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The Big Fix

How geoengineers are trying to save the world.

by Cynthia Graber

THE RUMBLINGS BEGAN IN MARCH 1991 AT MT. PINATUBO IN THE PHILIPPINES. GEOLOGISTS RUSHED TO THE SCENE TO STUDY THE RESTLESS VOLCANO. IN APRIL, THE MOUNTAIN SENT UP WARNING EXPLOSIONS THAT SPRINKLED ASH ON NEARBY VILLAGES, AND TENS OF THOUSANDS OF PEOPLE WERE EVACUATED. FINALLY, ON JUNE 15, THE PRESSURE HIT ITS LIMIT, AND THE VOLCANO ERUPTED, BELCHING LAVA, SMOKE, AND MILLIONS OF TONS OF SULFUR DIOXIDE GAS INTO THE ATMOSPHERE. HUNDREDS OF PEOPLE WERE KILLED AND MORE THAN 100,000 WERE LEFT HOMELESS.

As devastating as it was, the eruption provided climate scientists with a unique opportunity. This was the second-largest eruption of the 20th century, and the first to occur when scientists had satellites in place to measure the results. The sulfur dioxide that spewed from the mouth of the volcano created a haze far up in the stratosphere, the upper limits of our atmosphere. The haze reflected sunlight away from Earth, cooling the planet by almost one degree Fahrenheit (half a degree Celsius) over the two years that followed.

Scientists saw this as a ready-made scientific experiment: what happens when we pump sulfur dioxide into the upper atmosphere? Could this provide clues to dealing with a climate overheated by global warming? If Earth gets too warm, can we—and should we—mimic the volcano to cool the planet down?

This idea is part of a field of research known as geoengineering.

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How'd We Get Here?

The sun's rays penetrate our atmosphere to warm up Earth's surface. A naturally occurring combination of gases traps some of that heat, insulating the planet just enough to support life. But the gases that we've been releasing since the Industrial Revolution in the 1700s, when we began using machinery on a massive scale, are contributing to a thicker blanket, or stronger insulation, and an increasingly hot planet.

Scientists agree that Earth is heating up and that humans are causing the bulk of the warming. We're already seeing repercussions, as glaciers shrink in the Himalayas and ice melts in the Arctic. The results could be dramatic and, in some regions of the world, catastrophic: rising ocean levels, increasing droughts, and intensifying tropical storms.

Nobody can project exactly when any of this could take place, exactly how much the temperature may rise over the coming decades, or exactly what changes will occur. But nearly all scientists who study the climate are worried, and they agree that we need to make drastic reductions in our use of fossil fuels, such as coal, gasoline, and natural gas, which release carbon dioxide (CO_2) when burned. As sunlight heats Earth, the planet sends some of that heat back toward space as infrared radiation. CO_2 is called a greenhouse gas because it traps this infrared radiation, warming the planet.

As climate change grows more dire, researchers are becoming more interested in geoengineering—possible technological solutions to fight Earth's warming and its effects, whether by cooling the planet down or by sucking greenhouse gases out of the atmosphere.

Another reason for the increasing popularity of geoengineering research is that carbon dioxide has this annoying habit of sticking around. Each year, we release more than 36 billion metric tons of CO_2 (a metric ton is 1,000 kilograms, or about 2,200 pounds) through activities as varied as fueling cars with gasoline, burning coal for power plants, even cutting and burning forests for agriculture. That carbon dioxide will persist in the atmosphere for 50 to 200 years. Some could even stick around for thousands. So, even if we were to suddenly cut all CO_2 emissions to zero—something most people agree is nearly impossible—some of the carbon dioxide we've already released could remain in the atmosphere for a long time. Plus, around the world, the amount of greenhouse gas we're releasing continues to rise.

A LOT OF HOT AIR

Humans release more than 36 billion metric tons of carbon dioxide every year. Since it's hard to imagine how much that really is, here's a handy conversion table.

Unit	Number needed to weigh 36 billion metric tons
Beluga whale	15.6 billion
Flat-screen TV	3.2 trillion
Rhesus macaque	5.3 trillion
Cell phone	330 trillion
American cockroach	60 quadrillion

Learning from a Volcano

The eruption of Mt. Pinatubo gave scientists a useful controlled experiment. They knew exactly how much sulfur dioxide (SO_2) the explosion added to the atmosphere, and they were able to watch it spread and monitor the changes it caused in the climate over two years. (Unlike CO_2, which traps heat, SO_2 forms particles in the atmosphere that reflect sunlight, preventing some of it from reaching Earth's surface.)

