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News & Highlights

Geoengineering Research Moves from Laboratory to Field

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In March 2023, a converted Cold War Bomber took off from Eielson Air Force Base in Alaska, USA, carrying a payload of delicate scientific instruments (Fig. 1). Operated by the US National Oceanic and Atmospheric Administration (NOAA), the flight aimed to collect a plethora of information about the Earth's stratosphere. Such exploration sounds routine, but the mission's goal is unusual for a government entity: to inform policy decisions surrounding large-scale, deliberate interventions to alter the stratosphere for climate change mitigation [1]. The approach of deflecting sunlight to cool the planet, called solar radiation management or solar geoengineering, was long considered a fringe idea. But with recent funding and attention from government agencies like NOAA, the approach is moving mainstream.

"A decade in, and hundreds of peer reviewed scientific papers later, this field—while still very much fledgling—is beginning to pick up momentum," said Gernot Wagner, a climate economist at Columbia Business School (New York City, NY, USA). Wagner was previously the founding executive director of Harvard University's Solar Geoengineering Research Program in Cambridge, MA, USA, which launched in 2016.

The premise of solar geoengineering is that certain particles in the stratosphere—most notably sulfates—reflect sunlight. Studies suggest that such particles released at a mass scale could help cool the planet and counteract global warming (Fig. 2) [2,3]. The idea gained traction after the 1991 eruption of Mount Pinatubo in the Philippines (Fig. 3), which released an estimated 13.6 million tonnes of SO_2 into the stratosphere and led to a drop in the average global temperature of about 0.5 °C [4]. Projects to recreate this effect artificially include using balloons, drones, or planes that slowly release sulfate particles to blasting seawater from special nozzles into the air to create a reflective mist—a technology that was tested in Australia in 2021 [5].

At the same time, large-scale ocean-based CO_2 removal efforts, sometimes also dubbed climate engineering, are also progressing toward field testing; in May 2022, for instance, scientists added thousands of liters of alkaline lime-enriched seawater to a Florida estuary to neutralize its acidic waters and draw CO_2 out of the atmosphere [6].

For many years, scientists shied away from such geoengineering research, in part because of the "double jeopardy" concern that it might take attention away from the more pressing need to cut CO_2 emissions [7]. But recent reports by the United Nations' Intergovernmental Panel on Climate Change have, for the first time, stressed the importance of more aggressive tactics to address climate change in tandem with the slow progress being made in decreasing carbon emissions. The 2022 report described solar geoengineering as a pathway to "reduce some climate impacts, reduce peak temperatures, lower mitigation costs, and extend the time available to achieve mitigation" [8].

Given support like this, government interest in geoengineering has picked up. In 2020, the US Congress ordered NOAA to develop a geoengineering research program. Then, a 2021 report by the US National Academy of Science and Medicine recommended allocating 200 million USD in funding to research geoengineering approaches [9]. Public funding has not yet hit those levels, with the current NOAA budget for so-called Earth Radiation sitting at 10 million USD a year [9]. However, both public and private ventures to study and test geoengineering efforts are increasing—and moving from modeling to real-world data collection and testing.

The NOAA research flight came on the heels of what most serious researchers considered more provocative and less useful tests of geoengineering. In one of these, in April 2022, commercial venture Make Sunsets (Box Elder, SD, USA) launched a balloon in Baja, California, Mexico, to release sulfur dioxide into the atmosphere [10]. Then, in September 2022, an independent researcher in the

Fig. 1. Scientists prepare instrumentation for a National Oceanic and Atmospheric Administration (NOAA) research jet flight that gathered extensive and detailed measurements of trace gases and aerosols in the stratosphere above the Arctic, with the goal of better understanding how geoengineering interventions could alter the global climate. Credit: Chelsea Thompson/NOAA (public domain).

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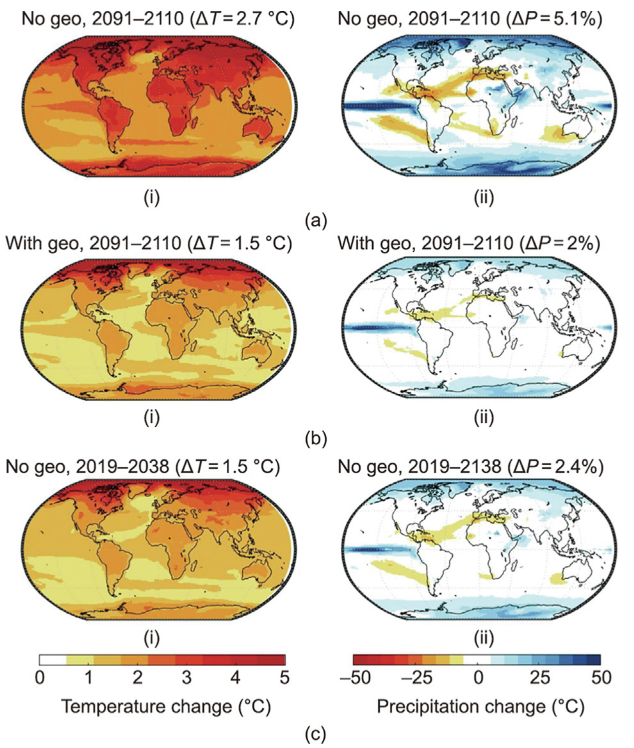

Fig. 2. (a–c) Modeling results have suggested that solar geoengineering (geo) could slow climate change impacts. In a 2018 paper [3], David Keith and colleagues projected that without geoengineering interventions the global mean temperature would increase (a-i) by 2.7 °C by the end of the century (2091–2110) and (c-i) by 1.5 °C by 2038; in contrast, (b-i) the use of solar geoengineering would limit the increase at the end of the century to 1.5 °C. Similarly, compared to (a-ii) a 5.1% increase in precipitation by the end of the century or (c-ii) a 2.4% increase by 2038 with no solar geoengineering, (b-ii) they projected that its use would limit the increase in precipitation to 2% by the end of the century. Credit: Douglas MacMartin/Wikimedia (CC BY-SA 4.0).

