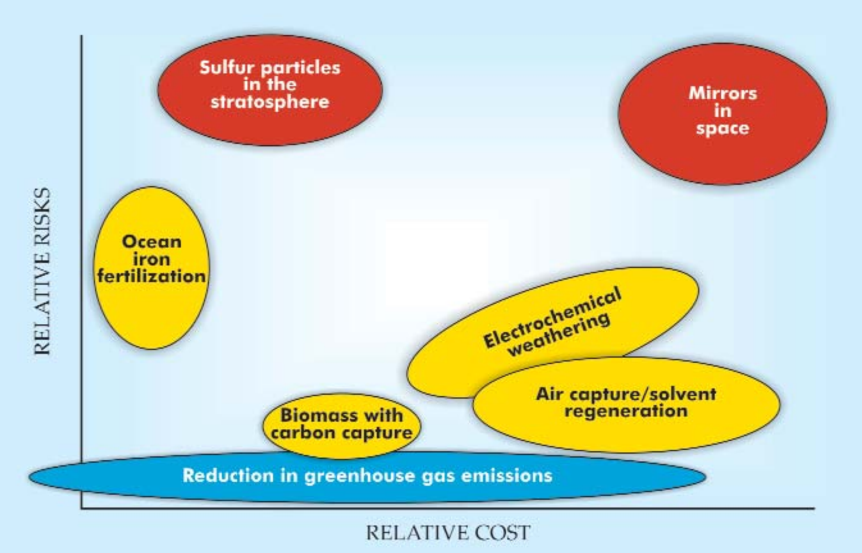
Will desperate climates call for desperate geoengineering measures?

Earth scientists ponder the wisdom of large-scale efforts to counter global warming.



Relative costs and risks of various geoengineering schemes. (Figure courtesy of Kurt House, Harvard University.)

The public is finally paying attention to anthropogenic climate change, but it has not yet kicked its carbon habit. Global emissions of carbon dioxide continue to rise, with output in recent years exceeding the worst-case projections of just a few years ago. At the same time, Earth is showing signs of accelerated warming, such as Arctic sea-ice melting and a shrinking Greenland ice sheet.

Concerned that Earth's climate will change to an unacceptable degree or at an unacceptable rate before economies can shift significantly away from carbon-based energy sources, some scientists have begun casting their eyes in a previously shunned direction: geoengineering, or intentional and large-scale intervention to prevent or slow changes in the climate system.

Geoengineering sometimes refers strictly to techniques for increasing Earth's albedo, or reflectivity, to lower its temperature and compensate for greenhouse warming. More broadly, the term can include efforts to accelerate some of the natural processes for removal of CO_2 from the atmosphere. Many such ideas have been around for decades. In the past few years, however, the debate over their potential deployment has intensified. (References to a review and to other work discussed here can be found in PHYSICS TODAY'S online version of this story.)

Extreme measures?

The idea of deliberately tampering with Earth's climate system raises the specter of unintended consequences, especially because the interventions would be imposed on a climate system already significantly perturbed by the unintentional consequences of human activity. Many scientists are averse to opening that Pandora's box, preferring to mitigate climate through emissions reductions and worrying that those reductions might be undermined by a premature faith in a technical fix.

Nevertheless, some scientists argue that the world needs an emergency backup plan. They advocate doing careful and thorough research to examine the efficacy, costs, side effects, duration, and reversibility of any potential climate-change intervention.

One such advocate is National Academy of Sciences president Ralph Cicerone. He favors separating research on geoengineering from actual implementation. Scientists should not proceed with an intervention, he asserts, until the proposed action is subjected to expert, international peer review, with opportunity for significant public involvement. He sees the need for a qualified agency to oversee the design, implementation, and monitoring of experiments, and he points to the actions of biologists in the 1970s who created ethical guidelines for genetic research.

David Keith of the University of Calgary points out that if serious scientists don't do the work, the field will be dominated by enthusiasts at the fringe, and that geoengineering schemes may be commercialized in a way that ends up being counterproductive.

Other scientists argue that doing any research on geoengineering schemes is dangerous. As Raymond Pierrehumbert of the University of Chicago puts it, "It is very unfortunate that the genie has been let out of the bottle just as the world has begun to awaken to the seriousness of climate change and the need to take real action." There's a real risk, he says, that unwarranted faith in the technology will "cut off at the knees actions that might start to make serious reductions in greenhouse emissions."

