Evaluating a technological fix for climate

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In this issue of PNAS, Matthews and Caldeira (1) report convincing model simulations of a controversial topic of widespread public interest: the possible geoengineering of earth's climate system to hold global warming in check. In the classic psychological sequence with which humans often face extraordinary and perhaps inevitable danger (denial, anger, bargaining, and acceptance), we appear now to be at the bargaining stage, where all kinds of solutions are sought and proposed with new vigor and intensity. This is fully understandable; the drumbeat of steadily rising climate warnings from the sequence of Intergovernmental Panel on Climate Change reports, the recognition of this by leading popular and political figures, and the public's own perception of the massive and increasing use of energy worldwide all augur for plans of action. But are such plans realistic? And what does this model tell us?

Engineering our way out of the climate change bind is widely discussed in the media: the faith in technology is high, and the desire to have the benefits of abundant fossil fuel energy without the unfortunate consequences is strong. Managing the carbon system is one approach: using less, and capturing some of the CO_2 before release to the atmosphere for underground sequestration. However, CO_2 capture and storage is expensive and energy-intensive (2) and would require a vast chemical engineering enterprise with its own heavy environmental footprint. Plans for cutting CO_2 emissions are now pressed daily, but the quantities required to make a meaningful contribution are huge. One respected analysis of a CO_2 stabilization pathway (3) shows that to stabilize atmospheric CO_2 levels at 550 ppmv (just under a preindustrial doubling) would require a deviation (active sequestration) from the already challenging Intergovernmental Panel on Climate Change IS92A "Business as Usual" scenario of $\approx$3.7 billion tons of CO_2 per year by 2025 and $\approx$15 billion tons of CO_2 per year by 2050.

These would be massive industrial efforts that right now societies are simply not prepared for, and the thermodynamic and mass transfer issues associated with such quantities are largely irreducible. Thus, some technologists have sought a more direct approach: managing not CO_2 but the incoming solar radiation itself. Initially, these adventurous schemes were the product of aggressive planners, some with a heritage in fields such as nuclear weapons defense strategies, who sought to directly confront the ΔT problem as one way of possibly avoiding the massive economic challenge of a shift from fossil fuels. These analyses were first largely dismissed by earth scientists, but as the awesome scale of the challenge has become formalized, discussion of these aggressive alternate tactics has emerged (4, 5) from some of the very same scientists who have studied the carbon management problem.

These schemes have varied from the simple, such as painting every rooftop and roadway white to increase planetary albedo, to the creation of space-based solar reflectors. The use of rockets, airplanes, and giant guns to deliver reflecting material to the stratosphere has been debated, and there is even a body of conspiracy theory on "chemtrails" where the gullible believe that experiments are already underway. However, the strategy reviewed here, the deliberate injection of stratospheric sulfate aerosols to artificially create the cooling that the earth experiences from some natural volcanic eruptions, has seen legitimate scientific discussion. The National Academies have a significant presence in this debate, publishing in 1992 a 918-page volume on the policy implications of greenhouse warming (6) with a full chapter on geoengineering as one of the options that must be on the table.

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Matthews and Caldeira (1) have used the University of Victoria Earth System Climate Model to simulate a situation in which CO_2 emissions are allowed to continue unabated and incoming solar radiation is reduced by technical means, such as with stratospheric modification of aerosols, so that the increased radiative absorption by CO_2 is precisely and uniformly compensated for. They find first that the thermal response of the climate is fast so that on the upside it is possible to keep pace and hold CO_2-induced warming in check. This is not surprising: the earth's temperature signal responds rapidly to a Pinatubo event. However, should the engineered system later fail for technical or policy reasons, the downside is dramatic. The climate suppression has been only temporary, and in this model the now-CO_2-loaded atmosphere quickly bites back, leading to severe and rapid climate change with rates up to 20 times the current rate of warming of $\approx$0.2°C per decade, depending of course on the scenario used. This could have enormous potential for harm.

One would normally look for experimental evidence to support model claims, but this may be difficult here. The cooling side of the equation is perhaps in better shape. It works, and there is widespread public recognition of the natural volcanic events that create it. The most recent episode, the June 1991 Mt. Pinatubo event, was well studied (7) and relatively benign, but this is by no means always the case. For example, the climate abnormalities (frosts, storms, and flooding) of the tragic "year without a summer" in 1816 (8) resulted from the April 1815 eruption of Mt. Tambora in Indonesia. The subsequent cooling devastated crop production in the American continental northeast, northern Europe, and China, resulting in famine and food riots, and possibly hundreds of thousands of untimely deaths. Clearly, the euphemism of calibration of the injection technique and the explanation of any erratic consequences would be an issue.

