noted that much of this is spent on developing environmentally friendly technology not linked directly to climate change. Nevertheless, 140m US\$ was earmarked for "Biological CO₂ fixation and utilization", and 70m US\$ for "CO₂ fixation in desert area using biological function".

Looking through the research projects, it seems that many of them are at the very detailed process level, far removed from the global environment. These are intended to develop commercial technological products for use at a local scale, not yet to manipulate the world's oceans or atmosphere. Some seem very sensible, for example reducing methane emissions from rice paddy fields, preventing acid rain in developing countries, or bio-recycling of waste water. Nevertheless the emphasis is very much on finding a technical fix to every problem, including climate change. "RITE recognise the urgency of accelerating progress in global environmental research, *which is still largely at the basic or 'idea' level* ." (my emphasis). It seems to imply that climate engineering is a necessary and inevitable successor to basic climate research. I am most concerned at RITE's focus on biotechnology, a fundamental research area being "improvement of catalytic functions of microbial CO₂-fixing enzymes", perhaps initially for capture of CO₂ from flue gases or to develop plants to green the deserts, but surely leading eventually to algae in the open ocean.

A colleague of mine suggested applying for RITE sponsorship of the next Iron Fertilisation experiment in the Southern Ocean, but the professors decided to avoid this, not wishing to promote the "technofix" implications of the experiment, and also concerned about the strings which might be attached.

For RITE does not intend to get nothing back for all this money. The grant application form states "Research findings may be presented at academic conferences etc. following the conditions prescribed by and upon the approval of RITE and NEDO, the commissioner of the programme. Intellectual property, such as inventions developed through the entrusted research, will be jointly owned by NEDO and the inventor." In other words, this technology "for the Earth" will be patented with the intention of making money for the organisation. RITE filed 86 patents in 1994.

Clearly the Japanese government (MITI) thinks there will be a large market for such technology. Moreover, they are keen to demonstrate it to the world. Japan has volunteered to host the 3rd Conference of the Parties of the UN Climate Convention, in Kyoto in December 1997, just next door to the headquarters of RITE.

An American summing up an IEA conference said "I assume the Japanese incentive, besides self interest and preservation, is also dedicated to the noble objective of world social order". Gaining a competitive advantage and intellectual property rights seem a more likely explanation.

Information about RITE and reports of its research projects can be obtained from the address given with the references.

3.4 US Electric Power Research Institute

EPRI was founded in 1973, and now has an annual research budget of £500m, funded by power and fossil fuel companies from all corners of the world. Most of this is spent on technology for generating and delivering electricity, however EPRI has also been

interested in climate engineering proposals for a long time. For instance, they supported much of the research on giant seaweed farms, and of course CO₂ capture and disposal. In 1991, EPRI hosted a conference on "geoengineering" jointly with the Scripps Institute of Oceanography. The review by Alpert (1992) of biospheric CO₂ sinks, with costs, came from EPRI, as did Glenn (1992)'s paper on greening the deserts.

Perhaps this long experience has shown EPRI that climate engineering alone is unlikely to save the fossil fuel industry from curbs on CO₂ emissions. In any case, the focus seems to have shifted, towards creating cost benefit analyses of climate change, which can be used to show that it isn't economic (from the US\$ point of view) to prevent the climate change in the first place. EPRI will spend 8m US\$ in 1997 on a new integrated cost-benefit analysis. It is also worth noting that EPRI was responsible for the controversial paper of Wigley, Richels and Edmonds (1996) advocating delaying a reduction in CO₂ emissions. The use of such analyses by the industry lobby in the climate negotiations is discussed later.

EPRI also employs many climate modellers to investigate uncertainties in global climate models. Whilst this work may be useful, it is explicit that the principal aim is not to save the world from global warming, but to avoid unnecessary regulatory burdens on the fossil fuel industry.

EPRI has a comprehensive [web site](#), the address is given with the references.

[Click here to continue to Part Four: Commentary on Impacts: Climate Science, Politics and Feedbacks](#)

[Click here to return to the beginning of the paper](#)
[Or here to return to Choose-Climate homepage](#)

Part 4. Commentary on Impacts: Climate Science, Politics and Feedbacks

4.1 History and future

It can be difficult to tell, reading papers related to climate engineering, whether the researchers themselves really take the proposals seriously. It is human nature to enjoy inventing crazy ideas, and so we should expect a few to appear from time to time. Of course, life on Mars perhaps excepted, the researchers have always pretended that these are serious proposals, because otherwise funding would dry up. There is always a sentence or two about making a responsible choice, and preserving options for the future.

However, in the early days, the authors could speculate freely, for they had little fear of the proposals becoming reality. Today in contrast, the dollars-per-tonne-Carbon ratio

must be carefully calculated relative to expected carbon taxes/credits. It seems, some of the sponsors have gone beyond the question, will we ever employ climate engineering, they are already choosing the cheapest scheme...

It was in the early 1970s, with the first wave of concern about greenhouse warming, that climate engineering schemes began to appear in the international academic literature. Before then, in the Soviet Union, various enormous engineering schemes were proposed to warm the Siberian tundra or irrigate their southern deserts, and in this tradition Budyko (1974) applied the idea to the world, proposing the stratospheric aerosol idea. Kellogg and Schneider (1974) even at this early stage foresaw many of the ethical objections. Marchetti (1977) coined the term "Geoengineering" and the subject slowly gained academic credibility in the US, perhaps culminating in the 1992 NAS report, by which time the Iron Fertilisation proposal was already well known.

These were academic studies, and the scale of such research is still relatively small. Most of the original ideas arose this way. But in these last five years, the scale of the research has expanded greatly, since industrial sponsorship is rapidly taking over as the driving force. And as the schemes become more realistic and the climate problem increasingly urgent, for there is little sign yet of decisive action from the politicians to curb emissions, I expect the funds to flow faster.

This could have three potentially disturbing impacts. Initially, it might seriously distort the science of global change. Following that, the prospect of a technical fix might distract politicians from the need to curb greenhouse gas emissions. Finally, in the worst case scenario, the proposals might actually be implemented. These impacts of climate engineering proposals are thus discussed in that order: the impact on climate science, the impact on climate politics, and the impact on the world's climate itself. I then ask whether such research should continue, and finally, what we might do to constrain it.

4.2 Will climate engineering sponsorship distort the science of global change?

It is now increasingly difficult to get a job in physics without working for the military, in plant biology without working for agribusiness giants, in chemistry without working for the chemical industry, or in medical research, without working for drug companies. Myself, I joined global change research, not because it was lucrative, but because I was inspired by the mysteries of the oceans, atmosphere, and how life controls our climate, and concerned that the balance of these systems was in grave danger from our pollution. But in this era of "wealth creation", such inspiration is no longer considered a valid driving force for science. We must all be seen to make money. Insecure young scientists may feel particularly that "beggars can't be choosers", and put their efforts into climate engineering. I already know colleagues drawn into this..

The "wealth creation" concept implies a marketable product. A healthy, beautiful, diverse planet belongs to nobody and cannot be sold, therefore there is little money to be made investigating it. The message that we should consume less fossil fuel cannot be sold. On

the other hand, industry can sell oil, coal, electricity, and then later the same companies can sell the technology - probably the price will have to be paid by future governments - to fix the problems they have caused: pipelines to the deep sea, rockets to the stratosphere, fertilisers for the ocean. This is also good for the national growth statistics: it is the classic story that if we make a mess and then have to clean it up, money changes hands twice so the economy seems to be booming and we are all working hard. However, we will not find the world a better place as a result! The technical fix is good for business and GNP figures, but not so good for the rest of us. The irony is summed up well by the title of another RITE project: "A study concerning Global Environmental Improvement through the development of air-pollution-philic plants" (plants which love pollution)!

