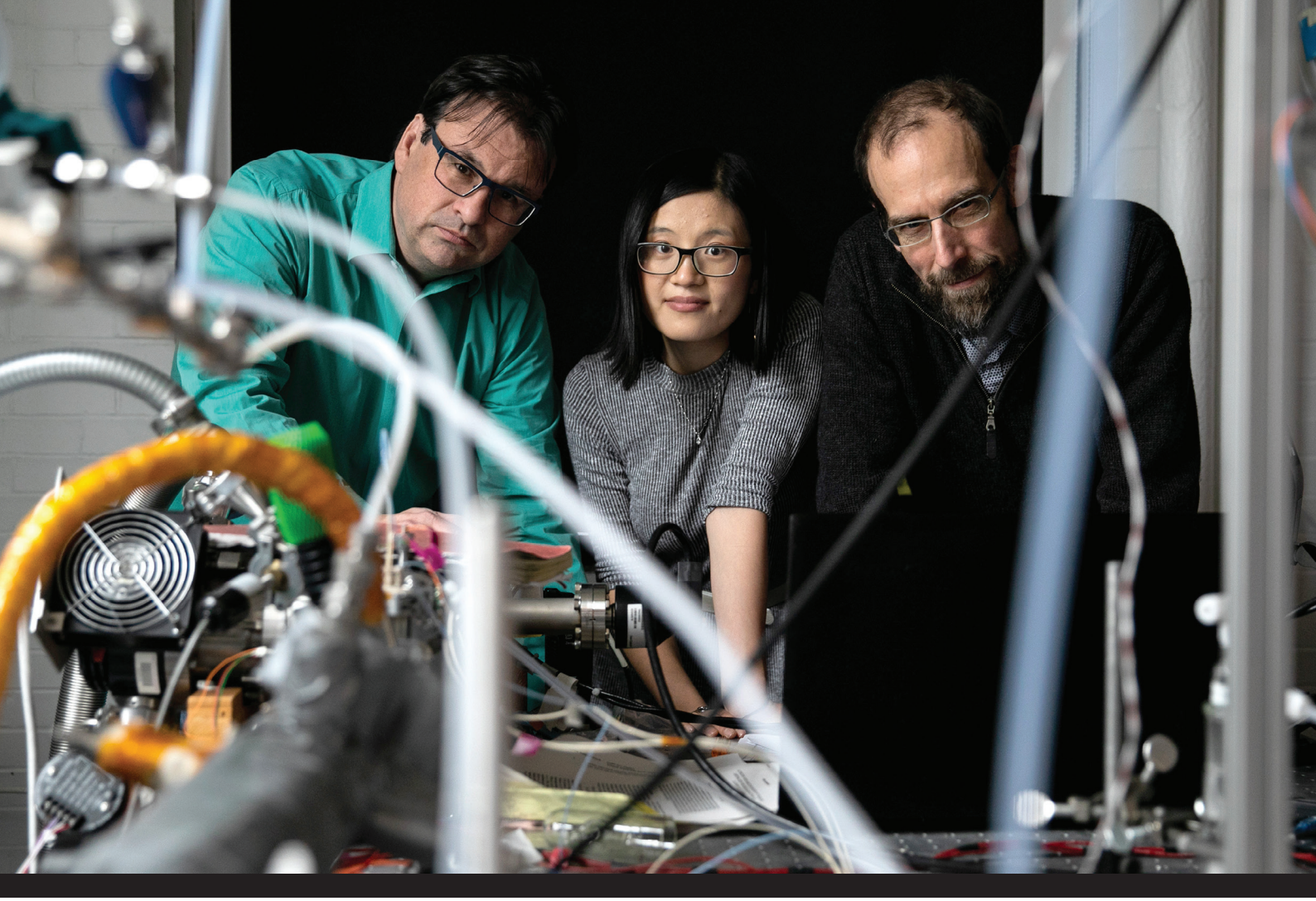


KAYANA SZYMCZAK

THE SUN DIMMERS

With dire climate scenarios on the horizon, researchers are getting serious about solar geoengineering.

