Engineering the Planet

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Humans transform their environment. While global-scale transformations are a recent consequence of industrial civilization, human transformation of nature is ancient. Some transformations are deliberate, such as the use of fire by aboriginal peoples who altered landscapes to suit their needs, or even the modern use of dams to create new lakes. Other transformations occur as an unintended side effect of resource use, such as the mass extinctions of indigenous fauna by early hunters in Australia and the Americas, or the more recent threat of climate change caused by our use of fossil energy.

While the scope of human impact is now global, we have yet to make a deliberate attempt to transform nature on a planetary scale. I call such transformation geoengineering (Keith 2000a). More precisely, I define geoengineering as intentional, large-scale manipulation of the environment. Both scale and intent are important. For an action to be geoengineering, environmental change must be the goal rather than a side effect, and the intent and effect of the manipulation must be large in scale. Two examples demonstrate the roles of scale and intent. First, consider intent without scale: Ornamental gardening is the intentional manipulation of the environment to suit human desires, yet it is not geoengineering because neither the intended nor realized effect is large-scale. Second, consider scale without intent: Climate change due to increasing CO_2 has a global effect, yet it is not geoengineering because it is a side effect of the combustion of fossil fuels to provide energy. Pollution, even pollution that alters the planet, is not engineering. It's just making a mess (Allenby 2000; Friedman 2000; Keith 2000b).

Manipulations need not be aimed at changing the environment, but rather may aim to maintain a desired environment against perturbations—either natural or anthropogenic. Indeed, the term has most commonly been applied to proposals to engineer climate, so as to counteract climate change caused by rising CO_2 concentrations. In this context, the primary focus of this essay, geoengineering implies a countervailing measure or a "technical fix"; an expedient solution that uses additional technology to counteract unwanted effects without eliminating their root cause.

In this essay I describe some of the tools that might be used to engineer the planet, and speculate about the ethics of their use. Before arguing the merits of geoengineering, I summarize some of the more important methods that have been proposed and show how geoengineering is woven into the history of debate about anthropogenic climate change.

Sun shades

If we decreased the amount of sunlight absorbed by the earth we might engineer a cooling effect sufficient to counterbalance the warming caused by CO_2. It might be possible to shield some sunlight by adding aerosols to the atmosphere, where they would scatter sunlight back into space and might also increase the lifetime and reflectivity of clouds (the average planetary reflectivity is called “albedo,” so such methods are often called albedo modification). Alternatively, it might be possible to engineer giant shields in space to scatter sunlight away from the planet. These are the oldest and best known geoengineering proposals so I will discuss them in some detail.

Like many other tools for geoengineering, the use of aerosols imitates natural phenomena. Aerosols injected into the stratosphere by large volcanoes can cause global cooling. The eruption of Mount Tambora in present day Indonesia, for example, was thought to have produced the “year without a summer” in 1816. Likewise, the 1991 eruption of Mount Pinatubo in the Philippines caused a readily detectible change in global temperatures. In the 1970s, when Budyko proposed injecting sulfate aerosols into the stratosphere, he called the process “artificial volcanoes” (Budyko 1982).

In addition to imitating natural processes, proposals for geoengineering the planet often employ methods that mimic or amplify existing human impacts. Combustion of fossil fuels, particularly coal, already creates great quantities of aerosols. Human activities have substantially increased the global aerosol burden, altered the lifetime and reflectivity of clouds, and so changed the amount of sunlight absorbed by the planet. Indeed, the cooling effect due to aerosols generated by industrial pollution currently offsets part of the warming caused by CO_2.

Geoengineering might therefore be seen as adding one pollutant—aerosols—to counteract the effect of another—CO_2. Like any technology, geoengineering will entail risks and side-effects. If reflective aerosols are injected into the stratosphere, for example, they will generate impacts such as ozone loss that may sensibly be called pollution. But, geoengineering is not in and of itself pollution. Intent matters. The political implications of geoengineering, the institutional coordination required to implement it, and the moral implications of so doing all differ radically from the generation of aerosol pollution as a byproduct of fuel combustion. Geoengineering may be ill-advised, the activity of geoengineering may generate pollution as a side-effect, but it is not simply a continuation of our long history of polluting the planet. Deliberate planetary engineering would be a new chapter in humanity’s relationship with the earth.