And to make this money, the companies will have to file patents on their new technology. As noted above, RITE already has many patents. Can we envisage patents for controlling the oceans, algae, forests, deserts, stratosphere? There is already an enormous outcry against genetic engineering patents. Will we now have to pay royalties to live in a world with a stable climate, something which we used to take for granted in the preindustrial age?

With patents will also come secrecy. This is inefficient, encouraging duplication of work and propagation of stupid ideas. It is also dangerous, if we have no warning of proposals before they are actually tried out on our only planet. And many climate engineering schemes which might be beneficial for one community might be harmful to another, we all have a right to know and respond to what is planned.

Moreover it was apparent to me from reading many papers particularly on CO₂ disposal, that those coming from industrial labs or private consultants were more likely to be over-optimistic and to ignore existing knowledge. Their papers are a commercial product: if the conclusion were that the proposal is a stupid idea or that it has been thought of many times already, they would be less likely to get a new contract. So each year many more miraculous cures are announced.

It seems that governments who commission such research are sometimes ignorant of fundamental laws of thermodynamics. You cannot get something for nothing. If you convert fossil fuel to CO₂ to gain energy, you cannot convert that CO₂ back into fuel without putting back even more energy. Yet many resources are spent on clever methods to fix CO₂, the specialists conveniently ignoring the full cycle.

Political dogma can be responsible for trusting research to industry or consultants rather than academics, who are more likely to point out the stupid ideas. It can also lead to patronage, encouraging a system which is less open than that of the universities. The problem of climate change was discovered in universities and institutes driven by curiosity about how the world works. They now receive considerable funding to keep doing that, on the grounds that this is a vital field which cannot be driven by the search for commercial applications. But as more and more technofix proposals appear, will political dogma drive government money away from the "blue skies" climate research and towards so called "wealth creation"?

On the other hand, it could be argued that the academics already know what the problem is, and the difficulty is getting the message clearly to the rest of society. Perhaps bringing in the engineers and the industrial research labs is one step towards this. They will have to find out about the climate system, reinventing some wheels perhaps, but we all learn best by mistakes, even transnational corporations!

Also I am not suggesting, that for industry to control the purse strings, is necessarily more dangerous than direct funding by governments. Indeed, the reverse may even be so, for government programmes have become so short-sighted that industry may take a more responsible view of the medium term future. And we must remember, it is governments that fund military research, and supported the most ludicrous proposals such as star wars (SDI). In the "military-industrial complex" the division between government and private industry is often indistinct, as it is also in the fossil fuel and power industries.

The danger is for global change research to be sucked into a system dominated by the ethical values and methods of those with money and power. We must be most wary of the strings attached to funding, and of who chooses which projects get funded. Ideally, there should be a common global change research fund, into which industry can contribute, with no strings attached, no intellectual property rights, where all decisions are made openly. We would then see whether the fossil fuel giants are really so motivated to "save the earth". For they do not have a good record in the game of climate politics, as the next section shows.

4.3 The impact on Climate Politics

4.3.1 The current situation

In Geneva this July (1996) 1500 people gathered for two weeks, for the second Conference of the Parties of the UN Framework Convention on Climate Change. to advance the negotiations of the UN Climate Convention. As a participant, I can confirm that very little happened. They even failed to agree even the voting procedure. In the words of one delegate, "this conference continues to discuss the sex of angels".

It is not surprising: the diplomats all know that their countries' economic growth is intimately linked to fossil fuel consumption, yet for all countries to increase consumption to the levels enjoyed by the richest few today, would clearly lead to a global catastrophe. Preventing this will require an enormous redistribution of consumption. It is the biggest power struggle the world has known, with a very high price of failure. The diplomats are still only sounding out their opponents and digging in their position. Yet many of them feel powerless, for so much of the current conference agenda - Joint Implementation, Economic Efficiency - is not there primarily to aid a political solution and save small islands from drowning or the Sahel from becoming desert, but to placate the international business interests. The industry lobby were there in force, many under the banner of the "Global Climate Coalition". The GCC just a month earlier had organised a letter to the US President signed by the chief executives of many major US companies including the fossil fuel giants, effectively demanding that the US do nothing in the negotiations. They

were also behind a vicious campaign to challenge the integrity of the IPCC scientists and thus deny that climate change was real, and also disseminated misleading information to developing countries about the effect of emissions reductions on their export markets. In response the environmental lobbyists spent most of their effort, not into searching for long-term political solutions, but in attacking the blocking tactics of the businessmen.

And so the world's media was told a great breakthrough had been made when, in his official statement the US minister Timothy Wirth openly scorned the GCC, calling them "naysayers and special interest groups deliberately obfuscating the science...". So a small battle was won. The GCC is discredited and companies are now switching their allegiance, and large lobbying payments, to other organisations. Yet that was just the first battle. Having now conceded, many years after the scientific consensus, that Climate Change is a real problem, the industry lobby now seeks to delay any curb in emissions with the argument that it is cost effective, rallying around an paper coauthored by a climate modeller and economists from the US Electric Power Research Institute (Wigley, Richels and Edmonds 1996). Recall that EPRI were among the first to fund research into climate engineering schemes. The paper proposes that it might be cheaper to delay immediate cuts in CO₂ emissions, in order to gain wealth and technology first which could pay for more rapid cuts in emissions later, to achieve the same final concentration in the atmosphere.

This approach not only denies consumption to future generations whilst encouraging more at present, and increases the risk of "surprises" from climate feedbacks not included in Wigley's model, but it is also fundamentally based on the assumption that there will be technical fixes to this problem. That assumption encourages complacency and reduces the incentive to find a political agreement. So, as long as they can fool governments to believe they can develop technical fixes, the fossil fuel giants have an interest in sponsoring such research, regardless of whether it really works...

4.3.2 Cost Benefit Analyses: How much is life worth?

There are other academic papers which are seized upon by the industry lobby to justify delaying any curb of emissions. In particular, they love to quote the figures from Global Cost-Benefit Analyses (CBAs) of climate change calculated by economists such as David Pearce and William Nordhaus. In chapter 7 of IPCC working group 3's report (IPCC 1996f), Pearce confidently claimed that the figures for damage due to future climate change were all converging on a figure 1.5-2.0% of Gross World Product, remarkably similar to the previous chapter's figure for "mitigation costs". They claimed to have considered all damages, from trees and fish to storm damage, agriculture, human health and morbidity. Everything had to be given a value in US\$, and these figures were based on the principle of asking people's "Willingness To Pay" to preserve what would be lost. It was only by reading the small print on one page of the original analysis (Fankhauser 1995), that the fundamental assumptions behind the figures became clear. Arguing that people in rich countries are "willing to pay" more than in poor countries where life is cheap, the values for everything, from biodiversity to human life, were taken from OECD countries and then divided by 15 for calculating damages in the rest of the world. Given

that the actual damages will be much worse in the poor countries which lie where the world is already warmest and people are most vulnerable, it is not surprising that the total figure (as % of GWP) came out much lower than it would have been were all lives valued equally. Effectively the analysis said, climate change may drown many people in Bangladesh, but this will not have much impact on the global dollar economy.