BY JEFF TOLLEFSON

Zhen Dai holds up a small glass tube coated with a white powder: calcium carbonate, a ubiquitous compound used in everything from paper and cement to toothpaste and cake mixes. Plop a tablet of it into water, and the result is a fizzy antacid that calms the stomach. The question for Dai, a doctoral candidate at Harvard University in Cambridge, Massachusetts, and her colleagues is whether this innocuous substance could also help humanity to relieve the ultimate case of indigestion: global warming caused by greenhouse-gas pollution.

The idea is simple: spray a bunch of particles into the stratosphere, and they will cool the planet by reflecting some of the Sun's rays back into space. Scientists have already witnessed the principle in action. When Mount Pinatubo erupted in the Philippines in 1991, it injected an estimated 20 million tonnes of sulfur dioxide into the stratosphere — the atmospheric layer that stretches from about 10 to 50 kilometres above Earth's surface. The eruption created a haze of sulfate particles that cooled the planet by around 0.5 °C. For about 18 months, Earth's average temperature returned to what it was before the arrival of the steam engine.

The idea that humans might turn down Earth's thermostat by similar, artificial means is several decades old. It fits into a broader class of planet-cooling schemes known as geoengineering that have long generated intense debate and, in some cases, fear.

Frank Keutsch, Zhen Dai and David Keith (left to right) in Keutsch's laboratory at Harvard University.

Researchers have largely restricted their work on such tactics to computer models. Among the concerns is that dimming the Sun could backfire, or at least strongly disadvantage some areas of the world by, for example, robbing crops of sunlight and shifting rain patterns.

But as emissions continue to rise and climate projections remain dire, conversations about geoengineering research are starting to gain more traction among scientists, policymakers and some environmentalists. That's because many researchers have come to the alarming conclusion that the only way to prevent the severe impacts of global warming will be either to suck massive amounts of carbon dioxide out of the atmosphere or to cool the planet artificially. Or, perhaps more likely, both.

If all goes as planned, the Harvard team will be the first in the world to move solar geoengineering out of the lab and into the stratosphere, with a project called the Stratospheric Controlled Perturbation Experiment (SCoPEx). The first phase — a US$3-million test involving two flights of a steerable balloon 20 kilometres above the southwest United States — could launch as early as the first half of 2019. Once in place, the

experiment would release small plumes of calcium carbonate, each of around 100 grams, roughly equivalent to the amount found in an average bottle of off-the-shelf antacid. The balloon would then turn around to observe how the particles disperse.

The test itself is extremely modest. Dai, whose doctoral work over the past four years has involved building a tabletop device to simulate and measure chemical reactions in the stratosphere in advance of the experiment, does not stress about concerns over such research. "I'm studying a chemical substance," she says. "It's not like it's a nuclear bomb."

Nevertheless, the experiment will be the first to fly under the banner of solar geoengineering. And so it is under intense scrutiny, including from some environmental groups, who say such efforts are a dangerous distraction from addressing the only permanent solution to climate change: reducing greenhouse-gas emissions. The scientific outcome of SCoPEx doesn't really matter, says Jim Thomas, co-executive director of the ETC Group, an environmental advocacy organization in Val-David, near Montreal, Canada, that opposes geoengineering: "This is as much an experiment in changing social norms and crossing a line as it is a science experiment."

Aware of this attention, the team is moving slowly and is working to set up clear oversight for the experiment, in the form of an external advisory committee to review the project. Some say that such a framework, which could pave the way for future experiments, is even more important than the results of this one test. "SCoPEx is the first out of the gate, and it is triggering an important conversation about what independent guidance, advice and oversight should look like," says Peter Frumhoff, chief climate scientist at the Union of Concerned Scientists in Cambridge, Massachusetts, and a member of an independent panel that has been charged with selecting the head of the advisory committee. "Getting it done right is far more important than getting it done quickly."

JOINING FORCES

In many ways, the stratosphere is an ideal place to try to make the atmosphere more reflective. Small particles injected there can spread around the globe and stay aloft for two years or more. If placed strategically and regularly in both hemispheres, they could create a relatively uniform blanket that would shield the entire planet (see 'Global intervention'). The process does not have to be wildly expensive; in a report last month, the Intergovernmental Panel on Climate Change suggested that a fleet of high-flying aircraft could deposit enough sulfur to offset roughly 1.5 °C of warming for around $1 billion to $10 billion per year[1].