Even with the best science, no one can fully anticipate all the unintended consequences of a geoengineering measure. Can one conduct an experiment large enough to give a realistic assessment of a countermeasure without making the experiment so large that it becomes a significant intervention?

Another set of questions concerns geopolitics. If the international community did convene a body to govern the implementation of a certain geoengineering scheme, how would that body decide when to give the go-ahead? The decision would be complicated by the unequal global distribution of climate impacts, such as drought or increased monsoons, and by the unequal distribution of the possible consequences, good and bad. It's possible that a single nation, suffering worse effects than others, might attempt climate modification on its own.

The proposed types of climate intervention vary widely, with the risks and benefits being quite specific to a particular action. During a public panel held in May at the University of California, Santa Barbara, Kurt House of Harvard University rated the commonly discussed actions by cost and risk, as sketched in the figure on page 26. Reducing CO_2 emissions has the lowest risk but the widest range of costs.

Albedo modifications

At the high end of the risk scale and low end of the cost scale fall techniques to reflect solar radiation with small particles in the stratosphere. Volcanic eruptions have given us some evidence for the impact of particles in the stratosphere. Eruptions large enough to loft soot into the stratosphere lowered global temperatures for a year or two afterward. Mount Pinatubo in 1991 hurled roughly 17 megatons of sulfur dioxide to heights of about 18 km. In the stratosphere, SO_2 gas forms highly reflective sulfate particles with residence times of a few years.

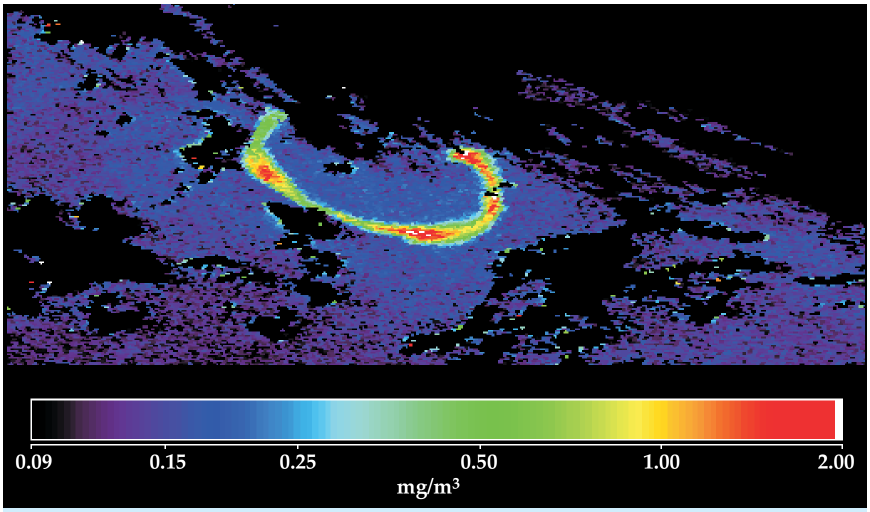
The cooling impact of volcanoes suggests that the artificial injection of aerosols might lower Earth's temperature. Paul Crutzen of the Max Planck Institute for Chemistry sparked the recent geoengineering debate in 2006 when he proposed the injection of about two megatons of SO_2 particles into the atmosphere annually to compensate for a doubling of CO_2. The paper attracted a lot of public attention because of its author: Crutzen won the 1995 Nobel Prize in Chemistry for his work on ozone chemistry in the stratosphere.

Alan Robock of Rutgers University is among those who have pointed to a number of problems with the sulfate idea. For one, increased albedo compensates only for higher temperatures; it does not mitigate the growing acidification of Earth's oceans or other consequences of greenhouse gases. For another, albedo enhancement is expected to reduce overall precipitation, especially in the tropics. Regional impacts such as reduced rainfall, soil moisture, and river flow were found in the wake of the Pinatubo eruption, and similar results have been seen in simulations of hypothetical geoengineering schemes.

Mount Pinatubo also contributed to an increased rate of ozone depletion at the poles by providing particulate surfaces on which the ozone-depleting reactions with chlorofluorocarbons (CFCs) can occur. Simone Tilmes at the National Center for Atmospheric Research and colleagues recently simulated the effect of intentional injection of sulfates. They found that geoengineering would prolong—or possibly worsen—the ozone depletion for decades, even with the reductions in CFCs mandated by the 1987 Montreal Protocol.