A campaign to reject such analysis was led by the Global Commons Institute, who applied a range of value assumptions to the same original figures as Fankhauser used, and showed that the damage could lie anywhere from 0.5 to 200% of GWP ([Meyer and Cooper 1995](#)). By playing the economists' game, GCI thus demonstrated that CBA is a useless tool for global climate policy. At a meeting in Montreal shortly afterwards, the government delegates effectively ridiculed the analysis in the IPCC in the only way they were able, by agreeing a summary for policymakers which was very critical of Pearce's chapter itself. This ridiculous stalemate continued into the published report despite calls for total rejection, and the debate received much media attention. The story of "defending the value of life", including letters and press clippings, is told on GCI's web page (<http://www.gn.apc.org/gci/vol/vol.html>).

However, there are plenty of more economists willing to reinvent these absurd analyses. The International Energy Agency followed with another global climate CBA (IEA 1995), claiming it was both the most comprehensive to date, and that all life was valued equally, and yet still the total "damage" figure was even lower. This is simply because they took a high-tech low-emissions scenario in which the climate would actually change much less than in Fankhauser's "business as usual" analysis. However, this figure has been quoted by the business lobby out of context, arguing that it implies emissions reductions are unnecessary.

A closer view suggests that this was not the IEA's intention. Their CBA is actually examining the cost of implementing technical fixes, notably CO₂ capture and disposal, and even includes figures for environmental damage due to deep sea disposal, for example (a small fraction of the total cost). It is amazing that anybody can claim to know such figures. But most revealing is the implication of this trade off, between the damage from global warming and the damage from technical fixes to reduce that warming. It implies that fossil fuel consumption will be a "fait accompli", and so the only choice is between the warming or the technofix. It is sometimes pointed out for instance, that global warming is expected to reduce marine primary productivity by stratification which hinders nutrient supply (a positive feedback since the algae then soak up less CO₂), so there would be less life in the sea. And therefore they claim, marine ecology might benefit globally from CO₂ disposal or ocean fertilisation which reduces that warming, although it harms marine ecology locally.

This assumption, that our wasteful consumption is inevitable and so we have the right to decide on behalf of the algae and whales what is their least-worse option, remains incredible to those of us with respect for the rest of life on earth, who are not brainwashed by the dogma of economics which requires that everything be judged by its direct monetary utility to individual humans. Surely the first question is whether the fish and the

plankton are intrinsically more valuable than profligate human consumption of fossil fuels? Yet even that question will be seized upon by the economists. They say they can measure the value of everything by asking people's "willingness to pay". For instance, such figures for the value of biodiversity, extremely low, were included in Fankhauser's analysis. No doubt they will soon be asking North Americans, on the one hand how much they value driving their cars, and on the other how much they are "willing to pay" for the plankton, krill and fish of the southern ocean. I only wish somebody could ask the whales the same question!

Perhaps, before the whales, we should consider first asking the opinions of people in majority of the world, living in undeveloped rural communities, who have never actually been asked these "Willingness to Pay" questions (Jamieson 1996). It is assumed that they would not have much money to pay to avoid climate damage, yet why should they? Since they did not cause the problem, they might instead be asked how much they are "willing to accept" as compensation. But there is little hope that economists preparing a cost-benefit analysis of any technical fix, which will have different impacts on different regions (Schnieder 1996), will ask this question. It will just show how to maximise the world production of dollars, and people whose lives are worth few of these, count for little.

These global CBAs draw data from many studies, and the critical number, be it for a climate engineering scheme, a damage estimation, or a proposed carbon tax, is the ratio of dollars/tonne of Carbon (as CO₂). For example, Fankhauser's (1995) controversial figure for climate damages, in which life in poor countries is cheap, is equivalent to 20 \$/t. These \$/t figures have also crept into most papers on climate engineering proposals. Disposal in the ocean or aquifers ranges from 100-300\$/t (Ormerod 1994), whilst Iron Fertilisation was once given a figure of 5 \$/t and Penner (1993) thinks he can put coal dust into the stratosphere for as little as 0.001\$/t (to achieve cooling equivalent to removing the CO₂). The NAS report (1992) also contains such figures, but Schneider (1996) recalls that many members of the panel were unhappy that the topic is becoming dominated by such considerations.

4.3.3 Scientific or political solutions?

Academics may be unhappy, but politicians like to be told such simple costs. Schelling (1996) points out that, whether or not climate engineering is actually cheaper than reducing emissions by reducing consumption, it is administratively simpler and thus convenient for governments. He says "it will involve merely deciding what to do, how much to do, and who is to pay for it". This is considered greatly preferable to the alternative "Social Engineering" which would be required to reduce consumption.

Many natural scientists and engineers have such an attitude. They scorn the softer social sciences, and dismiss any attempt to make the world a better place by changing the structure of society. Technical solutions to a problem are seen as providing opportunities for people, whereas political solutions restrict them. Technology is seen as more reliable

than fuzzy and unmanageable political solutions. In the context of global climate change, the opposite may be nearer the truth, but such attitudes die hard.

And thus such scientists assert, there may never be any political solution, so we must develop the technical fixes just in case. Certainly, the lack of progress so far seems to support their case. But such an argument is a self-fulfilling prophecy. If the scientists offer to relieve the politicians of this difficult task, they will jump at the opportunity. Today's politicians need to be seen to be doing something, but they will not be held accountable if the scientists' promises prove false in twenty years time. And meanwhile, many scientists are happily employed investigating the details. The less scrupulous amongst them, may be pleased that there is little progress towards a political solution.

The problem is exacerbated by the specialisation of reductionist science. Individuals work on the details of their own field, trusts their methods and those of their colleagues, and assumes that it is not his or her own problem to check the assumptions or quality of research in another field. Everything within the peer-review system is accorded the same trust, and is considered "scientifically correct". Pearce, defending his cost-benefit analysis, claimed the argument was a choice between "scientific or political correctness". His CBA hid many value assumptions, which a paper on ocean chemistry would not. However, he hoped to appeal to his IPCC colleagues' faith in the system, claiming that the economists, like the natural scientists, were merely describing the world as it is, not as it should be. To say that life is cheap in poor countries is descriptive, a "scientific" observation, whereas to insist that all life should be given equal intrinsic value, is prescriptive, merely "politically correct". He says he was just doing the job that IPCC asked him to do. And some scientists find it easier to work with colleagues who just do their job, for that way the specialists do not interfere too much in each other's business. Specialists may feel particularly annoyed when outsiders try to place their work in context, for criticism of their underlying assumptions is misinterpreted as criticism of their expertise, and to suggest that there may be a more responsible alternative "political" solution to the problem, may threaten the status of the niche which they have dug for themselves.

So many scientists effectively discourage political solutions to climate change. Nevertheless, many people do not yet trust their technical fixes, nor the analyses which attempt to boil the problem down to one simple global average \$/t ratio. With different value assumptions and unquantifiable positive feedbacks, climate change becomes simply an issue of survival, for themselves and all life on earth. In this case the political solution becomes much clearer: it requires a large (ca 60%) reduction in global fossil fuel consumption, and to get all countries to agree to this, a gradual equitable redistribution of that consumption from industrialised countries to developing countries is inevitable. Detailed proposals of how this might be achieved within a protocol to the Climate Convention, have been drafted by the Global Commons Institute ([GCI 1996, also available on the web](#)), and are receiving much interest from delegates. GCI believe that a long term political solution is very achievable, if only climate change is seen clearly as an issue of equity and survival. However, just as equity has been hijacked by economists who talk about "burden sharing" in order to obscure the real distributional issue, so the

survival issue is now brought into question by scientists' research into climate engineering schemes. If such "experts" continue to provide such distractions, they may fulfill their prophesy by defeating the political will. Then it will be their turn to deliver the promises.