Most of the solar geoengineering research so far has focused on sulfur dioxide, the same substance released by Mount Pinatubo. But sulfur might not be the best candidate. In addition to cooling the planet, the aerosols generated in that eruption sped up the rate at which chlorofluorocarbons deplete the ozone layer, which shields the planet from the Sun's harmful ultraviolet radiation. Sulfate aerosols are also warmed by the Sun, enough to potentially affect the movement of moisture and even alter the jet stream. "There are all of these downstream effects that we don't fully understand," says Frank Keutsch, an atmospheric chemist at Harvard and SCoPEx's principal investigator.

> *"There are all of these downstream effects that we don't fully understand."*

The SCoPEx team's initial stratospheric experiments will focus on calcium carbonate, which is expected to absorb less heat than sulfates and to have less impact on ozone. But textbook answers — and even Dai's tabletop device — can't capture the full picture. "We actually don't know what it would do, because it doesn't exist in the stratosphere," Keutsch says. "That sets up a red flag."

SCoPEx aims to gather real-world data to sort this out. The experiment began as a partnership between atmospheric chemist James Anderson of Harvard and experimental physicist David Keith, who moved to the university in 2011. Keith has been investigating a variety of geoengineering options off and on for more than 25 years. In 2009, while at the University of Calgary in Canada, he founded the company Carbon Engineering, in Squamish, which is working to commercialize technology to remove carbon dioxide from the atmosphere. After joining Harvard, Keith used research funding he had received from Microsoft co-founder Bill Gates to begin planning the experiment.

Keutsch, who got involved later, is not a climate scientist and is at best a reluctant geoengineer. But he worries about where humanity is heading, and what that means for his children's future. When he saw Keith talk about the SCoPEx idea at a conference after starting at Harvard in 2015, he says his initial reaction was that the idea was "totally insane". Then he decided it was time to engage. "I asked myself, an atmospheric chemist, what can I do?" He joined forces with Keith and Anderson, and has since taken the lead on the experimental work.

AN EYE ON THE SKY

Already, SCoPEx has moved farther along than earlier solar geoengineering efforts. The UK Stratospheric Particle Injection for Climate Engineering experiment, which sought to spray water 1 kilometre into the atmosphere, was cancelled in 2012 in part because scientists had applied for patents on an apparatus that could ultimately affect every human on the planet. (Keith says there will be no patents on any technologies involved in the SCoPEx project.) And US researchers with the Marine Cloud Brightening Project, which aims to spray saltwater droplets into the lower atmosphere to increase the reflectivity of ocean clouds, have been trying to raise money for the project for nearly a decade.

Although SCoPEx could be the first solar geoengineering experiment to fly, Keith says other projects that have not branded themselves as such have already provided useful data. In 2011, for example, the Eastern Pacific Emitted Aerosol Cloud Experiment pumped smoke into the lower atmosphere to mimic pollution from ships, which can cause clouds to brighten by capturing more water vapour. The test was used to study the effect on marine clouds, but the results had a direct bearing on geoengineering science: the brighter clouds produced a cooling effect 50 times greater than the warming effect of the carbon emissions from the researchers' ship[2].

Keith says that the Harvard team has yet to encounter public protests or any direct opposition — aside from the occasional conspiracy theorist. The challenge facing researchers, he says, stems more from a fear among science-funding agencies that investing in geoengineering will lead to protests by environmentalists.

To help advance the field, Keith set a goal in 2016 of raising $20 million to support a formal research programme that would cover not just the experimental work, but also research into modelling, governance and ethics. He has raised around $12 million so far, mostly from philanthropic sources such as Gates; the pot provides funding to dozens of people, largely on a part-time basis.

Keith and Keutsch also want an external advisory committee to review SCoPEx before it flies. The committee, which is still to be selected, will report to the dean of engineering and the vice-provost for research at Harvard. "We see this as part of a process to build broader support for research on this topic," Keith says.

Keutsch is looking forward to having the guidance of an external group, and hopes that it can provide clarity on how tests such as his should proceed. "This is a much more politically challenging experiment than I had anticipated," he says. "I was a little naive."