There is a surprisingly rich history of proposals to engineer the climate. As early as the 1960s, when modern knowledge of the CO_2-climate problem was in its infancy, there were suggestions that climate control using aerosols, or other methods to alter the earth's reflectivity, be used to offset the effects of rising CO_2 concentrations. Discussion of geoengineering is more than a passing aberration, it is deeply woven into the history of debate about CO_2 and climate. Consider, for example, "Restoring the Quality of Our Environment", delivered to US President Johnson in 1965 by the Presidential Science Advisory Committee, which was the first high-level government policy document to draw attention to the threat of CO_2-driven climate change. While the report's discussion of climate science is consistent with that found in similar reports today, the sole suggested response to the CO_2-climate problem is geoengineering, "The possibilities of deliberately bringing about countervailing climatic changes therefore need to be thoroughly explored". The report suggests modifying the albedo by dispersal of buoyant, reflective particles on the sea surface, concluding that "a 1% change in reflectivity might be brought about for about $500 million a year… Considering the extraordinary economic and human importance of climate, costs of this magnitude do not seem excessive" (PSAC 1965). The possibility of reducing fossil fuel use is not mentioned; a surprising fact which illustrates that our thinking about the appropriate tools for managing the climate problem is far less stable than is our understanding of the science.

Plans to modify the climate using space-based technology reflect an extreme confidence in human technological prowess. The most extravagant proposals date from the beginning of the space age. In Russia, where research on climate control was then a top priority, there were proposals in the 1950's to construct "Saturn rings" using metallic aerosols in the earth's orbit, that would supposedly have supplied heat and light to northern Russia, or would have shadowed equatorial regions to provide their inhabitants with the supposed benefits of a temperate climate.

The cost of injecting aerosols into the stratosphere was analyzed by the US National Academy of Sciences in 1992, they examined several delivery methods including high-altitude aircraft and naval guns, and found that annual costs of over $100 billion would be sufficient to produce a 1% reduction in effective insolation (average solar radiation) reaching the lower atmosphere. While this cost may sound high, it is roughly a factor of ten lower than the cost to achieve an equivalent reduction in climate change through reductions in CO_2 emissions[1]. Moreover, later analysis has shown that it is technically possible to design aerosols that are far more effective per unit mass at scattering light which could reduce costs by a factor of 10 to 1000 (Teller et al. 1997).

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[1] An atmospheric loading of ~10 g S offsets the effect of 1 t C, a S:C mass ratio of $1:10^5$ (NAS 1992; Crutzen 2006). The NAS estimated a 20 $/kg cost to place aerosols in the stratosphere using naval rifles. Assuming a one-century CO_2 lifetime with a CO_2 atmospheric fraction of 0.5 and a 2 year lifetime for stratospheric aerosols, and assuming that one can use elemental sulfur which is oxidized in the stratosphere, the undiscounted cost of offsetting CO_2 emissions is ~5 $/tC (current US dollars per metric ton of carbon). In comparison, the cost of making large reductions in emissions by use of low emission technologies is of order 100 $/tC or larger.

Using engineered high-scattering-efficiency aerosols, it is conceivable that the cost of climate engineering could be within reach of the world's richest individuals or private foundations. The deployment of such a system would herald a new era in planetary management. Any decision to deploy such a system would be, and should be, sufficiently controversial that its cost would be all but irrelevant in the ensuing debate.

The use of aerosols poses serious risks, including the alteration of atmospheric chemistry which might further deplete stratospheric ozone. The role of natural aerosols in forming the Antarctic ozone hole serves as a warning about the sensitivity of ozone concentrations to aerosols. However, Paul Crutzen (who received a Nobel Prize for work on stratospheric ozone) has argued that ozone depletion due to aerosol geoengineering might be acceptably small and could be made smaller still. While increasing CO_2 warms the lower atmosphere, it paradoxically cools the stratosphere which can lead to increased ozone depletion (Kirk-Davidoff et al 1999). Crutzen (2006) points out that if absorbing aerosols were used (black carbon in addition to sulfate), it would be possible to increase stratospheric temperatures, offsetting the current stratospheric cooling and partially or entirely offsetting the ozone depletion due to aerosol geoengineering.