It should be noted, in contrast, that some of the more astute would-be climate engineers are actually pushing for a "flexible" political agreement, lobbying through fora such as the "Business Council for Sustainable Energy". The market for their "product" depends upon governments or industry having a financial incentive to reduce their CO₂ emissions into the atmosphere, or to increase their CO₂ sinks if these are included in the budget. This will not happen until a carbon tax or tradable emissions quota system is introduced. On the other hand, they do not want such a political solution too soon, for then real consumption cuts might be made before the new technology is ready. A medium-term political agreement would suit them best.

4.4 From proposal to reality

4.4.1 Who might carry out climate engineering?

In an interview following the publication of results from "Ironex 2", Andy Watson hypothesised that Australia might be the most likely country to support a large-scale iron-fertilisation of the Southern Ocean (Pearce F. 1996). He did not believe that the politicians would ever agree to a global solution, and noted that the predicted CO₂ drawdown would anyway be limited, perhaps too small to be worth the effort of international coordination. Australia is closest to the southern ocean, and academics there have said they are interested in the idea. On the other hand, this scenario did not provide a clear incentive for the Australian government, whose delegation at CoP 2 in Geneva, dominated by right-wing economists, stubbornly resisted any progress towards agreement. The hypothesis must assume that there has, after all, been an international agreement and some system of carbon emission quotas or taxes has been imposed globally, and thus Australia would try to claim the CO₂ credit for increasing the CO₂ sink. It also assumes, incredibly to me, that one country has the right to exploit the ecology of the entire Southern Ocean, one of the few remaining true global commons, and trade this off against its own consumption of fossil fuels. This extension of property rights is in itself a horrifying prospect.

Yet it may not end there. One problem with a global political agreement based on national emissions quotas, is how to allocate the emissions of international airlines and shipping ("bunker fuels") to any one country. Another argument against quotas is that they encourage "leakage", if transnational companies (TNCs) move their operations to where emissions are cheaper, rather than investing in cleaner technology. On the other hand, quotas can be allocated to gradually decrease inequity, whereas a flat-rate carbon tax hits the poorer countries hardest. GCI (1996) noted that the leakage and bunker fuel problem might be solved, if the TNCs were required to purchase (but not sell, to avoid speculation) emissions quotas for their own activities, from any government. In other words, TNCs would be included in a global emissions quota trading scheme.

If the TNCs were directly liable to purchase emissions quotas or pay a carbon tax, they also would have an incentive to claim credit for climate engineering schemes to pull CO₂ from the atmosphere. So we might envisage several TNCs rushing to claim their own share of the algae in the Southern Ocean. Not even the tiniest creatures in the remotest seas would be independent of the might of the company executives!

4.4.2 The momentum of research

Much of the discussion above has assumed that decisions about climate engineering would be taken by governments or even TNCs, and that even if they take little account of wisdom or justice, they would be based on some rational and impersonal economic or political logic. It is as if a climate engineering scheme would be sitting complete on a shelf, and the decision-makers could simply decide whether or not to pick it up. This ignores a very critical factor, the momentum of the research community itself.

Researchers who have spent many years on a project do not want to see it abandoned, they want to see whether it really works, and to work on it further. Institutions set up for the purpose need to justify maintaining their staff and overhead costs. The directors of programmes, who have spent so much effort grappling for funds by promising good results, do not want to have nothing to show to their sponsors. And the sponsors do not want to look foolish by admitting it was all a waste of money. So in all there is an enormous vested interest in carrying a project to completion.

There is much evidence that it was factors like these, rather than any rational strategic objective, that led to the tragic decision to drop the atomic bombs on Hiroshima and Nagasaki. Its development at Los Alamos brought together more bright scientists than ever before or since, many of them motivated by the urgency of the supposed race to produce a bomb before Nazi Germany. When the project was nearly complete and that objective revealed to be no longer necessary, many of the scientists wrote letters requesting that it never be used. But by then the momentum was too great. The middle men, generals between the government and the scientists, were particularly keen to demonstrate the power of their creation. The story of the personalities involved is meticulously described by Jungk (1956) in his book "Brighter Than a Thousand Suns".

Likewise, Jamieson (1996) refers to case studies from medical research, in which a community of researchers functions as an interest group promoting the technology that they are investigating, and he suggests that such momentum is likely to apply to climate engineering projects. Therefore, the decision to begin such a project increases the risk that it will be implemented even if unwarranted. For this reason he asserts "we should reject the idea that ethical and societal concerns are relevant only to decisions about development and not to decisions about research".

4.4.3 Feedbacks and surprises

Although the history of nuclear physics or genetic engineering may provide useful case studies for the transition from science to technology, beyond that we enter completely unknown territory. For unlike genetic engineering or military technology, climate and

ecological systems are inherently unpredictable. They are dominated by a web of non-linear feedback processes, which tends to lead to sudden chaotic changes between different stable states. For instance, warming the ocean increases stratification which decreases the nutrient supply to algae, which cool the planet by removing CO₂ and adding DMS to the atmosphere. The latter affects the condensation of clouds, notoriously difficult to model. On land, snow cover is reduced by a northward movement of the tree line, whilst methane may be released from warming permafrost or flooded coastal areas. There may be many feedbacks which we have not even considered. The failure of "Biosphere 2" provides such a warning. It is an enormous greenhouse in the desert, designed to be a closed self-regulating model of the earth (for results of the first two years, see Nelson et al 1994). Among other things, the system's collapse was due to a proliferation of ants which converted Oxygen to CO₂. Nobody had predicted that ants could become so significant! Even if we knew all the feedbacks, and could quantify them, to model the consequences of a perturbation to such a chaotic system is a very difficult task, and we are at very early stages. It will be a long time before such models could be used to reliably test climate engineering schemes.

And there is a danger that as our understanding of the feedbacks develops, it will lead to suggestions of more cheap, "elegant" climate engineering proposals, directly manipulating positive feedbacks to get a large response from a small initial effort. For example, the control of deep water formation in the Greenland Sea is currently of great interest, because the descending cold salty water drags behind it the Gulf Stream which warms Western Europe, and sediment records show that in the past this process has rapidly switched on or off, dramatically changing the climate in just a decade. It seems to be a chaotic bistable system, which is dependent on ice melting in the Greenland Sea, and also on freshwater from the St Lawrence river. Some time in the future, people might consider controlling the river flow or the ice albedo, to flip the system. Another physical bistable system, El Nino, affects the climate in the tropics all around the world. We are far from controlling it yet, but many people are striving to understand the critical trigger that causes an El Nino year. Where will we stop when we know?

Biological feedbacks are potentially even more powerful. I have already considered the possibility that a combination of genetic engineering and climate engineering might produce new ocean algae to cool the planet.

Most climate engineering schemes are less dramatic, and are often considered "reversible". But while it is true, that we could stop the initial action - e.g. putting iron into the southern ocean or dust into the stratosphere -, it is by no means certain that the response would cease too. The possibility of a runaway iron fertilisation has already been mentioned. Whether the proposed mechanism is correct or not, we do know that there must be positive feedbacks associated with cooling, since the ice ages began and ended very suddenly. Eventually it might be "reversible", but we might shiver for a long time whilst searching for a reverse positive feedback process to recreate the interglacial.