SCoPEx faces technical challenges, too. It must spray particles of the right size: the team calculates that those with a diameter of about 0.5 micrometres should disperse and reflect sunlight well. The balloon must also be able to reverse its course in the thin air so that it can pass through its own wake. Assuming the team is able to find the calcium carbonate plume — and there is no guarantee that they can — SCoPEx needs instruments that can analyse the particles and, it is hoped, carry samples back to Earth.

"It's going to be a hard experiment, and it may not work," says David

PAUL JACKMAN/*NATURE*

Fahey, an atmospheric scientist at the National Oceanic and Atmospheric Administration in Boulder, Colorado. In the hope that it will, Fahey's team has provided SCoPEx with a lightweight instrument that can reliably measure the size and number of particles that are released. The balloon will also be equipped with a laser device that can monitor the plume from afar. Other equipment that could collect information on the level of moisture and ozone in the stratosphere could fly on the balloon as well.

UP TO THE STRATOSPHERE

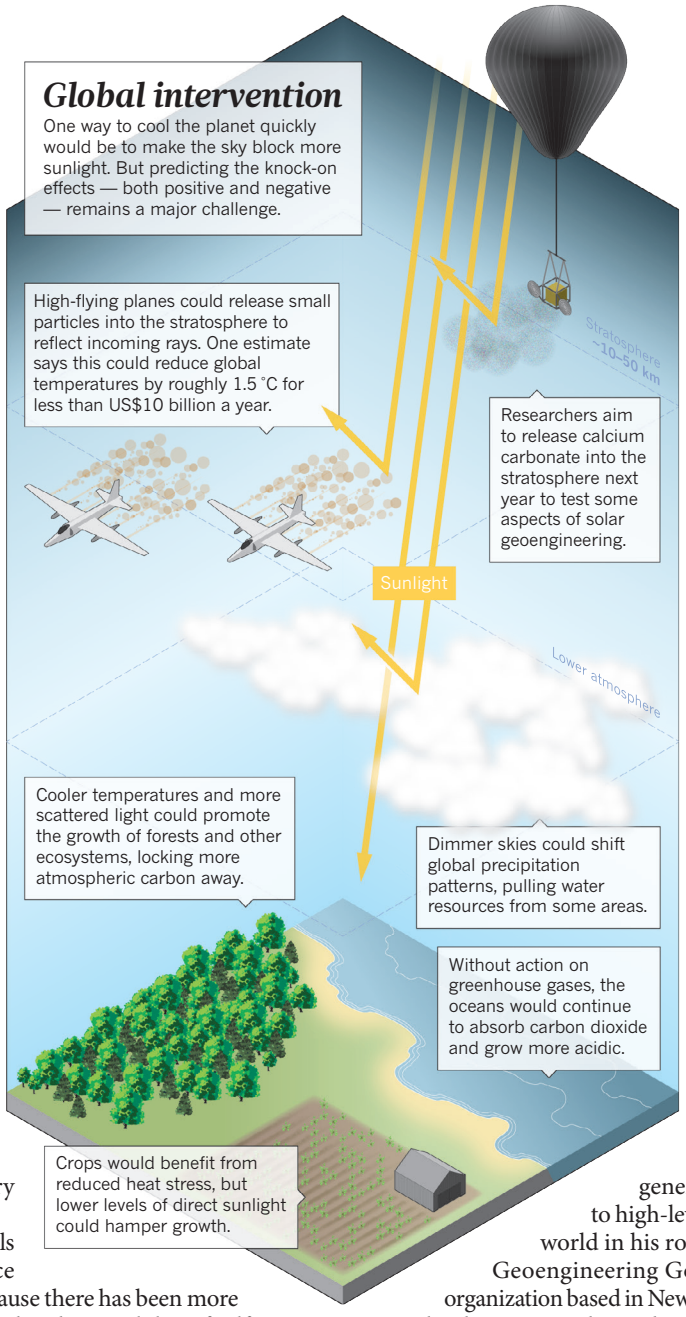
Keutsch and Keith are still working out some of the technical details. Plans with one balloon company fell through, so they are now working with a second. And an independent team of engineers in California is working on options for the sprayer. To simplify things, the SCoPEx group plans to fly the balloon during the spring or autumn, when stratospheric winds shift direction and — for a brief period — calm down, which will make it easier to track the plume.

