IS THIS WHAT IT TAKES TO SAVE THE WORLD?

Long marginalized as a dubious idea, altering the climate through 'geoengineering' has staged something of a comeback. Oliver Morton reports.

In the first week of June 1991, Michael MacCracken, a climate physicist from Lawrence Livermore National Laboratory in California, was attending a small conference in Palm Coast, Florida, to discuss technological approaches to cooling the Earth. There he gave a paper that looked at various approaches that had been suggested in the decades before, from burying carbon dioxide underground to increasing the proportion of sunlight that bounces off hazes in the atmosphere and back into space.

At the same time half a world away, something like 20 million tonnes of sulphur dioxide dissolved in searingly hot magma a few kilometres underneath the Philippines was preparing to show him and his audience how it's done.

The day after the conference ended, the first of that magma emerged from the crater of Mount Pinatubo. After a week of intensifying eruptions, on 15 June the volcano exploded cataclysmically, blowing a plume of molten rock, ash and gas as high as 40 kilometres into the atmosphere. Much of the plume's sulphur dioxide ended up in a cloud of tiny particles spread around the stratosphere, more than 20 kilometres up, and there it remained for years. The thin global veil of sulphates made the planet's sunlight more diffuse, its skies a touch whiter, its sunsets more spectacular — and its climate a little cooler.

The Pinatubo particles cooled the Earth more or less exactly in line with the figures that MacCracken had offered at the meeting for the effects of 'artificial volcanoes'— any technology for injecting sulphur high into the atmosphere. Had there not been a simultaneous El Niño, 1992 would have been 0.7 degrees cooler, worldwide, than 1991. And this demonstration of cooling power took place at a crucial time. The first report of the Intergovernmental Panel on Climate Change (IPCC) warning of greenhouse warming came out the year before Pinatubo; the UN Framework Convention on Climate Change was opened to signatures while its aerosols were still enlivening the skies. In a world awakening to the prospect of global warming, you might have expected such an object lesson in global cooling to sharpen the debate over artificial volcanoes of the sort that MacCracken had reviewed.

First cut is the deepest

But things went the other way. Once global warming started to be seen as real and important, climate scientists shied away from such speculation, preferring to hammer home the message that greenhouse-gas emissions had to be cut quickly and deeply. 'Geoengineering' the climate through artificial modifications was seen as a dangerous distraction from the business of slashing emissions. In the decade and a half that followed Pinatubo, talk of geoengineering went into eclipse. From 1995 to 2005, more research went into technological responses to asteroids that might one day endanger the Earth than into direct responses against the sunlight already heating the planet.

Much of the climate community still views the idea with deep suspicion or outright hostility. Geoengineering, many say, is a way to feed society's addiction to fossil fuels. "It's like a junkie figuring out new ways of stealing from his children," says Meinrat Andreae, an atmospheric scientist at the Max Planck Institute for Chemistry in Mainz, Germany. But in the past year the idea has begun to re-emerge, and it now seems to be making up for lost time. In particular, the idea of blocking some of the Sun's light before it gets to the Earth — sometimes euphemistically referred to as 'radiation management' — is receiving more attention now than ever before, with new ideas about how, why and when such an approach might be taken. The most recent IPCC report, released last week, scoffs at such

NASA

Mount Pinatubo's eruption in 1991 made sunsets much brighter (right) than before (left).

B. MARQUEZ/AP

The sulphur dioxide Mount Pinatubo injected into the stratosphere acted as a filter to the Sun's rays.

notions — but underlines the need for drastic approaches to stave off the effects of rising planetary temperatures. And in the context of the drastic, curiosity about geoengineering looks likely to grow. "It's a natural question to ask," says MacCracken, now chief scientist for the Climate Institute in Washington DC. "If we can do something inadvertently, can we do something deliberate to counter it?"