And even if a climate engineering scheme is truly reversible, this implies that it will not be long lasting. To offset the accumulated greenhouse gas warming, future generations

would have the burden of continuously engineering the climate to stay cool. The engineers have to face not only the problems of predicting biogeochemistry and dynamics, but also to get international cooperation and money to sustain it. Economists still assume that growth will continue for ever, and that we will always be able to develop more technology to cope with the legacy of the past. They do not include in their models the possibility of a collapse of world social order, and with it, the programmes to artificially cool an otherwise overheated planet.

James Lovelock's Gaia hypothesis observes that the planet is kept in a comfortable state for life, by simple darwinian selection between organisms which have some feedback effect on their local environment. But this process relies on the presence of a diversity of abundant species. If, through modern agriculture and fisheries, pollution, or perhaps climate engineering itself, we drastically reduce that diversity, then we reduce the planet's resilience to bounce back from a perturbation. In this case the task facing our own species would be much harder. He writes "I would sooner expect a goat to succeed as a gardener, than expect humans to become responsible stewards of the earth" (Lovelock, 1991). To force ourselves into a position where we have such a responsibility, where the World Bank has to rule the algae in the sea, because we were encouraged to be complacent by the possession of climate engineering options, would be like, to use another of Lovelock's analogies, running down our kidneys to the state where we have to be permanently attached to a dialysis machine. Steven Schneider (1996) similarly likens fossil fuel consumption to heroin addiction, and climate engineering to injections of the cheaper drug methadone to relieve the symptoms. He prefers to get slowly unhooked from the drug addiction.

4.5 So should this research continue?

Yet, continuing Lovelock's analogy, is it not wiser to have that dialysis machine available, just in case the kidneys, the global ecological feedback systems, do indeed collapse because humans are unable to limit our consumption at a sustainable level? This is the strongest case for continuing climate engineering research. If we cause a catastrophe by unintentional climate engineering (i.e. greenhouse gas emissions), our children will not thank us for failing to develop the technofix solution because it was considered ethically unacceptable or because it risks causing another catastrophe. The counter argument, already developed above, is that to develop technofix solutions just in case political solution might fail, will become a self-fulfilling prophesy. Likewise, it could be argued that continued research might both discredit stupid ideas, or instead propagate them, depending on the openness of the science.

There are many such pairs of arguments for and against continued research, most of which are not easily resolved, but have already been discussed in previous sections. Rather than develop them again here, I will simply list them in a table below. Similar arguments on related topics are also well developed in a series of essays appropriately entitled "Science for the Earth" (Wakeford 1995). The earth needs good science, but does it need the transition from that science to technology, as seems to be implicit in the title of the RITE?

Science of the Earth becomes Technology for the Earth?	
Should we encourage climate engineering research?	
Yes	No
non-linear feedback system	
Might avert catastrophe	Might cause catastrophe
Elegant solutions possible	May be terrible surprises
responsibility for future generations	
Useful tool	Terrible burden to maintain
Technology is capital asset	Encourage waste now
choice of climate	
Choice is always welcome	Who has right to choose?
Can optimise net benefit	Rich and powerful choose, poor ignored
Climate best for humans	Other species ignored
.	Climate warfare?
impact on climate science	
Wealth Creation"	Will distort the science
Good for economy and jobs	Unnecessary effort
Industry learns about climate	Patents, Secrecy, Inefficiency
More Private funding	Reduced public funding
Image: do something useful?	Public Mistrust
Foster research community	Unstoppable momentum
impact on climate politics	
Reduce the problem	Encourage complacency, reduce political will
Reduce speculation and silly ideas	Propogate and legitimise stupid ideas
Preferable to social engineering	Delays inevitable redistribution
knowledge is power	
Be clever	Be wise

It is the story of nearly all scientific endeavours, that knowledge brings power. Personally, I would prefer that we are wise before we are clever, questioning rather than automatically accepting the benefit of that knowledge. Research should not go ahead on any climate engineering proposal without prior public consultation and an open discussion of the specific ethical issues, including equity between peoples, and the impact on other species. I would also be much happier if industrial sponsorship was channeled through a common international fund. But most of all, we must raise the scientists' awareness of the dirty political game of climate politics, where any excuse to do nothing will be eagerly seized. Timing is critical: if disaster looms, develop the technical fix before it is too late, but do not invite that disaster by doing so too early. It is a tricky game of bluffing, which is unfamiliar to naive scientists in their specialist shells. We should not race into this game, it is not worth the risk.

Part 5. Where do we go from here?

5.1 Overview

It would in any case be futile for me to provide a simple answer to the question, should the research continue? Nobody has such power of censorship, and nor should we desire it. Instead, we might gather together friends and colleagues, to influence public opinion and the media, and to convince decision makers to consider the widest implications of what they are backing. One person may feel powerless to influence decisions, particularly because so many are taken by obscure committees behind closed doors. However, so long as a few people familiar with this research community are willing to bridge these gaps, not afraid to enter the dirty world of climate politics and research agendas, or to talk with politicians and media, then there are open fora in which to raise concerns, and innovative ways to get more people involved in the debate. A non-governmental organisation such as Scientists for Global Responsibility could provide a focus for such activities.

5.2 Climate Convention CoP 3 in Kyoto, and the IPCC

One key event will be the third Conference of the Parties of the UN Climate Convention in Kyoto, December 1997, at which governments are expected to agree some protocol to restrict CO₂ emissions. Nobody has high hopes of an effective long term agreement by then, but there will be great pressure to demonstrate that something is being done. At this point, delegates will no doubt be encouraged to visit RITE headquarters which is just adjacent, and see a dazzling array of technical fixes. Problem solved... It is critical that some people are there in Kyoto, ready to present the other side of the story, to raise some of the concerns raised above. I hope this paper will encourage the "environmental" NGOs to be prepared for this well in advance.

Meanwhile the Intergovernmental Panel on Climate Change will be producing new reports, although another comprehensive report is not expected for some years. The IPCC is now chaired by Bob Watson, a former US government climate policy advisor who has

recently been working in the World Bank, and the new agenda is becoming very dominated by "western" economists. Integrated assessment is the buzzword, in which cost-benefit analysis can be used to subtly incorporate the value assumptions of those with most dollars and power. Recently circulated "technical working papers" give a foretaste of this. Organisations such as EPRI and RITE may be asked to provide data on the costs of their proposals, and thus become closely involved with the IPCC. They will then want more attention given to climate engineering, probably several chapters, in which it is portrayed much more favourably than in the recent report (IPCC 1996a) which effectively ridicules most proposals.

If we fail to resist this transformation, if the IPCC is effectively hijacked by the economists and engineers of the high-consumption countries, it may be better to risk discrediting it and instead gathering around some alternative authoritative scientific report. Some of the key natural scientists themselves, who were lead authors of IPCC 1996 and earlier reports, may drop out of the process as it becomes infiltrated by the business lobby. One such professor told me of his intention to do this. If many follow suit, the IPCC would have no claim to represent world science, and other organisations such as the International Geosphere Biosphere Programme (independent of the UN system but backed by national science academies from many countries) might provide an alternative authority. Again, the environmental NGOs must be ready for this, not to dig themselves into a hole, as at present, from which they cannot be seen to criticise the IPCC.

5.3 The Antarctic Treaty and International Law

Bodansky (1996) considers whether climate engineering would actually be permitted under international law. It is, of course, too new to be specifically forbidden, but he considers that there are ways for governments to raise objections, and it would then be very hard to reach international agreement on such issues. In particular, any attempt to fertilise the Southern Ocean (south of 60 degrees) by adding Iron, would be subject to the Antarctic treaty, which has a mandatory procedure for resolving disputes. Any member government might thereby be able to delay even a preliminary experiment. If this happened, the scientists might be forced to wait for several years, and to consider ethical matters and public opinion before rushing ahead with the experiment. They could do this thoroughly, without fearing as at present that another research group might get there first. Concerned environmental NGOs might consider lobbying a friendly government to initiate this procedure.