Scientists then plugged all that information into computer models to learn how those changes in the atmosphere affected the climate. From volcanoes, some scientists got the idea that we could cool the planet by pumping SO_2 up into the stratosphere.

Ken Caldeira, at the Carnegie Institution for Science, says that at first he thought this was a crazy notion. Caldeira is a climate change modeler, which means he inserts variables such as CO_2 and SO_2 levels into computer programs to test how changes in those variables affect the climate. "It's sort of like playing a video game," he explains. After hearing about a scheme to inject sulfur dioxide into the atmosphere, he set about modeling what might happen. He thought it wouldn't work because sunlight warms different parts of the world unequally, depending on latitude, elevation, and a region's weather. To his surprise, the results of his calculations show that this plan could, in fact, cool the planet.

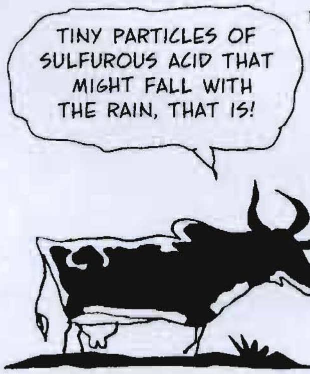
"Basically, any type of dust would work," says Caldeira. "But the particles must be very fine. Sulfur has the benefit that it can be put up as a gas." When it reacts with water and oxygen in the stratosphere, it turns into tiny particles that reflect sunlight.

This isn't, however, a simple undertaking. First, how would we get the gas up into the stratosphere? And it couldn't be a one-time event. The effects of Mt. Pinatubo lasted only two years, and scientists say if we undertook a solution such as this, we would have to keep it going for generations—unless we removed carbon dioxide from the atmosphere at the same time. They're also not sure that it would work: maybe the particles would clump together, maybe they wouldn't reflect as well as we expect, maybe they'd just fall back down to Earth. Some researchers say that other types of particles might be better at reflecting sunlight and less likely to clump together.

A high-flying plane called the ER-2 soars above the clouds. David Keith thinks planes like this could be used to release sulfur dioxide into the stratosphere, creating a protective haze over the planet.

To better predict the success of this approach, researchers must create more detailed models of what to do and what the effects might be. Then they have to test the process in the sky.

David Keith, a climate researcher at Canada's University of Calgary, proposes using special high-flying planes that can soar 75,000 feet (22,860 meters) up into the stratosphere. These planes would release plumes of gas—such as the proposed sulfur dioxide—and then fly back and forth through the plumes. Researchers could evaluate whether the released gas forms the desired particles, and at what size, and whether they effectively reflect sunlight back into space.



Even if demonstrated to work, this plan involves plenty of potential

who decides when it's time to try something as drastic as spreading a haze above the planet?

hazards. Alan Robock, a professor of environmental science at Rutgers University, has been carefully studying the Mt. Pinatubo eruption. He says that instead of inspiring us to mimic a volcano, Mt. Pinatubo should serve as a warning. After the volcano erupted, the haze affected evaporation and rainfall. That year produced some of the least rainfall in history, causing extensive droughts. Decreased sunlight caused by SO_2 haze could have a significant impact on weather all over the world.

Plus, if fewer of the sun's rays reach Earth, how would that affect the growth of plants and food crops? And there are also political implications: for instance, who decides when it's time to try something as drastic as spreading a haze above the planet? What happens if a rich country tries this out, but a poor country suffers worse droughts or storms? Alan Robock worries this could lead to war, as does David Keith.

But maybe this scheme could be used in a limited area. Michael MacCracken at the Climate Institute proposes one such approach. Scientists are particularly worried about the North and South Poles, which are showing the effects of global warming before most of the rest of the world. If the ice on Greenland and Antarctica continues to melt, it could contribute to the rise of sea levels. The melting of Arctic sea ice could disrupt food chains in the ocean. Also, that huge swath of white ice reflects sunlight. If it disappears, the planet could get even hotter.

MacCracken suggests imitating the effects of the SO_2 that comes out of coal-fired power plants, which creates a white haze and tends to cool the lower atmosphere. Testing the scheme over the Arctic could reduce the rate of warming there and help the area keep its ice cover.