While expensive, the use of space-based sunshields offers a "clean" alteration of the effective solar constant with side effects that would be both less significant and more predictable than for aerosol-based modification methods. Assuming that the shields were steerable, their effect could be eliminated at will. Additionally, steerable shields might be used to direct radiation at specific areas, offering the possibility of weather control. In recent decades, proposals have focused on space-based systems that would be located in stable orbits on a line between earth and the sun, well beyond the moon's orbit. Edward Teller and collaborators (Teller et al. 1997) have found that such a shield could be made with much lower mass than was previously thought, implying that costs could be dramatically reduced. While the costs of a space-based shield might approach a trillion dollars, the cost per-unit-of-mitigation would likely be less than many earth-based technologies; however, as with aerosols, costs are unlikely to be a deciding factor.

Regardless of how it is achieved, a reduction of solar input cannot perfectly compensate for CO_2-induced warming. If insolation could be arbitrarily adjusted, then one may assume that it could be adjusted so as to produce any desired globally-averaged surface temperature, such as the pre-industrial mean. This would not, however, necessarily reproduce pre-industrial climate due to changed vertical and latitudinal distributions of atmospheric heating. In addition, both the increase in CO_2 and the decrease in the apparent solar intensity might have significant effects on plant growth. A recent exploration of these effects with a climate model has shown that albedo geoengineering may nevertheless reproduce pre-industrial climate with reasonable fidelity (Govindasamy and Caldeira 2000). Even the impacts on the biotic productivity might be engineered. Lowell Wood has pointed out, for example, that one might cool the climate without reducing photosynthetic productivity if the alteration in albedo could be spectrally tailored to reduce insolation in areas of the spectrum that are not used by photosynthesis.

Controlling the weather

After the Second World War, successful demonstration of cloud seeding—the use of aerosols dispersed from aircraft to induce cloud formation and produce rain—brought modern technology to bear on the ancient dream of weather control. Buoyed by the technological optimism of that era, climate and weather control became a centerpiece of research in the atmospheric sciences during the 1950s and 1960s. Scientific understanding of the CO_2-climate problem emerged from a scientific community interested in climate and weather control. Indeed, the problems posed by CO_2 emissions—now called 'global warming' or 'anthropogenic climate change', were then described as 'inadvertent climate modification' to distinguish them from the deliberate climate modifications being contemplated.

Interest in weather control waned during the 1970s in concert with growing environmental consciousness and a skeptical backlash against the unbridled technological optimism of the postwar era. Cloud seeding, moreover, was found to be far less effective than was originally claimed.

The possibility of weather control remains. Just as growing knowledge of the role of aerosols in the atmosphere might enable more efficient and precise geoengineering, advances in the science of weather prediction are inadvertently producing tools that enable more effective weather control. The key tool is the development of specialized numerical models that are able to efficiently predict the impacts of small changes in the atmospheric state (temperatures, winds, etc) on the evolution of weather systems[2]. These tools are used in advanced weather prediction systems to estimate the effect of errors in current observations of atmospheric conditions on the accuracy of weather forecasts a few days later.

This ability might be used to build a system for weather control by exploiting a paradoxical feature of chaotic systems. We often assume that chaos makes systems hard to control. The hallmark of chaotic systems is their extreme sensitivity to initial conditions, the proverbial flapping of a butterfly's wings that alters the global weather. It is this sensitivity that makes it hard to predict the future state of a chaotic system, because errors in one's knowledge of the system's initial state are rapidly amplified. Sensitivity to initial conditions can, however, facilitate dynamic control or guidance of the system's evolution because small control inputs are subject to the same amplification. Given sufficiently accurate models and observations, it is possible to steer

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[2] So-called "tangent linear ajdoint models" enable one to efficiently run forecast models backwards in time, allowing computation of the perturbation in the initial state required to produce some specified perturbation in the final state some days later. The full model is not actually run backwards in time; instead a linearized model is generated that is valid only for small perturbations to the forward evolution of the atmospheric state.

the time evolution of chaotic systems with surprisingly small control inputs. Ross Hoffman and collaborators have shown, for example, that this strategy might be used to steer hurricanes (Hoffman 2004; Henderson et al. 2005).

