Chapter 49

Engineering the Planet

David W. Keith

While the scope of human environmental impact is now global, we have yet to make a deliberate attempt to transform nature on a planetary scale. I call such transformation geoengineering.[1] 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, 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, scale without intent: Climate change due to increasing carbon dioxide (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.[2]

Manipulations need not be aimed at changing the environment, but rather may aim to maintain a desired environment against perturbations—either natural or anthropogenic. In the context of climate change, geoengineering entails the application of countervailing measure, one that uses additional technology to counteract unwanted side effects without eliminating their root cause, a "technical fix."

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. Cooling might be achieved by adding aerosols, fine particles suspended in air, to the atmosphere, where they would scatter sunlight back into space and might also increase the lifetime and reflectivity of clouds.[3] Alternatively, it might be possible to engineer giant shields in space to scatter sunlight away from the planet.[4] 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 nature. Sulfate aerosols injected into the stratosphere by large volcanoes can cause rapid 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 rapid decline in global temperatures that persisted over several years. In fact, "artificial volcanoes" have been proposed to deliberately inject sulfate aerosols into the stratosphere.[5]

As well as imitating natural processes, proposals for geoengineering often mimic existing human impacts: combustion of coal already creates great quantities of aerosols that offset 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 entails risks and side effects. Sulfate aerosols injected into the stratosphere will, for example, generate impacts such as ozone loss. But, geoengineering is not 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 aerosol pollution that arises as a by-product of fuel combustion. 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 open 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 be used to offset the effects of rising CO_2 concentrations. Consider, for example, "Restoring the Quality of Our Environment," a report delivered to U.S. president Lyndon 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, which reflects extreme confidence in human technological prowess: "The possibilities of deliberately bringing about countervailing climatic changes therefore need to be thoroughly explored." The report suggests dispersing of buoyant, reflective particles on the sea surface, concluding that "a 1 percent 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."[6] The report does not mention the possibility of reducing fossil fuel use; this surprising fact illustrates that our thinking about the appropriate tools for managing the climate is far less stable than is our understanding of the underlying science.

The cost of injecting aerosols into the stratosphere was analyzed by the U.S. National Academy of Sciences in 1992; it examined several delivery methods including high-altitude aircraft and naval guns, and found that annual costs of greater than \$100 billion would be sufficient to produce a 1 percent reduction in effective insolation (average solar radiation) reaching the lower atmosphere.[7] 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.[8] The amount of sulfate that would need to be injected would be about twenty to fifty times smaller than the amount of sulfur now added to the lower atmosphere by fossil fuel combustion, so the contribution to acid rain might be negligible. 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 more than a factor of ten.[9]

Costs are unlikely to be a deciding factor in the implementation of geoengineering. 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. Decisions about implementation should balance the reduction in climate risk against the direct risks of geoengineering; cost would be a minor factor in this risk-risk decision.

The use of sulfate aerosols poses serious risks, including the alteration of atmospheric chemistry that 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.[10] Crutzen 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.[11]

While expensive, space-based sunshields have side effects that would be both less significant and more predictable than would be the case with aerosols. 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 the Earth and the sun, well beyond the moon's orbit. Edward Teller and collaborators have found that such a shield could be made with much lower mass than was previously thought, implying that costs might be dramatically reduced.[12] While little technical analysis has been done, it seems certain that the cost and technical challenges of creating space-based sunshields are far larger than the costs in injecting aerosols into the stratosphere.

Regardless of how it is achieved, a reduction of solar input cannot perfectly compensate for CO_2-induced warming. While insolation could presumably be adjusted so that a geoengineered climate matched the preindustrial mean surface temperature, the result would still be significantly different than from the preindustrial climate. Several climate model experiments have shown that albedo geoengineering may nevertheless reproduce preindustrial climate with reasonable fidelity.[13]

Controlling the Weather

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, and so forth) on the evolution of weather systems.[14] 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 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.[15]

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 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 postwar 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. Paradoxically, our growing understanding of the dynamics of the Earth system increasingly grants us leverage that may be used to manipulate the Earth system and deliberately engineer environmental processes on a planetary scale. The manipulation of solar flux using stratospheric scatterers is the best example of leverage: we could reduce solar input sufficiently to initiate an ice age at an annual cost of less than 1 percent of global economic output.

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 further ahead the question is far less easily answered. Should geoengineering substitute, even partially, for mitigation? 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?

Just as safer cars may encourage more aggressive driving, the mere knowledge that geoengineering is possible may reduce the incentive to cut emissions by reducing (or appearing to reduce) the worst-case consequences of climate change.

Geoengineering may nevertheless be needed even if we pursue an aggressive mitigation strategy: suppose that several decades hence real collective action is underway to reduce CO_2 emissions under a robust international agreement. Suppose further that 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 prevent rapid deglaciation and consequent sea-level rise. Under such conditions, temporary albedo modification to limit climate impacts during the period of peak CO_2 concentrations might be warranted to control climate risk, not to substitute for mitigation.

Figure 49.1 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 were 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. In this case, one might view mitigation as a strategy to minimize the risks of the side effects of geoengineering. On the other hand, geoengineering might be used in conjunction with mitigation to reduce the risks of climate change during the period of peak CO_2 concentrations.