Soggy Mirrors

Decades ago, John Latham was strolling in the mountains of Wales (near England) with his son, Mike, who was then eight years old. The setting sun lit up the clouds with a brilliant glow. Mike turned to his dad and asked, "Why are the clouds so bright and shiny?" Latham explained that the clouds are bright because they're made up of little water droplets that reflect and bounce sunlight around. Mike laughed and said, "Soggy mirrors!"

That idea struck him years later, says Latham. "I was thinking about whether I could apply what I know about clouds to climate change, and Mike's phrase came to mind." Latham is an expert in cloud physics and global warming. He thought about the enormous cover of low-lying clouds that hovers over about one-third of the world's oceans. Those clouds don't move much. Could we make that cloud cover even brighter to reflect more sunlight away from the atmosphere?

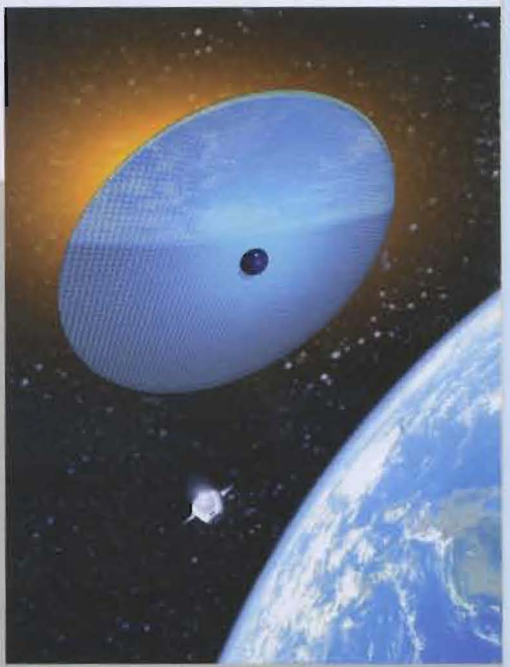
The ocean clouds already bounce back about 50 percent of the sunlight that strikes them. Latham thinks we could increase that reflectivity to 60 percent, which could significantly cool off the planet.

It works like this: each water drop in a cloud reflects a certain amount of light. Smashing those water droplets into smaller drops would create more surface area to reflect even more sunlight. Instead of smashing drops, though, Latham wants to make more drops by sending up particles that will attract water. Salt, for instance, could form the core of cloud droplets. If we can seed the clouds with tiny particles of salt, then drops will grow on them. So the number of drops in the clouds will increase, and the clouds will bounce more sunlight back up into space.

How would this be accomplished? Latham envisions boats out in the ocean pumping seawater through billions of small holes. This would break the seawater into tiny droplets and salt particles that are then sprayed up through spinning cylinders, like upside-down watering cans, into the clouds. More salt will make more droplets, and brighter clouds.

Latham and his collaborators are currently developing a test boat.

With this scheme as well, much more research is needed. How much cooling is enough? What would it mean to the surface of the ocean if less sunlight reached it? Could that interfere with marine food chains? Surface water temperatures affect wind and weather around the world, so how might this change weather patterns? Could it lead to less evaporation and less rainfall? These questions must all be answered.



SPACE MIRRORS AND COPEPOD BUFFETS

When it comes to climate-cooling schemes, science often sounds like science fiction. Imitating a volcano and making the clouds brighter are two of the most popular geoengineering ideas, but they're far from the only ones.