This new interest in geoengineering was set off by an article by Andreae's friend and colleague Paul Crutzen, published in the journal *Climatic Change* in August 2006 (ref. 1). The article contained relatively little that wasn't already in the literature when Pinatubo blew its top, but it had a major impact because of who was saying it. "In this case, the messenger is the message," says Stephen Schneider, a climate scientist at Stanford University in Palo Alto, California, and editor of the journal. "Nobelist and general environmental worrier Paul Crutzen — someone who showed the world the risks of ozone depletion very early on — is a natural to get big attention for thinking about the environmentally unthinkable." It was for exactly this reason that Crutzen's colleague Andreae urged him not to publish.

Pollution to save the world

If the identity of the author was striking, so too was the matter-of-fact way that he chose to frame the issue. Mankind, Crutzen pointed out, already puts more than 100 million tonnes of sulphur dioxide into the atmosphere every year — the equivalent of at least five Pinatubos. Unfortunately, the aerosols that this sulphur produces sit in the lower atmosphere, the part we breathe, and they do us no good; they are estimated to contribute to 500,000 premature deaths every year. But clearing away this pollution has the unintended consequence of increasing the rate of global warming, because even in the lower atmosphere the sulphates stop sunlight from reaching the surface. Crutzen looked at the idea of introducing one or two million tonnes of sulphur into the stratosphere every year, where it could produce a long-lived aerosol, as a way to keep the protective effects while getting rid of the short-lived aerosols in the lower atmosphere.

"The role of a geoscientist is to understand nature, not to change it." — Hans Feichter

At both the beginning and end of his article, Crutzen stressed that he would rather see global warming controlled by a reduction in emissions. But he admitted that, so far, he saw little cause for optimism. He also pointed out that sulphate aerosols can act to cool the climate immediately; reducing emissions, on the other hand, takes decades or generations. If something really bad starts to happen, aerosols could provide a prompt cooling response in a way that emissions control simply could not.

On hearing of Crutzen's paper, Tom Wigley, a veteran climate scientist at the National Center for Atmospheric Research in Boulder, Colorado, decided to look at what such a programme might achieve in the short term. He realized that the almost instantaneous cooling effect of the sulphates could be used to buy the time needed for emissions reductions to start having an effect. Using a very simple climate model, Wigley looked at the possibility of capping atmospheric carbon dioxide levels at 450 parts per million around the middle of the century. (Before the industrial revolution the level of carbon dioxide was 280 parts per million, and today it is 381 parts per million.) Never going above 450 parts per million would offer a decent chance of limiting future warming at or below 2 °C. But such restraint looks increasingly implausible to many.

A little geoengineering might make an equivalent objective a lot more achievable, Wigley argued[2]. Imagine an aerosol effort that starts fairly soon and is quickly ramped up to a Pinatubo's worth of sulphates being injected into the upper atmosphere every two years, before being phased out completely after 80 years. The resulting cooling effect would allow carbon dioxide emissions to keep climbing for a few more decades without the world warming any more than if they levelled immediately. In Wigley's model the peak level of atmospheric carbon dioxide could climb to well over 500 parts per million without the Earth's temperature getting any higher than it would with stabilization at the much-harder-to-obtain 450 parts per million. Emissions would still have to be cut very steeply from the middle of the century on. But for Wigley, those extra decades of room to manoeuvre are all important.

Realms of the unknown

If a burst of sulphates might allow the world to postpone the effects of emissions control for a few decades, would a consistent effort allow the world to do without control altogether? Wigley points to at least one reason why not. Carbon dioxide does more than just warm — it also acidifies the ocean[3]. Even if the warming effects of ever-increasing carbon dioxide could be cancelled out, the effects on corals, shellfish and eventually the entire marine food web would still be disastrous. And even the most vigorous proponents of geoengineering do not suggest that it can defer any need to reduce emissions indefinitely. "If you are digging a hole and want out of it, certainly slowing your digging rate is good," says Gregory Benford, an astrophysicist at the University of California, Irvine, who is also a noted science-fiction writer and something of a geoengineering enthusiast. "But," he continues, "you need a ladder."