On the other hand, the treaty might just be ignored. Determined governments are not afraid of international condemnation on isolated issues such as this. We should recall how France and China defied world opinion when conducting recent nuclear tests. Meanwhile the World Court had been asked by the UN General Assembly to advise whether the use of nuclear weapons could be legal, and this July delivered a verdict that it would not. But the nuclear states have little intention of heeding the Court's opinion. Nevertheless, it represents a swing of opinion and sets a hopeful precedent for legal restraint on climate engineering.

5.4 Common Research funding

Neither individual governments nor specific industries can be relied upon to support a balanced programme of global climate change research. Government sponsored research is biased towards impacts on the rich countries around 45 degrees north (where there is least warming), and industrially sponsored research is biased towards technical fixes which can be a commercial asset. Research into impacts on the poorest, equatorial countries dependent on traditional agriculture does not attract such funds. Nor does research on ways to reduce consumption, to break away from the crazy assumption that continued fossil fuel burning is inevitable and so can only treat the symptoms and not the cause of the problem.

To ensure that such issues receive a fair hearing, and that not all scientists are forced to work under the auspices of "wealth creation", a global climate research fund should be set up, with contributions from both governments and industry, but with no strings attached to the funders. A truly diverse international committee of academic scientists should allocate this money, to proposals sent in by independent researchers. Again, the IGBP might help to play such a role. Since there is no particular incentive to contribute to such a fund, an small international carbon tax, for example, might eventually be set up by the UN climate convention, specifically to collect money from both governments and multinationals for such research.

In addition to this, Jamieson (1996) proposes that new national and international laws could be passed requiring a certain percentage (eg 5%) of all money spent on climate engineering research to be earmarked for ethical considerations and consultation. This is already standard practice in medical research, and would force the scientists to think beyond their narrow speciality.

5.5 Consensus conferences

Consensus Conferences evolved in Denmark (Hansen et al 1992), and are designed to sample informed public opinion on controversial technical matters. A lay-panel of non-specialist members of the public are brought together for several days to hear and discuss the views of the "experts" whom the panel invites, and can question as much as it wishes. When the panel feels it understands the issues sufficiently, it delivers a verdict. The idea was recently imported to the UK, in a much publicised conference on plant biotechnology (Science Museum 1994). Although it was expensive, and some observers felt that the choice of "experts" was biased towards the biotechnology establishment, there was general enthusiasm about the method. Perhaps such a conference should be arranged for climate engineering.

5.6 Consumer pressure and boycotts

Multinational companies are not invulnerable to pressure from consumers, particularly when the protest concerns an optional activity such as climate engineering research, which they are being asked not to spend money on. Boycotts have also been effectively

used against a few governments. But in most cases the public's apathy is jolted only by really horrendous events. The terrible environmental destruction in Ogoniland, Nigeria, and the murder of those who tried to campaign to stop it, brought many first-time protestors out onto the streets. Shell seems slow to respond, but we should keep trying, for there is a less well-publicised facet to the issue. The gas flaring and leakage responsible for those scorched crops and pollution, also emits to the atmosphere 34 million tonnes of CO₂, and 12 million tonnes of methane each year, contributing more to the greenhouse effect than all the domestic heating in the UK, for example (figures from Nigerian scientists via the WWF, printed in the Independent November 1995). We should not be protesting about climate engineering, whilst ignoring such an enormous waste which could so easily be prevented, probably at less than zero net cost. The same probably applies to many grab and run oil operations in the crumbling infrastructure of Siberia. That would make another good target for such protest.

5.7 Question value assumptions

Section 4.3.2. told how GCI, a small group of friends with little money, could take on many prestigious economic institutions and win the "value of life" debate in the UN, by exposing to the world the fundamental values underlying the economists' analysis. Their sophisticated cost benefit analysis, with hundreds of equations and hundreds of thousands of pounds behind it, fell due to a few simple questions about its underlying assumptions. This should encourage us to keep asking those questions, and by doing so to revive our respect for the intrinsic value of life and our common sense. This, more than any technical fix from the "experts", will save the earth from climate disaster.

5.8 Notes of caution

One note of caution regarding the media: We should not create the impression that climate engineering is already the mainstream of global change research. The popular image of science is already biased towards irresponsible inventors who want to rule the world, and we don't need to add to this science fiction, while we are trying to prevent it from becoming reality. We still need to encourage people to support good responsible science, and beware that the media thrives more on controversy than on any intention to "save the world".

I will conclude where I began, with a gathering of "greens" motivated to "save the world", now suddenly concerned about the new prospect of climate engineering. Such potential "new luddites" should bear in mind that this prospect has not arisen primarily due to the overenthusiasm of oceanographers, meteorologists, and biogeochemists. We are already immersed in an enormous global experiment, which began in the industrial revolution, when people first began the large scale extraction of coal and oil. Luddites could lay the "blame" instead on geologists who discovered the oil, physicists who found by chance how to generate electricity, or engineers who invented steam engines, trains and cars. Given that we are already in this predicament, it is better that other scientists have now warned us how the ocean and atmosphere might respond. Green campaigners should concentrate not on criticising individual scientists, but on our "technofix" culture

and concept of "progress", and on key turning points where science becomes large-scale technology. For in this case we have only one Earth for the engineers to play with.

[Click here to continue to References, Addresses and Acknowledgements](#)

[Click here to return to the beginning of the paper](#)

[Or here to return to Choose-Climate homepage](#)

REFERENCES

Alpert S.B., Spencer D.F., Hidy G., 1992, "*Biospheric options for mitigating atmospheric carbon dioxide levels*", Energy Conversion and Management 33 no 5-8 pp729-736

Auerbach D., Herzog H., Adams E., Caulfield J., 1996, "*Environmental Impacts of CO2 release in the ocean*", DoE Topical Report, Energy Laboratory, Massachusetts Institute of Technology. Also summarised in IEA 1996 (below).

Bacastow R.B., Dewey R.K., 1996, "*Effectiveness of CO2 sequestration in the post industrial ocean*", in "*Ocean Storage of CO2, Workshop1, Ocean Circulation*", International Energy Agency Greenhouse Gas Research and Development Programme, Cheltenham, UK.

Baum, R, 1994, "*Researchers, other experts examine Climate Engineering issues*", Chemical and Engineering News 72, no10, pp26-27

Bodansky D., 1996, "*May we engineer the climate*", Climatic Change 33, no3, pp309-321

Brown L.M., 1996, "*Uptake of carbon dioxide from flue gas by microalgae*", Energy Conversion and Management 37, no6-8, pp1363-1367

Budyko M.I., 1974, "*Climate Changes*", translated from Russian, American Geophysical Union, Washington DC,.