The ozone hole was an unforeseen consequence of CFC emissions, notes Meinrat Andreae of the Max Planck Institute for Chemistry. He asks, "What makes us think we won't be in for another surprise if we inject so much sulfur into the atmosphere?"

Some view the stratospheric injection of sulfur as a stopgap measure, to shield Earth from higher temperatures while or until global greenhouse emissions can be reduced. If no such progress is made, the greenhouse gases will continue to build in the atmosphere, but the sun shield would mask the temperature rise. If the world for some reason stopped lofting sulfur into the stratosphere, Earth would be abruptly exposed to the far hotter temperatures expected in a world with far higher greenhouse gases.



Phytoplankton bloom following an iron-fertilization experiment in the Southern Ocean. The area covered spans about 1 degree of latitude and 2 degrees of longitude. Color scale indicates the mass of chlorophyll per cubic meter of seawater, mostly contained in phytoplankton. (Image provided by the NASA Goddard Earth Sciences Data and Information Services Center.)

Another way to reduce the solar heat flux reaching Earth's surface is to put deflectors in space. University of Arizona astronomer Roger Angel envisions a cloud of trillions of 0.6-meter-diameter, thin refractive screens to deflect sunlight. To offset a doubling of CO_2 over preindustrial levels would require a total mass of 20 million tons to block 1.8% of the solar radiation. Angel suggests a combination of electromagnetic acceleration and ion propulsion to loft a mass that large into space, at a projected cost of a few trillion dollars.

Removing CO_2

Other geoengineering ideas concern ways to accelerate removal of CO_2 from the atmosphere. The least contentious idea is to capture CO_2 as it is emitted from the stack of a coal-fired power plant and to sequester it in reservoirs. (For more on the storage of CO_2 see the article by Don DePaolo and Lynn Orr on page 46 of this issue.) A related idea is to pull the CO_2 out of the ambient air, but that research is still in its infancy. Growing trees and other biomass also takes CO_2 out of the atmosphere, and carbon credits are now given for reforestation projects.

A technique considered to pose higher risk than reforestation is ocean iron fertilization (OIF). The iron helps stimulate greater growth of phytoplankton in nutrient-rich regions of the ocean. The photosynthesis in these microorganisms takes CO_2 from the ocean's surface and releases oxygen. When the microorganisms die or are eaten, about 5–30% of their biomass sinks to the ocean's depths. Anthony Michaels of Proteus Environmental Technologies LLC in Los Angeles refers to OIF as "time shifting" since the carbon eventually gets reintroduced to the atmosphere after decades or centuries. Because of its relatively low price tag, OIF has become the focus of several companies interested in carbon removal technologies, presumably with the intent to sell carbon credits or offsets.

In 12 field studies conducted since 1993, OIF was found to stimulate increased phytoplankton growth (see the figure at left), but those studies were not conducted at sufficiently large spatial scales or adequately long time scales to address OIF's efficacy in storing carbon. How much additional atmospheric CO_2 would be removed, and how long would it be sequestered? Might the blooms include harmful algae, or could biochemical processes produce methane or nitrous oxide—more potent greenhouse gases? Michaels is among a group of 16 scientists who have publicly asserted that it would be premature to sell carbon offsets for OIF unless the method is shown to remove CO_2, retain it for a quantifiable period of time, and have acceptable and predictable environmental impacts.

Accelerated weathering

Raindrops contain some CO_2, so that the drops constitute a weak carbonic acid. Over geologically long time periods, weathering by rainfall dissolves rocks such as magnesium silicate, with magnesium and bicarbonate ions washing eventually into the oceans. The bicarbonate ions can combine with calcium to form calcium carbonate. When the calcium carbonate sinks to the deep ocean, it is sequestered for more than 1000 years, and the carbon is eventually recycled through Earth's mantle.

The oceans absorb about one-quarter of the CO_2 added annually to the atmosphere. The absorption is dependent, among other factors, on the alkalinity of the oceans' surface layer. As atmospheric CO_2 has increased, so has the acidity of Earth's oceans.