Even a strictly term-limited scheme has potential pitfalls. Wigley's model deals only with average global temperatures, and there is much more to the climate than that. For decades, climate scientists dubious about geoengineering schemes have pointed out that the pattern of warming expected from carbon dioxide, and the pattern of cooling expected from aerosols, would differ in both space and time. Aerosols cool things only when the Sun is shining, and they cool things most where the Sun shines brightest. They thus cool only in the day and more in summer and the tropics. Greenhouse gases warm things night and day, and their effect is greater at the poles. The two factors could thus cancel each other out in terms of global average, while fundamentally changing the way that the climate works region by region.

In 2000, Ken Caldeira — then of the Livermore lab — decided to look in detail at how strong the mismatch was. With his colleague Bala Govindasamy he used a general circulation model (GCM) to compare a world with doubled carbon dioxide to a world with both doubled carbon dioxide and an offsetting 1.8% drop in sunlight. In the carbon-dioxide only world, 97% of the surface had statistically significant warming; in the world with a cooling aerosol, that figure was cut to just 15% (ref. 4).

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Roger Angel proposed a high-altitude sunshade to help cool the Earth.

Simple solutions

The result surprised Caldeira, who had undertaken the research in part to show a colleague, Lowell Wood, that geoengineering was more complex than Wood imagined. Wood is a forceful spokesman for extreme ideas, most notoriously the proposed X-ray laser that was to have formed the cornerstone of Ronald Reagan's Star Wars programme. In the 1990s, he had become enamoured of radiation management, as had his mentor, Edward Teller, Livermore's hydrogen-bomb-begetting eminence gris. If geoengineering had not already had a bad name among climate scientists concerned about the environment, Teller's championing of the idea in the pages of the *Wall Street Journal* would have won it one.

Caldeira had wanted to show that the world was more complex than simple physics suggested. His results, though, edged things the other way, making geoengineering look more plausible, rather than less. Perhaps as a result, they were hardly followed up at all. Only six years later, under the influence of the Crutzen paper, are other researchers with GCMs starting to look at radiation management. Last month, for instance, Wigley's colleague Phil Rasch unveiled some preliminary results in a seminar at the National Center for Atmospheric Research. Again, the amount that warming from emissions and cooling from aerosols cancelled each other out was surprising. But the differences were not zero. Temperature shifts in some places, and precipitation in others — although the differences were not as large as those to be expected in a greenhouse-only world.

Caldeira, too, while stressing that he is not an advocate of moving ahead with geoengineering, has recently revisited the topic using a different GCM to the one he used in 2000. He finds similar results, with somewhat larger shifts in precipitation than in temperature. His new work also suggests that natural sinks for carbon might expand in a geoengineered world. With more carbon dioxide, plants are more productive and thus suck up more carbon dioxide. In a greenhouse world, this tendency is counterbalanced by the effect of temperature increases on the respiration of soil microbes — warmer microbes produce more carbon dioxide. But in a greenhoused-and-cooled world, the plant effect remains while the respiration effect is capped, and so significantly more carbon dioxide gets used up.

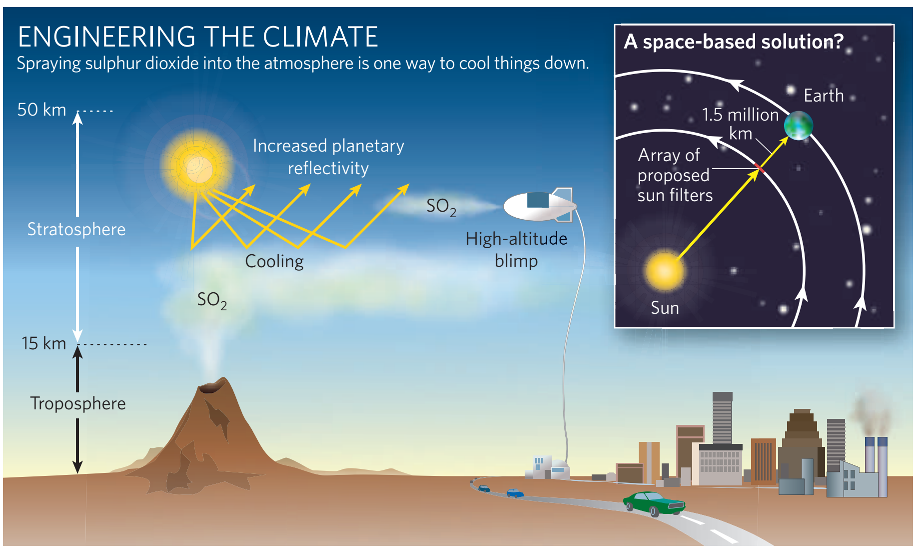
Paul Crutzen kickstarted a renewed interest in geoengineering.