For all of these reasons, Keutsch characterizes the first flight as an engineering test, mainly intended to demonstrate that everything works as it should. The team is ready to spray calcium carbonate particles, but could instead use salt water to test the sprayer if the advisory committee objects.

Keith still thinks that sulfate aerosols might ultimately be the best choice for solar geoengineering, if only because there has been more research about their impact. He says that the possibility of sulfates enhancing ozone depletion should become less of a concern in the future, as efforts to restore the ozone layer through pollutant reductions continue. Nevertheless, his main hope is to establish an experimental programme in which scientists can explore different aspects of solar geoengineering.

There are a lot of outstanding questions. Some researchers have suggested that solar geoengineering could alter precipitation patterns and even lead to more droughts in some regions. Others warn that one of the possible benefits of solar geoengineering — maintaining crop yields by protecting them from heat stress — might not come to pass. In a study published in August, researchers found that yields of maize (corn), soya, rice and wheat[3] fell after two volcanic eruptions, Mount Pinatubo in 1991 and El Chichón in Mexico in 1982, dimmed the skies. Such reductions could be enough to cancel out any potential gains in the future.

Keith says the science so far suggests that the benefits could well outweigh the potential negative consequences, particularly compared with a world in which warming goes unchecked. The commonly cited drawback is that shielding the Sun doesn't affect emissions, so greenhouse-gas levels would continue to rise and the ocean would grow even more acidic. But he suggests that solar geoengineering could reduce the amount of carbon that would otherwise end up in the atmosphere, including by minimizing the loss of permafrost, promoting forest growth and reducing the need to cool buildings. In an as-yet-unpublished analysis of precipitation and temperature extremes using a high-resolution climate model, Keith and others found that nearly all regions of the world would benefit from a moderate solar geoengineering programme. "Despite all of the concerns, we can't find any areas that would be definitely worse off," he says. "If solar geoengineering is as good as what is shown in these models, it would be crazy not to take it seriously."



There is still widespread uncertainty about the state of the science and the assumptions in the models — including the idea that humanity could come together to establish, maintain and then eventually dismantle a well-designed geoengineering programme while tackling the underlying problem of emissions. Still, prominent organizations, including the UK Royal Society and the US National Academies of Sciences, Engineering, and Medicine, have called for more research. In October, the academies launched a project that will attempt to provide a blueprint for such a programme.

Some organizations are already trying to promote discussions among policymakers and government officials at the international level. The Solar Radiation Management Governance Initiative is holding workshops across the global south, for instance. And Janos Pasztor, who handled climate issues under former UN secretary-general Ban Ki-moon, has been talking to high-level government officials around the world in his role as head of the Carnegie Climate Geoengineering Governance Initiative, a non-profit organization based in New York. "Governments need to engage in this discussion and to understand these issues," Pasztor says. "They need to understand the risks — not just the risks of doing it, but also the risks of not understanding and not knowing."

One concern is that governments might one day panic over the consequences of global warming and rush forward with a haphazard solar-geoengineering programme, a distinct possibility given that the costs are cheap enough that many countries, and perhaps even a few individuals, could probably afford to go it alone. These and other questions arose earlier this month in Quito, Ecuador, at the annual summit of the Montreal Protocol, which governs chemicals that damage the stratospheric ozone layer. Several countries called for a scientific assessment of the potential effects that solar geoengineering could have on the ozone layer, and on the stratosphere more broadly.

If the world gets serious about geoengineering, Fahey says that there are plenty of sophisticated experiments that researchers could do using satellites and high-flying aircraft. But for now, he says, SCoPEx will be valuable — if only because it pushes the conversation forward. "Not talking about geoengineering is the greatest mistake we can make right now." ■

Jeff Tollefson *is a reporter for* Nature *in New York City.*

1. Intergovernmental Panel on Climate Change. *Global Warming of 1.5 °C* (IPCC, 2018).
2. Russell, L. M. *et al. Bull. Am. Meteorol. Soc.* **94**, 709–729 (2013).
3. Proctor, J., Hsiang, S., Burney, J., Burke, M. & Schlenker, W. *Nature* **560**, 480–483 (2018).

CORRECTION

The News Feature 'The sun dimmers' (*Nature* **563**, 613–615; 2018) said that David Keith received money from the Bill & Melinda Gates Foundation. In fact, the money came directly from Bill Gates.