One of several ideas to accelerate the natural weathering cycle is to increase the oceans' alkalinity. For example, House and others have proposed a scheme to remove hydrochloric acid electrochemically from the oceans and to neutralize it by reacting it with silicate rocks. To offset the output of 1 gigaton of carbon per year—one-seventh of today's annual global emissions—House estimates that his weathering scheme would require a seawater flow rate equal to that of 100 large sewage treatment plants and the consumption of about 10 gigatons of basalt rock.

The enormous scale of such geoengineering schemes helps to underscore the importance of getting things right. **Barbara Goss Levi**

Path integrals, Les Houches, and other adventures of Cécile DeWitt-Morette

Entrée to Paris got Cécile DeWitt into physics. Working with great physicists kept her in the field.

One of the first things Cécile DeWitt-Morette said to me was that she wished she was better known for her science. Instead, if people know of her, it tends to be as founder of the Les Houches School of Physics in France. Her involvement in Les Houches—which continues today, 57 years later—may even have been used to harm her research. For example, she says, in the 1980s, she had a grant proposal turned down with the comment that she was "busy raising children and doing administrative work."

DeWitt was born in Paris, France, in 1922. She went to the US in 1948 for a postdoc and has since split her time between the two countries. She recently recounted to PHYSICS TODAY how she chanced into physics thanks to travel restrictions during World War II; how she met Frédéric Joliot-Curie, Paul Dirac, Richard Feynman, Erwin Schrödinger, Louis de Broglie—who was her PhD supervisor—and other physics giants of the 20th century; how she started Les Houches as a self-imposed condition of marrying fellow theoretical physicist Bryce DeWitt; and many other adventures on her way to her present position as professor emerita at the University of Texas at Austin.

PT: Why did you go into physics?

DEWITT: You've opened a can of worms, but I'll give it to you.

I wanted to go to medical school, but that was during the war, and there were several issues why I couldn't. I got my BS in 1943 in physics, math, and chemistry at the University of Caen in Normandy. Then I wanted to do something a little more exciting. I wanted to go to Paris. Because it was wartime and Caen was in the coastal zone, I had to ask for a pass. And the only reason I could give to look reasonable was to say I was getting my MS in physics. I knew that if it were on my pass, I'd better do it, so I signed up for a course in quantum mechanics. I had vaguely heard the term, but it sounded good to me, and it sounded very good to the German officer.

To tell you how bad the course was, in two semesters of quantum mechanics, I do not recall hearing the word "Hamiltonian" once. But it was my condition to have a pass, so I stuck to it.

I was shuttling back and forth between Paris and Normandy, and the exam for that course turned out to be on D-day, June 6, 1944. At that point the Allied bombing was terrible. I mean, they were bombing all the trains, all the stations. Everyone around me said I shouldn't go to Paris for an exam that I didn't care about.

But one lesson I learned during the war is that you don't know where the danger is, you don't know what it is. If it's on your agenda, you just do it. Eventually I was taking that exam on D-day, so I was not at home. And our house got the first bombs, and everybody in the house got killed.

At that point, particularly since my mother died, I felt like an adult. The days of looking for adventure were over. My family was very matriarchic, so with my mother dead, I was in charge.

I felt I better have a job. It happened that I had had, before D-day, an offer from Joliot to work in his lab. I really was not interested, but I had not yet got around to telling him no.

The reason he offered me the job, I think, is that he was a very good experimenter but he had no room for theoretical physics. And he could not ignore the letters from his theoretical colleagues. He felt that a young woman with not many degrees would just be a glorified scientific secretary. By 1944 we were not liberated, but the mail was beginning to come, and he would pass on to me letters he received—on [Niels] Bohr's liquid-drop model or the Bohr–Rosenfeld paper, for example. I had to go somewhere to learn my job. I'd heard the word Schrödinger, so I picked up a book about Schrödinger. The only thing I understood in the Schrödinger equation was π.

Part of my job was to prepare [Joliot's] lectures on the diffusion of slow neutrons. I knew nothing about it. He didn't have time to prepare his lectures because he was very busy with the government. He was a good speaker and had a lot of charisma, and he gave interesting lectures in spite of my poor contribution.

PT: You ended up doing your PhD work in Dublin, right?

DEWITT: Yes. [Walter] Heitler wrote to Joliot and wanted young people to join him and other Jewish refugees in Dublin. Joliot asked me if I wanted to go, and I said sure. Because we were still under war conditions, I needed an exit visa. Joliot asked a secretary to pre-