Unstable foundations

Climate modellers at NASA's Goddard Institute for Space Studies in New York have also started to study the potential effects of geoengineering in GCMs. The people who run similar models at the Met Office Hadley Centre in the United Kingdom and the Max Planck Institute are looking on with interest, and will probably follow them. But Rasch cautions that these are early days. A confident understanding of geoengineering's promises and problems would require years of dedicated work from groups all over the world, an effort comparable to that reflected in the IPCC's massive reports on the natural science of climate change. And even that, say critics, would not be enough. GCMs are useful tools, but they do not provide a perfect understanding of the climate system. And it is the lack of such an understanding that critics point to as geoengineering's biggest scientific problem.

The very thing that motivates people like Crutzen to study geoengineering — the risk of large surprises that require immediate action — leads others to see the whole idea as fundamentally unworkable. Although models agree that the world will warm and climatic patterns will change as carbon dioxide rises, they don't agree on the amount of warming or the patterns of change. Indeed, that uncertainty is one of the reasons that climate change is such a difficult issue. "How can you engineer a system whose behaviour you don't understand?" asks Ronald Prinn, a climate scientist at the Massachusetts Institute of Technology in Cambridge.

One answer to this question is "as carefully and reversibly as you can". Caldeira and MacCracken have now joined Wood and Benford to investigate a radiation-management proposal aimed at the Arctic. It is in the Arctic, Caldeira thinks, that they can get the greatest effect for the least effort, because cooling the Arctic will encourage the growth of sea ice



Dimming the lights: the effect of the Sun is already dampened by atmospheric pollution.

G. LUDWIG/PANOS

— which will itself cool things even further, both by reflecting away sunlight in the summer and by acting as an insulating lid on the warmer water below. The Arctic has endangered ecosystems with inhabitants that might benefit from the cooling — as did the polar bears born in the winter of 1991–92, who grew big and strong on the particularly long-lived sea ice of the following spring, and who scientists dubbed the 'Pinatubo cubs'. And it is in the Arctic, the team suggests, that greenhouse warming might spring one of the 'surprises' not foreseen in models but endlessly speculated about elsewhere: the sudden pell-mell melting of the Greenland ice cap.

Polar focus

Caldeira and his colleagues reason that cooling the Arctic requires much less material than cooling the planet as a whole. What's more, they propose putting it low enough in the stratosphere that much of it will fall out less than a year after it is lofted up in the spring — as there is no point having a reflecting layer up there in the sunless winter. Engineering a year at a time, in a small and sparsely populated region, might be as low-impact an option as the geoengineer's toolbox offers. The technology could be quite simple: cargo aircraft towing sulphur-distributing parasails behind and above them, or very high-altitude blimps pumping sulphur dioxide up from the ground through 20-kilometre-long hoses. As Wood points out, you really only need a few dozen litres per second of output to do the job —less if you use something more reflective than sulphate particles.

But even modest, local geoengineering could have disproportionate effects far away. Alan Robock and his colleagues at Rutgers University in New Jersey, working with climate modellers at the Goddard institute, have studied the effects of volcanic eruptions that belch out sulphur at high latitudes — natural analogues to the sort of thing Caldeira and colleagues are talking about. These eruptions seem to have an unfortunate side effect; the 1783 Laki eruption in Iceland, for instance, weakened the Indian monsoon and cut rains in the Sahel, in Africa, to boot[5].