Fig. 3. The 1991 eruption of Mount Pinatabu in the Philippines injected about 13.6 million tonnes of SO_2 into the stratosphere and led to a drop in the average global temperature of about 0.6 °C, inspiring some current solar geoengineering efforts. Credit: US Geological Survey (public domain).

United Kingdom led a test run of a recoverable balloon system designed for geoengineering [11]. While these commercially driven tests were met with much criticism, Wagner said the time has come for more tempered research to move from the lab to the field.

"We have already learned from models that if one were to intervene with a slowly ramped up, rationally governed solar geoengineering intervention, the benefits would outweigh the costs," he said. "It is time to move to well-run, well-organized, hypothesis-driven, and tiny-scale outdoor field experiments." Small experiments, he said, carry almost no risk; they have no measurable impact on the planet—they could collect valuable data on the efficacy and risks of solar geoengineering while emitting less sulfate than a commercial airline releases in one minute of flight.

At the same time, though, more work is needed on the logistical details of solar geoengineering at a mass scale. How would the technology be deployed and governed? In February 2023, a United Nations Environment Programme report stated that geoengineering is humanity's "only option" to quickly cool the planet and called for global research and a multinational framework for governing the technology [12].

David Keith, who founded Harvard's Solar Geoengineering Research Program, is now launching a *Climate Systems Engineering initiative* at the University of Chicago (Chicago, IL, USA) as a professor of geophysical sciences. He agrees that global coordination is needed. "The most immediate step is not implementation of this technology, it is establishing an international mechanism for coordinating research," he said. Conversations about such coordination have become more frequent in recent years, but no single framework has yet been implemented [13].

China's first research project on solar geoengineering was launched in 2015 through a collaboration between the Chinese Academy of Sciences (Beijing, China), Beijing Normal University (Beijing, China), and Zhejiang University (Hangzhou, China) [14]. The efforts revolved mostly around modeling the possible mechanisms and impacts of geoengineering and stopped short of field testing any technologies [15]. Experts say coordination between China, the United States, and other developed nations will be key to deploying any global-scale geoengineering [14].

Similar multinational oversight is needed to scale up ocean-based carbon removal projects, said David Koweek, chief scientist of Ocean Visions (Leesburg, VA, USA), a non-profit organization devoted to ocean-climate restoration. "Ocean-based CO_2 removal is in a very exciting phase where lots of ideas are moving out of the modeling realm and laboratory benchtop testing and starting to get into the water for real world testing," Koweek said. "But there are no existing international governance frameworks fit for the purpose of regulating and governing this technology."

For the ocean-based interventions, Koweek said, standardized metrics are also needed to objectively compare the efficacy and impacts of a wide variety of ocean-based CO_2 removal technologies. While the Florida intervention used lime to boost the alkalinity of the water, thereby increasing its capacity to absorb atmospheric CO_2 (Fig. 4) [6], other researchers have taken other tacks—in 2014, for example, researchers added lye to part of the Great Barrier Reef, successfully raising pH levels and boosting levels of calcification in the reef [6]. And in April 2022, researchers from India and the United Kingdom spread iron-coated rice husks across the Arabian Sea in the hopes of fertilizing an algae bloom, which could soak up carbon when it began to decay; unfortunately, a storm swept most of the husks away and the results were inconclusive [6].

Even as interest in geoengineering research picks up, many climate scientists—as well as concerned citizens and governments—remain skeptical of its feasibility and safety. A geoengineering balloon test planned for northern Sweden and organized in part by the Harvard research program, although it was not slated to release any particles, was cancelled in 2021 after outcry from environmental and indigenous groups [16]. More recently, in January, shortly after Make Sunsets released sulfur dioxide from a pair of weather balloons in Mexico, the country announced a ban on

Fig. 4. In May 2022, scientists injected lime into a Florida estuary to neutralize its acidic waters and increase its absorption of CO_2 from the atmosphere. They used a red, nontoxic dye to track the movement of the lime. Credit: Wade McGillis/Ocean Acidification International Coordinating Centre (public domain).

related experiments. Although Make Sunsets has said their own launches are "indefinitely on hold" [17], in February 2023 the two entrepreneur employees of the so-called sunlight reflection company launched several more SO_2-containing balloons in Reno, NV, USA [18]. In March 2023, more than 60 scientists—headed by former NASA climate researcher James Hansen—signed an open letter endorsing the further study of solar geoengineering, shortly after more than 400 academics, largely social scientists, had signed a document calling for the complete non-use of solar geoengineering [19].

Tests like the NOAA data collection flight, though, run a middle ground that might help move the research forward without raising concerns about the safety or morality of geoengineering. "This research is not a few crazy people who have invented a new technology they think will fix everything," said Keith. "The core of these geoengineering approaches comes out of the mainstream of the climate science community. We have known for decades that these approaches might be able to reduce the risks of climate change and could actually work."

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