

Should solar geoengineering be part of how humanity counters climate change?

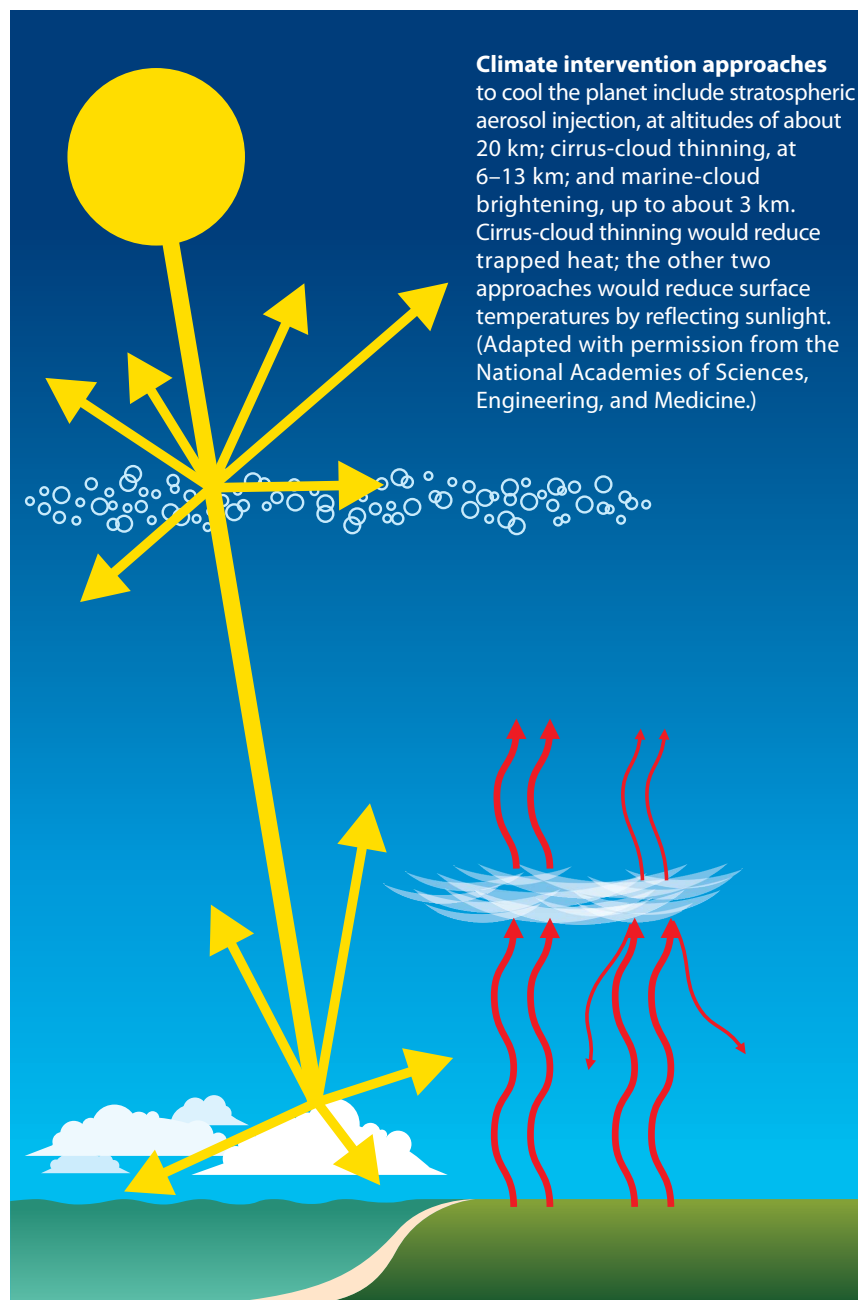
Moving forward requires research and international and intergenerational participation.

Solar geoengineering research should be cautiously ramped up, says the US National Academies of Sciences, Engineering, and Medicine (NASEM) in a report released on 25 March. Tools to cool the planet cannot undo global warming, but they may avert some of its worst impacts.

Today's average global temperature is 1.2 °C higher than preindustrial levels, and last year was among the three hottest on record, according to the World Meteorological Organization. The 2015 Paris Agreement's long-term goal is to keep the rise well below 2 °C and to try to limit it to 1.5 °C. But models predict that unless extraordinary measures are taken, the increase could reach or even exceed 4 °C by the end of the century.