Chisholm S.W., Morel M.M., (eds) 1991, Preface to special issue "*What Controls Phytoplankton Production in nutrient-rich areas of the open sea?*", also "*Resolution: Ocean Fertilisation and atmospheric carbon dioxide*", Limnology and Oceanography 36 no 8

Cooper D.J., Watson A.J., Nightingale P.D., 1996, "*Large decrease in ocean surface CO2 fugacity in response to in-situ iron fertilisation*", Nature 383, no 6600, pp511-513

DeBaar, H.J.W., 1992, "*Options for Enhancing the Storage of Carbon Dioxide in the Oceans -A Review*", Energy Conversion and Management, 33, no5-8, pp635-642

Dickinson, R.E., 1996, "*Climate Engineering: A review of aerosol approaches to changing the global energy balance*", Climatic Change 1996, 33, no3, pp279-290

Drange H., Haugan P.M., 1992, "*Sequestration of CO₂ in the deep ocean by shallow injection*", Nature 357, pp318-320

ECN 1996, "*Statoil to bury carbon dioxide in the North Sea*" European Chemical News 66 no1731, p20

Fankhauser S., 1995, "*Valuing Climate Change*", EarthScan, 120 Pentonville Road London

Fogg, M.J., 1994, "*Terraforming: Engineering Planetary Environments*", Society of Automotive Engineers, 400 Warrendale PA. (a) Chapter 4 "Planetary engineering on the Earth", (b) pp 490-495 of Chapter 9, "*Terraforming and environmental ethics*".

Fuhrman J.A., Capone D.G., "*Possible Biogeochemical consequences of Iron Fertilisation*", Limnology and Oceanography 36, no 8, pp1951-1959

Fukuzawa H., Uemura K., Ohyama K., 1995, "*Understanding and utilization of inorganic carbon concentrating mechanism to improve plant CO₂ fixation*", Energy Conversion and Management 36 no6-9 pp747-750

Glenn, E.P., Pitelka L.F., Olsen, M.W., 1992, "*The use of Halophytes to Sequester Carbon*", Water Air and Soil Pollution 64, pp251-263

Global Commons Institute 1996, "*Contraction and Convergence: Draft Proposals for a Climate Change Protocol*", available on the web (<http://www.gn.apc.org/gci/protweb.html>) or from GCI at 42 Windsor Road, London NW2 5DS, UK.

Hansen T., Danielsen O., Raun J., 1992, "*Technology assessment in Denmark - A briefing*"

Harrison W.J., Wendlandt R.F., Sloan E.D. 1995, "*Geochemical interactions resulting from Carbon Dioxide disposal on the sea floor*", Applied Geochemistry 10 no4, pp461-475

Haugen H.A., Eide L.I., 1996, "*CO₂ Capture and disposal - the realism of large scale scenarios*", Energy Conversion and Management 37 no6-8 pp1061-1066

Honjou T., San O.H., 1995, "*Huge CO₂ storage in Antarctic Ice Sheet*", Energy Conversion and Management 36 no6-9, pp501-504

International Energy Agency 1996a, "*Ocean Storage of Co2, Workshop 2, Environmental Impact*", IEA Greenhouse Gas Research and Development Programme.

International Energy Agency 1996b, "*Technical Responses to Climate Change*", IEA Greenhouse Gas Research and Development Programme

International Energy Agency 1995, "*Global Warming Damage and the benefits of mitigation*", IEA Greenhouse Gas Research and Development Programme

Intergovernmental Panel on Climate Change 1996 (Cambridge University Press):

(a) R.Leemans, "*Concepts for counterbalancing climate change*", in Working Group 2 Chapter 25 pp811-813

(b) Ishitani H., Johansson T.B., "*Decarbonisation of Fuels and Flue Gases*", in Working Group 2 Chapter 19 pp597-599

(c) Ishitani H, Johansson T.B., "*Low CO2-emitting Energy Supply Systems for the World*", in Working Group 2 Chapter 19 pp621-640

(d) Melillo J.M., Prentice I.C., Farquhar .G.D., Schulze E.D., Sala O.E., "*Terrestrial biotic responses to environmental change and feedbacks to climate*", Working Group 1 Chapter 9 pp445-481

(e) Denman K., Hofmann E., Marchant H., "*Marine biotic responses to environmental change and feedbacks to climate*", Working Group 1 Chapter 10, pp483-509

(f) Pearce D.W., Cline W.R., Achanta A.N., Fankhauser S., Pachauri R.K., Tol R.S.J., Vellinga P., "*The Social Costs of climate change: Greenhouse damage and the Benefits of control*", Working Group 3 Chapter 7

(g) Trenberth K.E., Houghton J.T., Meira-Filho L.G., "*The Climate System, an Overview*", Working Group 1 Chapter 1 pp55-64

Jamieson, D., 1996, "*Ethics and intentional climate change*", Climatic Change 33, no3, pp323-326

Jones I.S.F. 1996, "*Enhanced carbon-dioxide uptake by the world's oceans*", Energy Conversion and Management 37, no6-8 pp1049-1052

Jungk, R. 1956, "*Brighter than a Thousand Suns*", Penguin Books

Kaarstad O., 1995, "*Fossil Fuels and responses to global warming*", Energy Conversion and Management 36 no 6-9 pp869-872

- Kellogg W.W., Scheider S.H., 1974, "*Climate Stabilisation, for better or worse?*", Science 186, pp1163-1172
- Kheshgi, H.S., 1994a, "*Sequestering Atmospheric Carbon Dioxide by Increasing Ocean Alkalinity*", Energy 20, no9, pp915-922
- Kheshgi H.S., 1994b, "*The effectiveness of marine carbon dioxide disposal*", Energy 19 no9, pp967-974
- Lovelock, J.E., 1991 "*Gaia: The Practical Science of Planetary Medicine*" (concluding chapter), Gaia books, 66 Charlotte St, London W1
- Lovelock J.E. 1988 "*The Ages of Gaia*" Chapters 1 and 8 (The second home), Oxford UP
- Mackenzie, D., 1996, "*Norway's Fish Plan, a Recipe for Disaster*", New Scientist 149, p4.
- Marchetti C., 1977, "*On Geoengineering and the CO2 problem*", Climatic Change 1 no1, pp59-68
- Marland G., Marland S., 1992, "*Should we store carbon in trees?*", Water, Air and Soil Pollution 64 no1-2, pp181-196
- Matuo E., Fujiyoka Y., Takeuchi K., Ibaraki S., 1995, "*CO2 Fixation by promoting large-scale marine food production*", Energy Conversion and Management 36 no6-9, pp907-910
- Meyer A., Cooper T., 1995, "*A recalculation of the social costs of climate change*", Ecologist, Occasional Paper October 1995, [also available on the web \(http://www.gn.apc.org/gci/soccosts/soccosts.html\)](http://www.gn.apc.org/gci/soccosts/soccosts.html) or from the Global Commons Institute, 42 Windsor Road, London NW2 5DS UK
- Muir H., 1995, "*Striking back at lightning*", New Scientist (Feature) 148 no 1998, p27-31
- Murray, C.N., Visintini L., Henry B., 1996, "*Permanent storage of carbon-dioxide in the marine environment - the solid CO2 penetrator*", Energy Conversion and Management 37 no 6-8, pp1067-1072
- National Academy of Sciences 1992, "*Policy Implications of Greenhouse Warming: Mitigation, Adaptation and the Science Base*", National Academy Press, Washington DC
- Nelson M., Dempster W., Alvarezromo N., Maccallum T., 1994, "*Atmospheric dynamic and bioregenerative technologies in a soil-based ecological life-support system - Initial results from Biosphere 2*", Advances in Space Research 14 no 11, pp417-426

Ormerod W.G., Webster I.C., Audus H., Riemer P.W.F., 1994, "*An Overview of Large Scale CO₂ disposal options*", in "*Global Climate Change, Science Policy and Mitigation Strategies*", eds Malthai C.V., Stensland G., Ar WMA, Phoenix Arizona.