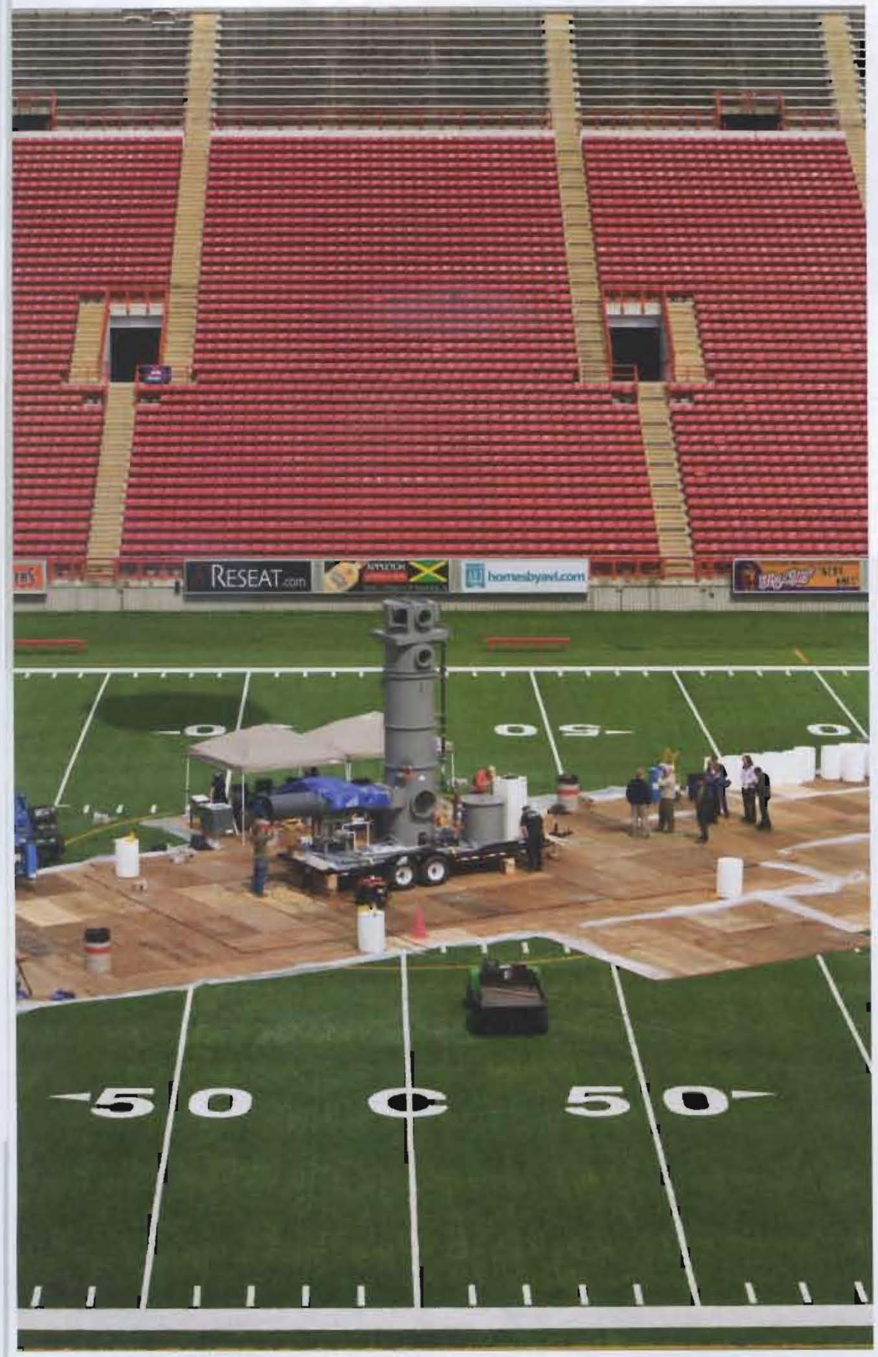
This computer artwork shows one of the more far-fetched proposals: a giant mirror that would orbit Earth and bounce sunlight away from the planet. A similar idea calls for a fleet of tiny, orbiting mirrors—thousands, or even millions. One astronomer described a plan to launch into orbit, instead of millions of mirrors, *trillions* of fragile lenses that would bend light away from our planet. These ideas are probably too costly and difficult to be realistic.

Some schemes involve sunlight reflectors that wouldn't need to be all the way in outer space. Shiny, hydrogen-filled balloons, for example, could be launched into the atmosphere billions at a time, where they would float above airplane traffic and block the sun. (The amount of trash these balloons would create when they eventually fell to earth is a little daunting.) Or reflective materials could be spread across deserts, or floated on top of the ocean (never mind how this might affect desert or ocean ecosystems).

In 2009, a team of German and Indian scientists were able to actually test another geoengineering idea: fertilizing the ocean with iron. The scientists dumped 13,000 pounds (6,000 kilograms) of iron into the southern Atlantic Ocean, hoping the fertilizer would cause a huge amount of algae to grow on the ocean's surface. This algal bloom would suck carbon dioxide out of the air, just as trees do. When the algae died and sank to the bottom of the ocean, they would take all that carbon with them, hiding it far away from the atmosphere.