> **"Geoengineering is like a junkie figuring out new ways of stealing from his children."**
> — Meinrat Andreae

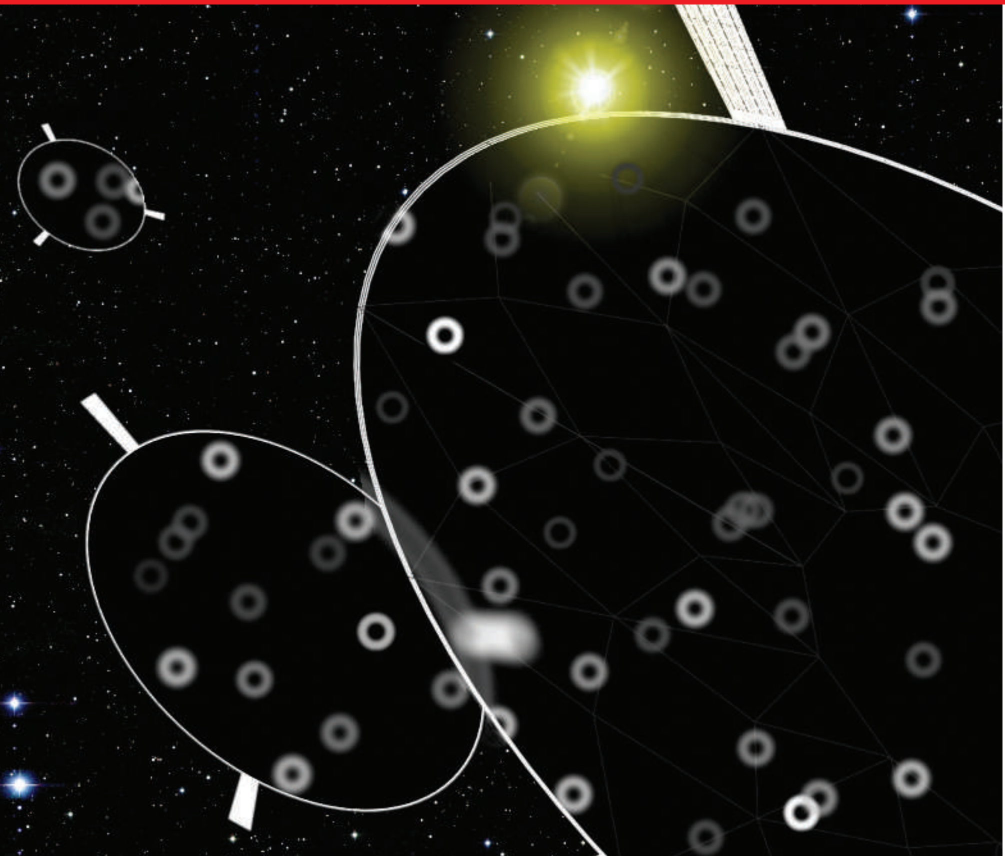
The fact that that is what seems to have happened in the past does not necessarily mean that it would happen in a geoengineered future. But it is easily argued that betting the monsoon on the ability of models to accurately capture such subtleties would require a foolhardy level of trust, a remarkable lack of concern for hundreds of millions of livelihoods or a startling desperation in the face of the alternative.

One source of such problems is the fact that the stratosphere is not just a sheet of glass to be tinted at will. It is a circulating system in which physics and chemistry interact; it is tied to the troposphere below in complex ways that greenhouse warming is already changing; and aerosols warm it or cool it in different ways depending on the size of the particles involved. True, compared with most other components in Earth's system it is relatively simple. (For a start, nothing lives there.) But it still has its subtleties.

A tempting way around this problem is to put the sunblock even higher — in orbit, where among other things it can be turned off at will. Discussions of orbital sunshades have been around almost as long as those of artificial volcanoes. The most technically sophisticated was published by Roger Angel of the University of Arizona, Tucson, last year[6].