The rate of warming predicted in this model from cessation of the aerosol injection is dramatic, and we are not likely to be able to test this. How realistic is this prediction? For a useful simple and classic scaling, we might turn to the work of Hansen *et al.* (9), who estimated climate response times to a step function in greenhouse gas forcing. They found particular sensitivity to climate

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feedbacks (that is, to the created temperature change itself) and to the representation of ocean mixing. For a climate sensitivity of 3°C at CO_2 doubling, they estimated the time scale for the ocean mixed layer to achieve 63% of equilibrium thermal response to be 50–100 years, and many earth scientists carry around such a reasonable sense of a measured time scale and slowly evolving thermal signal as they go about their work. However, recall that here we are discussing not a change in CO_2 but an abrupt shift in incoming radiation as the aerosol injection experiment is turned off. What this means is that the initial atmospheric "bounce back," as reported by Matthews and Caldeira (1), is fast, reasonably mimicking the opposite side of the rapid volcanic cooling, as heat transfer to the oceanic mixed layer cannot initially keep up, and the extraordinarily rapid climate warming predicted would appear to be real.

The dangers are clearly large. It is widely reported that ecosystems already have difficulty in coping with today's rate of change; far more rapid shifts from such a technical or policy initiative followed by failure would pose astonishing challenges. There are other changes to consider: unabated growth of atmospheric CO_2 would continue the already massive transfers of CO_2 to the upper ocean, now some 1 million tons of CO_2 per hour, with significant lowering of pH (10–12) and poorly understood marine ecosystem consequences.

The consequences for regional precipitation patterns were more subtle, but these are notoriously hard to predict. The hydrologic cycle pattern that emerged from the model was that in a temperature-moderated, CO_2-rich world, the effect of elevated CO_2 was to enhance land plant water use efficiency, with large decreases in precipitation over vegetated surfaces, particularly in the tropics. It was long believed that elevated atmospheric CO_2 levels would result in a greener world, with positive benefits for land vegetation because leaves could then take in CO_2 without releasing as much water through their stoma. It was this thinking that, in part, resulted in the extraordinary emphasis on forestation in the Kyoto Protocol. The model here supports this to a degree, in that the negative effects of temperature change on vegetation are held in check during the successful injection phase. However, less evapotranspiration from trees means lower transfer of water vapor to the atmosphere, and so large decreases in tropical rainfall are predicted to occur. In practice, there is some doubt as to this scenario. Early work on greenhouse-contained plants did show the expected CO_2 fertilization effect, but questions were raised (13), and decades of open free air CO_2 enrichment (FACE) experiments did not yield the predicted enrichment effects (14). The consequences for the terrestrial plants, and thus agriculture, of starting, and then abandoning, the geoengineering experiment would thus again be large, although a more accurate prediction could not come from the class of model used here.

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Matthews and Caldeira (1) point out that efforts to mitigate greenhouse gas emissions should "not become hampered or slowed by the specter of false certainty in our ability to geoengineer the climate change problem away." I agree. It is easy in a model to create a uniform global change in the radiative properties of the stratosphere. In practice, this would be an enormously challenging undertaking, with patchy distributions and local anomalies even from successful launches and injections.

These schemes are last-resort solutions at best and contain many large and unknown consequences for human society. The questions of global versus local benefit, unilateral or international action, and the opposition of negatively affected nations have not yet been addressed. The consequences of botched injections, and now the Faustian bargain that once a commitment has been made to this course there is no danger-free way out, do not bode well for geoengineering of this kind as a policy solution.

What then is the answer? Earth scientists warn society at large of the dangers of climate change, but the remedies offered are typically that of slowing the rate of emissions, not of creating a true emission-free world. In this case, we simply move more slowly toward global warming and its partner, ocean acidification. The difficulty of providing basic energy services (electricity, transportation, and manufacturing) for a global population should not be underestimated; the fixing of atmospheric nitrogen by the Haber–Bosch process to create fertilizer is now essential to feed a significant fraction of the people on this planet, and that too is a major demand on our fossil fuel supply. Must we now move from denial, anger, and bargaining to acceptance? Maybe not, but the options are becoming increasingly narrow.

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