If atmospheric models and measurements are the software of weather control, the hardware is the tools used to manipulate atmospheric conditions. At the simplest, manipulation of atmospheric conditions might be accomplished by perturbing the altitude or course of commercial aircraft, which already effect atmospheric heating by generating cirrus clouds. Alternatively, manipulation might be accomplished by cloud seeding, or most extravagantly, by the use of space-based systems that could direct solar infrared radiation to selectively heat the atmosphere or the surface. Better measurement of atmospheric conditions and better models of the global atmosphere together allow the use of smaller levers to achieve a given degree of weather control. Better software allows the use of less hardware.

The most obvious utility of weather control is the ability to minimize the impact of severe storms on human welfare; sustained and large-scale use of weather control is, however, a form of climate control. Like other means of geoengineering, such power might be used to alter the climate to suit human desires or counteract climatic changes arising from other causes.

Should we engineer the planet?

The post-war growth of the earth sciences has been fueled, in part, by a drive to quantify environmental insults in order to support arguments for their reduction, yet paradoxically the knowledge gained is increasingly granting us leverage that may be used to deliberately engineer environmental processes on a planetary scale. The manipulation of solar flux using stratospheric scatterers is perhaps the best example of this leverage: we could reduce solar input by several percent—likely sufficient to initiate an ice age—at an annual cost of less than 0.5% of global economic output. Alternatively, consider the possibility that improvements in weather prediction necessarily enable more effective weather control. In any case, our growing understanding of the dynamics of the earth system grants us ever increasing leverage that may be used to manipulate the system, even when research is motivated by the goal of understanding and minimizing human impacts (Figure 1).

How should we use our growing ability to engineer the planet? There is no immediate prospect that geoengineering will be employed as a tool for managing the CO_2-climate problem, but looking farther ahead the question is less easily answered. In my view, a crucial part of the answer turns on the ultimate objectives of climate policy. Why should we spend money to reduce climate change? What consequences concern us most? Is human welfare the sole consideration, or do we have a duty to protect natural systems independent of their utility to us?

To sharpen the issue, consider the use of space-based shields to offset global warming. Some have argued, in effect, that if such methods are the most cost effective way to deal with the risks of climate change, then they should be used in preference to a reduction in CO_2 emissions (mitigation). I reject that view, but there are conditions under which I might advocate geoengineering the albedo. Suppose that several decades hence real collective action is underway to reduce CO_2 emissions under a robust international agreement. Suppose further that the cost of mitigation, the climate's sensitivity to CO_2, or the sensitivity of natural systems to changed climate and increased CO_2 turn out to be higher than we now anticipate. Finally, suppose that because of the long lifetime of CO_2 in the atmosphere, even strong action to abate emissions is insufficient to protect the most sensitive natural ecosystems, such as the Arctic and Antarctic. Under such conditions, I might well support a temporary, albedo modification system designed to limit climate impacts during the period of peak CO_2 concentrations.

Figure 2 illustrates the distinction between geoengineering as a substitute for mitigation and geoengineering as a means to reduce the risks of climate change while mitigation is ongoing. If geoengineering was used as a substitute, as in the left panel of the figure, the scale of the engineered compensation for CO_2-driven warming would have to grow to offset growing CO_2 concentrations. The risks of unanticipated side effects would therefore grow without bound. Such a policy would be reckless. If geoengineering was instead used to reduce the risks of climate change during the period of peak CO_2 concentrations, it would (arguably) be justified if the additional risks of geoengineering were smaller than the risks of high CO_2 concentrations alone.

It is tempting to discount geoengineering because of the risk of unintended consequences. For example, Kiehl (2006) asserts that "A basic assumption to this approach [geoengineering] is that we, humans, understand the Earth system sufficiently to modify it and 'know' how the system will respond." If geoengineering is used temporarily to reduce impacts of peak CO_2 concentrations, however, then it is misleading to argue against it solely because of the impossibility of predicting the system's response. Consider the choice between enduring a period in which CO_2 concentrations exceed 600 ppm, and living with the same CO_2 concentration in conjunction with geoengineering that reduces insolation by 1%, as illustrated schematically in the right panel of Figure 2. It is impossible to predict exactly how the planet will respond to either case, yet it is plausible to argue that the risks of 600 ppm alone would be larger than the risks of experiencing the same concentrations with a little geoengineering to reduce peak temperatures.