Orr J.C., Sarmiento J.L., 1992, "*Potential of Marine Macroalgae as a sink for CO₂: Constraints from a 3-D general circulation model of the Global Ocean*", *Water, Air and Soil Pollution* 64, pp405-421

Ozawa H., Okabayashi T., Komiyama H., Kaya Y., 1995, "*Research of arid land afforestation technologies for carbon dioxide fixation*", *Energy Conversion and Management* 36 no 6-9 pp911-914

Pearce F., 1996, "*Extra Iron makes blue deserts bloom*", *New Scientist* 152 no2051 p4

Pearce J.M., Holloway S., Wacker H., Nelis M.K, Rochelle C., Bateman K., 1996, "*Natural occurrences as analogues for the geological disposal of carbon dioxide*", *Energy Conversion and Management* 37 no 6-8, pp1123-1128

Peng T.H., Broecker W.S., 1991, "*Dynamic Limitations on the Antarctic Iron Fertilisation Strategy*", *Nature* 349, pp227-229

Penner, S.S., 1993, "*A low-cost no-regrets view of greenhouse gas emissions and global warming*", *Journal of Ocean Technology and Environmental Sciences* 3, no3-4, pp255-259

Penner S.S., Schneider A.M., Kennedy E.M., 1984, "*Active measures for reducing the global climatic impacts of escalating CO₂ concentrations*", *Acta Astronautica* 11 no 6, pp345-348

Porrit, J., 1996, "*Beware the quick fixes of nutty professors*", *Daily Telegraph* 19th October

Rangno A.L., Hobbs P.V. 1995, "*A new look at the Israeli cloud seeding experiments*", *Journal of Applied Meteorology* 34 no5 pp1169-1193

Riemer P. 1996, "*Greenhouse Gas mitigation technologies, an overview of the CO₂ capture, storage and future activities of the IEA Greenhouse gas R&D programme*", *Energy Conversion and Management* 37 no6-8, pp665-670

Research Institute for Innovative Technology for the Earth, 1995 Report (budget etc.), 1994 Research Report vol 2 (proposals). Available from RITE, 9-2 Kizugawadai, Kizuchicho, Soraku-gun, Kyoto, 619-02, Japan.

Ritschard, R.L., 1992, "*Marine Algae as a CO₂ sink*", *Water, Air and Soil Pollution* 64, pp289-303

Santer B.D., Taylor K.E., Wigley T.M.L., Johns T.C., Jones P.D., Karoly D.J., Mitchell J.F.B., Oort A.H., Penner J.E., Ramaswamy V., Schwarzkopf M.D., Stouffer R.J., Tett S., 1996, "*A Search for human influences on the thermal structure of the atmosphere*", Nature 382 no 6585 pp39-46

Schelling, T.C., 1996, "*The economic diplomacy of geoengineering*", Climatic Change 33, no 3, pp303-307

Schneider, S.H., 1996, "*Geoengineering, Could - or should - we do it?*", Climatic Change, 33, no3, p291-302

Science Museum 1994, "*UK National Consensus Conference on Plant Biotechnology - Final Report*", obtainable from the Science Museum, London SW7 2DD

Seifritz, W. 1993, "*The Terrestrial Storage of CO₂ Dry Ice*", Energy Conversion and Management 34, pp1121-1141

Stegen G., Cole K., 1995, "*Biogeochemical impacts of CO₂ storage in the ocean*", Energy Conversion and Management 36 no 6-9 pp497-500

Takano H., Matsunaga T., 1995, "*CO₂ fixation by artificial weathering of waste concrete and coccolithophorid algal cultures*", Energy Conversion and Management 36 no 6-9, pp697-700

Turner S.M., Nightingale P.D., Spokes L.J., Liddicoat M.I., Liss P.S., 1996, "*Increased Dimethyl Sulphide concentrations in seawater from in situ iron enrichment*", Nature 383 no6600, pp513-517

Wakeford T., Walters M. (eds), 1995, "*Science for the Earth - Can science make the world a better place?*" Wiley, Chichester, UK

Watson, A.J., Law, C.S., Van Scoy K.A, Millero, F.J., Yao, W., Friederich G.E., Liddicoat M.I., Wanninkhof R.H., Barber R.T., Coale, K.H., 1994, "*Minimal Effect of Iron Fertilisation on Sea-Surface Carbon Dioxide Concentrations*", Nature 371, pp143-145

Wigley T.M.L., Richels R., Edmonds J.A., 1996, "*Economic and environmental choices in the stabilization of atmospheric CO₂ concentrations*", Nature 379, no 6562, p240-243. See also recent news item, Nature 383 p657.

VanScoy K.A., "*Tracer Release experiments: Applications in ocean physics and chemistry experiments*", in "Ocean Storage of CO₂ Workshop 1, Ocean Circulation", International Energy Agency Greenhouse Gas Research and Development Programme, Cheltenham UK

Addresses and web pages:

Ben Matthews

email benjhm@benjhm.free-online.co.uk

Web (including other climate pages): www.benjhm.free-online.co.uk

US Electric Power Research Institute:

3412 Hillview Avenue, Palo Alto, CA 94303 -1395, USA

tel (415) 855 2000

<http://www.epri.com/mecca/>

<http://www.epri.com/eg/gcc/>

Global Commons Institute

42 Windsor Road, London NW2 5DS, UK

tel +44 (0) 181 451 0778, fax +44 (0) 181 830 2366

<http://www.gci.org.uk/>

International Energy Agency Greenhouse Gas R&D Programme:

CRE Group Ltd, Stoke Orchard, Cheltenham, Gloucestershire GL53 4RZ, UK

Fax +44 (0) 1242 680 758

<http://www.ieagreen.org.uk/>

Research Institute for Innovative Technology for the Earth:

9-2 Kizugawadai, Kizu-cho, Soraku-gun, Kyoto, 619-02, Japan.

Fax 0774 75 2314

Scientists for Global Responsibility

Unit 3, Down House, The Business Village, Broomhill Rd, London SW18 4JQ, UK

Tel +44 (0) 181 871 5075

<http://www.gn.apc.org/sgr/>

Japan Central Research Institute of Electric Power Industry

<http://criepi.denken.or.jp/RD/nenpo/>

United Nations Framework Convention on Climate Change

<http://www.unfccc.de/>

Acronyms

EPRI, GCI, IEA, RITE, SGR: see addresses above

CBA Cost Benefit Analysis,

GWP Gross World Product

IGBP International Geosphere Biosphere Programme

IPCC Intergovernmental Panel on Climate Change

NGO Non Governmental Organisation
TNC Trans National Corporation
NAS National Academy of Science (US)
NEDO New Energy Development Organisation (part of MITI)
MITI Ministry of International Trade and Industry, Japan
COP Conference of the Parties (of the United Nations Framework Convention on Climate Change)

Acknowledgements

I acknowledge especially the committee of SGR for encouraging me to complete this paper.

Debates here in UEA and the "Science for the Earth" meeting in Cambridge also helped to crystallise ideas.

In addition I acknowledge much inspiration from Aubrey Meyer, who introduced me to the game of climate politics, and Tom Wakeford who introduced me to SGR and the "new luddites".

I thank Peter Liss for supporting me here in UEA and allowing me the freedom to work both with the algae in the lab and occasionally with the delegates in the UN! Such diversity is essential if we are to see the wider context of our specialist science.

And thanks to all friends and colleagues who have helped me by reviewing earlier drafts of this paper and suggesting ideas.

[Click here to return to the beginning of the paper](#)

[Or here for Choose-Climate homepage](#)