The experiment worked at first: the iron caused lots of algae to grow. But that algae patch was just one big lunch buffet for tiny crustaceans called copepods, which gobbled it all up. This showed researchers that dumping iron in the ocean will probably not help take carbon out of the atmosphere—and that real life doesn't always work like a computer model.

—*E. P.*



David Keith's carbon scrubber is demonstrated on a football field. (We're waiting for the pocket-sized version.)

A Giant Sucking Machine

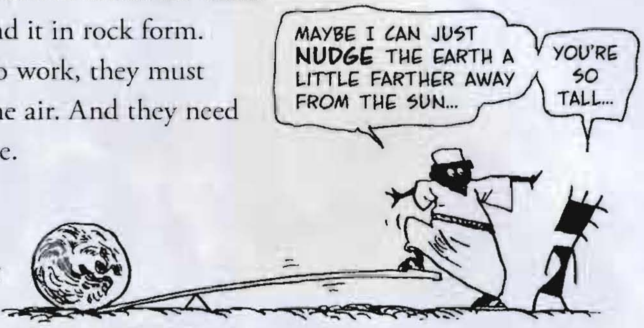
Even if these plans work, they won't solve all the problems global warming causes. First of all, unless we rid the atmosphere of existing greenhouse gases, we'd theoretically have to continue the cooling schemes for decades, if not centuries. As soon as we stop, the climate might heat right back up again. Plus, carbon dioxide threatens more than Earth's temperature. As the oceans absorb it, they become increasingly acidic, which is already starting to bleach and kill coral reefs and eat away at the shells of sea creatures. So scientists are also discussing ways to suck carbon dioxide out of the atmosphere.

The most obvious and least controversial approach is as simple as planting more trees, which naturally absorb and trap CO_2. While this is probably part of the answer, it might not work fast enough, or take enough carbon dioxide out of circulation. So researchers are coming up with geoengineering solutions.

David Keith has a plan, and he started a company to make it a reality. He and his colleagues are developing a giant sucking machine that pulls air in at one end and brings it into contact with a liquid that captures the carbon dioxide. Then the cleaned-up air is exhaled out the other end of the machine. The captured carbon dioxide can be collected and stored.

Instead of a liquid, Klaus Lackner at Columbia University has devised a solid material composed of a substance that carbon dioxide gloms onto—a sort of artificial tree. When the material is heated up, it releases the gas, which can then be easily captured. Another team at Columbia is studying rocks that naturally react with carbon dioxide to form different minerals. These could remove the gas from the atmosphere and bind it in rock form.

These ideas are all still in the testing phase. To work, they must produce less carbon dioxide than they pull from the air. And they need to operate at a cost that isn't outrageously expensive.



No Cure-All

Until recently, most scientists have been reluctant to discuss geoengineering publicly. They worried that people would latch onto these technological fixes and think that if we can manage climate change with technology, we don't need to worry about global warming or reduce our greenhouse gas emissions. But now, scientists say, the problem isn't going away, so it might be time for drastic measures.

How can we learn more about which geoengineering approaches might work and what the results might be? The answer is simple: research. Even though more people are discussing potential plans, very few scientists—only a few dozen in the entire world—are devoting significant time and research to studying how geoengineering plans could be carried out, whether the schemes would work, and what their intended and unintended consequences might be.

Part of the appeal of geoengineering is that it seems to be relatively cheap—at least, it seems cheaper than finding alternatives to coal and gasoline. Plus, some of the approaches would be fast acting. It might take a long time to switch the way we generate electricity from fossil fuels to solar power, but potentially, with geoengineering, cooling could begin almost immediately.

But geoengineering is far from perfect. Scientists agree that many of these technological fixes could cause any number of side effects, such as droughts or storms, or they could affect how crops grow. But, in case of emergency—in case we can't reduce emissions quickly enough, and global warming affects the planet in ways that are so harmful as to be unacceptable—scientists say that we need to do the research so we're ready with geoengineering solutions.

Cynthia Graber is a journalist living in Massachusetts. Her reporting appears in many publications, including Scientific American's *"60-Second Science" podcasts, which you can find at scientificamerican.com. To reduce her own carbon emissions, she's traded in her car for a pogo stick.*