Climate policy is often framed as a choice among various energy technologies and policy instruments. Beyond this choice of tools, however, lie hard choices about the objectives of planetary management. Should the planet be managed using all available tools so as to maximize human benefit, or should we seek to minimize human interference with nature? Advocates of active management argue that simple minimization of impacts is naive because the Earth is already so transformed by human actions that it is, in effect, a human artifact. According to this view, the proper goal of planetary management is the maximization of the planet's functionality to humans (Allenby 2000). A strategy of active management might freely employ a mixture of responses, including the reduction of CO_2 emissions, geoengineering and strategic adaptation to changing climate (Allenby 2000). Under this view, it makes little sense to minimize impacts in order to let nature run free if there is no free nature left to protect.

If human utility is our sole concern, then active management seems an appropriate strategy. We may sensibly argue against geoengineering because it is too risky, too expensive, or too uncertain; but if methods of planetary engineering are proposed that are demonstrably less risky and more cost-effective than alternative measures, then, under this interpretation, we should use them.

An alternative view of climate policy demands that we attribute intrinsic rights or values to natural systems independent of their utility. Under this view, we should minimize our impact on the natural world—for its own sake—not solely to reduce the risk that manipulation of natural systems poses for humanity. Accepting such rights does not require that they trump all others, humans have rights too, but attributing rights to nature does provide a basis for arguing that concerns other than pure human utility ought to enter into climate politics, and therefore that minimizing our impact on natural systems is a legitimate goal of climate policy.

Accepting minimization as a goal does not rule out geoengineering. What it does rule out is the use of geoengineering simply because it provides an expedient way of advancing human interests. The goal of minimization (arguably) allows the use of geoengineering as a temporary measure if it provides an efficient method of minimizing impacts on the natural world.

As a thought experiment, imagine that alien visitors arrive and give us technology for climate and weather control. For illustration, imagine a box with knobs that allow independent control of global temperature and CO_2 concentration. Any adjustment of the knobs would inevitably benefit some and harm others. We do not yet possess a system of global governance that would allow a robust, let alone democratic, decision about how to set the knobs. One might readily imagine conflict arising from disputes about how the knobs should be set. Absent a credible system of global governance, perhaps the only robust decision would be to return the knobs to their pre-industrial settings. That is, to minimize human influence rather than actively manipulating the planetary environment.

While an alien climate-control box is fiction, the ability to control nature on a planetary scale is not. Such powers are being gradually accumulated by the evolution of scientific knowledge and technologic ability. Unless a global war or other catastrophe should dramatically arrest or reverse technological progress, it seems inevitable that we will soon have such abilities.

Debate about deliberate modification of the global climate dates back at least a century. In 1908, Arrhenius, who was the first to analyze the role of CO_2 in regulating climate, suggested that warming resulting from fossil fuel combustion could increase food supply by allowing agriculture to extend northward. His contemporary, Eckhom, went further by suggesting that extra CO_2 could be injected into the atmosphere (by setting fire to shallow coal beds) to prevent the onset of ice ages and to enhance agricultural productivity via the fertilizing effect of CO_2. In the century since Arrhenius and Eckhom first considered these questions, our ability to manipulate the planet has grown in concert with knowledge of the global impacts of human activities. As remedies for the CO_2-climate problem, all proposed geoengineering schemes have serious flaws. Nevertheless, I judge it likely that this century will see serious debate about—and perhaps implementation of—deliberate planetary-scale engineering. Active planetary management may be an inevitable step in the evolution of a technological society, but I urge caution. We would be wise to practice walking before we try to run, to learn to minimize impacts before we try our hand at planetary engineering.