Up and away

Angel was looking for a way to put up a sunshade that, unlike earlier proposals, did not require humans in orbit or the resources to be found on the Moon or nearby asteroids. His solution was to use a fleet of almost-transparent 'fliers', the size of dustbin lids, that would be launched from Earth in prepacked stacks by means of a vast electromagnetic cannon. Once in orbit, the gossamer-thin fliers would



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Trillions of sliver-like fliers could be used to shield the Earth from the Sun's rays.

peel off these stacks and arrange themselves in orbits that keep them between the Earth and the Sun at almost all times. The shadow of this cloud of spacecraft 1.85 million kilometres away, Angel calculated, would be a little larger than the Earth, and would cut down sunlight by about 1.8%. The details of Angel's proposal are meticulously worked out, and their cost is suitably astronomical — about $5 trillion, or a decade's worth of US defence spending. The cannons, and the power systems required to pulse gigawatts through them on demand, are impressive but borderline plausible. The really mind-boggling bit is the sheer number of fliers required to do the job: 16 trillion. The US military gets through 1.5 billion bullets a year. If fliers could be mass-produced at a hundred times the rate that those bullets are, it would still take a century to produce enough of them.

Setting the standard

Nevertheless, Ralph Cicerone, a climate scientist and president of the US National Academy of Sciences (and one of those who shared Crutzen's Nobel prize), singles the paper out for praise for the painstakingly careful way it was done. "He went back to it again and again," Cicerone says. "In its standard of elegance and completeness it was exemplary." For him and many others, such academic excellence is the main point of publishing research on geoengineering. For these researchers, the aim is not to find feasible solutions but to do good science that provides a standard against which to judge the less good, or flatly foolish, schemes that might otherwise accrete around the idea. Cicerone points to quack schemes for ozone replacement in the 1980s as the sort of thing that needs to be forestalled: back then, he says, "poor ideas got as far as they did because of [the community's] silence."

Cicerone says he would welcome a body of work on geoengineering that is substantial enough to deserve a chapter of its own in the next IPCC assessment report, due in about six years. At the same time, he favours a moratorium on any moves towards deploying such a system, and agrees with the consensus of the climate community that much greater efforts towards mitigation of emissions remain the highest priority. After all, no one thinks that, in the short term, a world cooled by engineering would be preferable to one cooled by a reduction in carbon dioxide levels. And no one thinks that, as yet, we know enough to embark on any sort of large-scale engineering. Models of geoengineering's benefits need to be a lot more accurate than models of the harm that will be done in its absence. As Caldeira puts it, if you can be no more precise about the chances of harm under the status quo than to give them as 50%, that's still something to worry about. But if a proposed intervention has a 50-50 chance of doing good or harm, that's something to avoid.

> "How can you engineer a system whose behaviour you don't understand?"
> — Ronald Prinn

A few voices argue that it is too late for this thinking — that we are already engineering nature by exerting a vast influence over the nitrogen cycle, the carbon cycle, the radiative balance of the atmosphere and everything else. In this sense we live in an engineered world, and the question is simply how to engineer it better. But in the scientific community this argument has achieved little traction. The key point, articulated by climate scientist David Keith from the University of Calgary in Canada, is that making a mess is not the same as engineering. Humanity has shown a great capacity to make a mess, mostly as a side effect of just trying to make a living. But that is not engineering. Engineering involves intention.

That is why economist and philosopher Herbert Simon famously grouped it with the social and some of the human sciences under the rubric of 'the sciences of the artificial', a category created as a deliberate counterpart to the intention- and imperative-free natural sciences.

Artificial intelligence

Although in the past two decades climate scientists have been confronted with the social, technological and economic implications of their work, they are not scientists of the artificial. Hans Feichter, a climate modeller at the Max Planck Institute for Meteorology in Hamburg, speaks for the vast majority of his colleagues when he says "the role of a geoscientist is to understand nature, not to change it." Climate scientists have proved themselves happy to advocate massive changes aimed at shifting the climate. But they are massive changes in technology, in geopolitics, in social norms — changes that require the sciences of the artificial. Not changes in the workings of the stratosphere. Not changes in the natural.

In the past year, climate scientists have shown new willingness to study the pathways by which the Earth might be deliberately changed, although many will do so in large part simply to show, with authority, that all such paths are dead-end streets. But they are not willing to abandon the realm of natural science, and commit themselves to an artificial Earth. ■

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See Editorial, page 115.