It is tempting to discount geoengineering because of the risk of unintended conse-

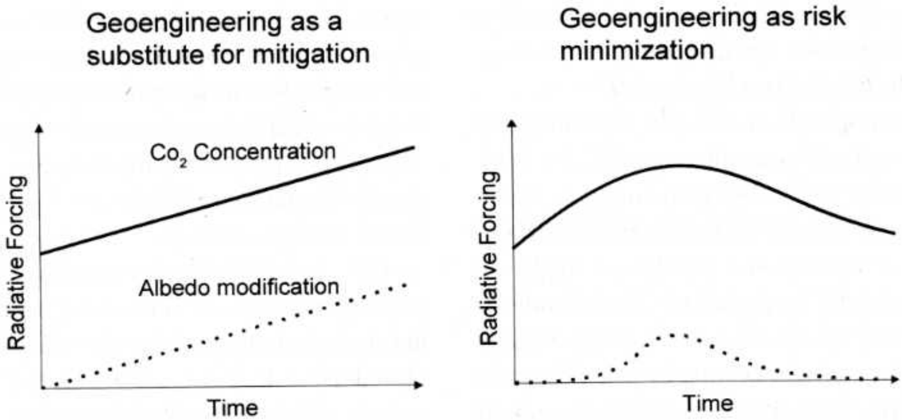

FIGURE 49.1. Schematic illustration of the distinction between geoengineering as a substitute for mitigation (left panel) and geoengineering as a supplement to mitigation used as a means to reduce the risks of climate change during the period of the peak radiative forcing (right panel).

quences. For example, Jeff Kiehl 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."[16] 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 parts per million (ppm) and living with the same CO_2 concentration in conjunction with geoengineering that reduces insolation by 1 percent, as illustrated schematically in the right panel of figure 49.1. It is impossible to predict exactly how the planet will respond to either case, yet it is hard to argue that the risks of 600 ppm alone would be larger than the risks of 600 ppm 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.[17] 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.[18] In 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 demands that we attribute intrinsic value to natural systems independent of their utility. According to 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. 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 preindustrial settings, that is, to minimize human influence rather than actively manipulating the planetary environment.

While a 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 through 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. The continued acceleration of anthropogenic emissions coupled with growing concern about the possibility of dangerous nonlinear responses to climate forcing argue for more systemic exploration of the feasibility and risks of geoengineering. 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.

Notes

1. Keith, D. W. (2000a). Geoengineering the climate: History and prospect. *Annual Review of Energy and Environment* 25: 245–84.

2. Allenby, B. (2000). Earth systems engineering and management. *IEEE Technology and Society Magazine* 19: 10–24; Friedman, R. M. (2000). When you find yourself in a hole, stop digging. *Journal of Industrial Ecology* 3: 15–19; Keith, D. W. (2000b). The Earth is not yet an artifact. *IEEE Technology and Society Magazine* 19: 25–28.

3. The average planetary reflectivity is called "albedo," so such methods are often called albedo modification.

4. Angel, R. (2006). Feasibility of cooling the Earth with a cloud of small spacecraft near the inner Lagrange point (L1). *Proceedings of the National Academy of Sciences* 103: 17184–89.

5. Budyko, M. I. (1982). *The Earth's Climate, Past and Future*. New York, Academic Press.

6. PSAC. (1965). President's Science Advisory Committee, *Restoring the Quality of Our Environment*. Washington, DC, Executive Office of the President.

7. Panel on Policy Implications of Greenhouse Warming, Committee on Science, Engineering, and Public Policy, National Academy of Sciences, 1992. *Policy Implications of Greenhouse Warming: Mitigation, Adaptation, and the Science Base*. Washington, DC: National Academy Press.

8. An atmospheric loading of around 10 g S offsets the effect of 1 ton of carbon, a S:C mass ratio of 1:105 (NAS, 1992 op. cit.; Crutzen, P. J. [2006].

Albedo enhancement by stratospheric sulfur injections: A contribution to resolve a policy dilemma? *Climatic Change* 77: 211–19). The NAS estimated a $20-per-kilogram 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 two-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 around $5 per ton of carbon (in 2009 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 per ton of carbon or larger.

9. Teller, E., L. Wood, and R. Hyde. (1997). *Global Warming and Ice Ages: I. Prospects for Physics Based Modulation of Global Change*. Livermore, CA, Lawrence Livermore National Laboratory, p. 20.

10. Kirk-Davidoff, D. B., E. J. Hintsa, J. G. Anderson, and D. W. Keith. (1999). The effect of climate change on ozone depletion through changes in stratospheric water vapor. *Nature* 402: 399–401.

11. Crutzen, 2006 op. cit.

12. Teller et al., 1997 op. cit.

13. Govindasamy, B., and K. Caldeira. (2000). Geoengineering Earth's radiation balance to mitigate CO_2-induced climate change. *Geophysical Research Letters* 27: 2141–44.

14. So-called tangent linear adjoint models enable one to efficiently run forecast models backward 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 backward in time; instead a linearized model is generated that is valid only for small perturbations to the forward evolution of the atmospheric state.

15. Hoffman, R. N. (2004). Controlling hurricanes. *Scientific American* 291: 68–75; Henderson, J. M., R. N. Hoffman, S. M. Leidner, T. Nehrkorn, and C. R. Grassotti. (2005). A 4D-Var study on the potential of weather control and exigent weather forecasting. *Quarterly Journal of the Royal Meteorological Society* 131: 3037–51.

16. Kiehl, J. T. (2006). Geoengineering climate change: Treating the symptom over the cause? *Climatic Change* 77: 227–28.

17. Allenby, 2000 op. cit.

18. Ibid.