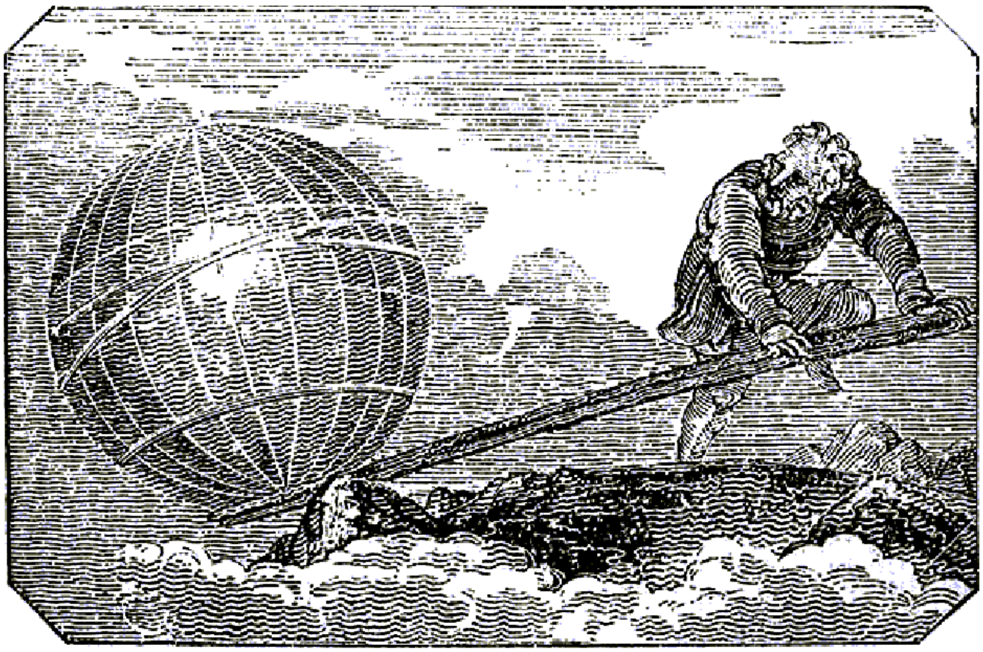

Figure 1. Scientific understanding grants us growing leverage that may be used to deliberately engineer environmental processes on a planetary scale. As Archimedes put it, “Give me but one firm spot on which to stand, and I will move the earth.” Engraving from Mechanics Magazine London, 1824.

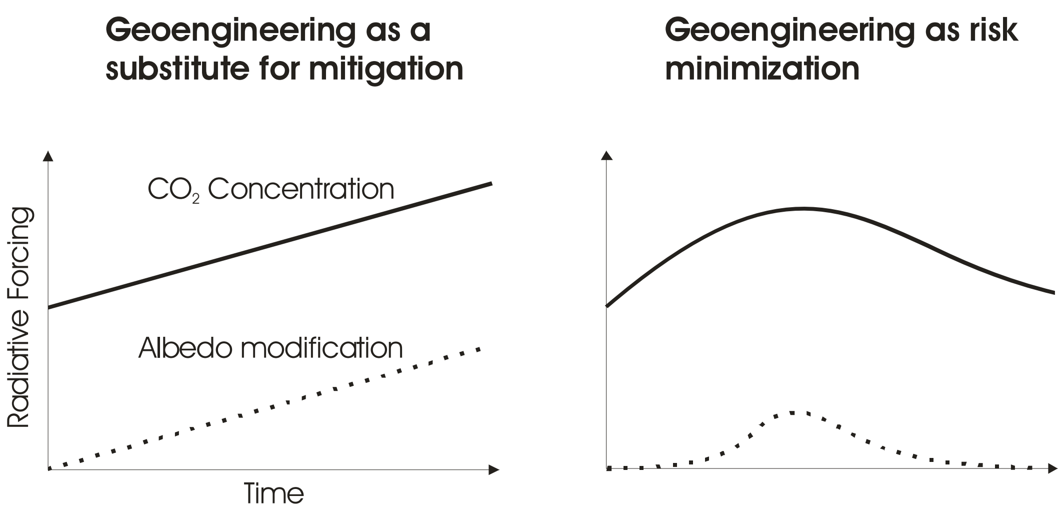

Figure 2. Schematic illustration of the distinction between geoengineering as a substitute for mitigation (left panel) and geoengineering as a supplement to mitigation used as a means to reduce the risks of climate change during period of the peak radiative forcing (right panel).

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