"We are in a critical time for tackling climate change," says Chris Field, an environmental scientist at Stanford University who chaired the NASEM committee. "We know it's difficult to make societal changes to get to zero greenhouse gas emissions. That difficulty provides a compelling motivation to understand the full portfolio of options." Solar geoengineering may be a useful addition to the existing options of reducing emissions, removing carbon from the atmosphere, and adapting to warming. (See, for example, the article "Negative carbon dioxide emissions," by David Kramer, *PHYSICS TODAY*, January 2020, page 44.)

The report, *Reflecting Sunlight: Recommendations for Solar Geoengineering Research and Research Governance*, urges that research be pursued in the intertwined areas of science, technical feasibility, impacts, risks, and benefits. Ethics, public perceptions, and governance of climate interventions also need to be considered. It recommends that the US government invest \$100 million–\$200 million over five years. Such a funding level would repre-



sent a multifold increase over current global spending on climate intervention but would be a small fraction of the overall funding for climate studies.

The report emphasizes inclusivity; the whole world should be involved in de-

cisions that have universal impact. And while it endorses research, it also stresses that neither NASEM nor the report's authors advocate the deployment of solar radiation modification. Research into solar geoengineering "is a threat-reduction

study,” says Paul Wennberg, an atmospheric chemist at Caltech and a member of the NASEM committee. “It’s shocking that we are thinking about doing this kind of stuff. It shows we are globally in a pickle. It highlights how critical it is to quickly reduce our greenhouse gas emissions.”

Stratospheric aerosol injection

The NASEM report examines three approaches to climate intervention. (Climate researchers use various terms for climate modification, including solar geoengineering, solar radiation management, and solar radiation modification.) The best-understood approach is stratospheric aerosol injection: Particles or gaseous precursors such as sulfur dioxide are added to the stratosphere at altitudes of about 20 km, leading to an increase in reflected sunlight and reduced surface temperatures. The effect has been observed with volcanic eruptions. For example, the 1991 eruption of Mount Pinatubo spewed 15 megatons of SO_2 into the stratosphere, which cooled the planet by about 0.4 °C. Because the stratosphere is stable, such effects persist for a few years.

Suppose the world does its best to cut greenhouse gas emissions but still winds up heading for 2.5–3 °C warming, says Douglas MacMartin, a climate researcher at Cornell University. “If you reflect about 1% of sunlight, you would keep temperatures below 1.5 °C warming.” That could be done, he says, by annually injecting about 10 megatons of SO_2 into the stratosphere. “It might be enough to avoid catastrophic sea-level rise, and limit the risk of forest fires and hurricanes.” For comparison, he notes that industrial pollution includes about 100 megatons of SO_2 a year.

Stratospheric aerosol injection would undoubtedly cool the planet. But many questions remain: What types of aerosols should be used? At what latitudes should they be injected? What’s the best time of year to inject them? What would the regional effects be? What are the risks? What are the unknown unknowns?

Helene Muri is a research professor of physics at the Norwegian University of Science and Technology in Trondheim. To date, she says, “there are no monsters in the models. We haven’t seen anything that says we should remove climate intervention from the toolbox.” But, she says, the risks are not yet clear. “We know

some things about natural climate responses to stratospheric aerosol enhancement, like temperatures and precipitation, but when it comes to health-related impacts, changes in air quality, vector-borne diseases, we have many questions.”

Research in stratospheric aerosol injection so far rests on modeling; measurements to date are from volcanic eruptions and rocket plumes. A group at Harvard University plans the Stratospheric Controlled Perturbation Experiment, or SCoPEX. It involves sending a balloon to the stratosphere, releasing small amounts of aerosol, and then using instruments on the balloon to monitor the plume evolution, small-scale turbulence, atmospheric chemistry, light scattering, and other parameters.

“One of the issues that keeps me up at night concerns using sulfate aerosols,” says SCoPEX leader Frank Keutsch. Sulfate not only destroys the stratospheric ozone layer, it also heats the stratosphere. That heating changes atmospheric dynamics and circulation. “We understand the chemistry of ozone fairly well,” he says, “but more studies about how stratospheric aerosol injection would affect dynamics and circulation are needed.”

The first step for the experiment is to test balloon navigation, communication, and instrumentation in the cold, low-pressure stratospheric environment. A June balloon launch from near Kiruna in northern Sweden was canceled in response to opposition by the Indigenous Sami and other local groups; now that test flight plus a later one in which 2 kg of calcium carbonate would be released are on hold.

Daniel Bodansky, a law professor at Arizona State University who focuses on international climate law, says that small experiments such as SCoPEX that do not have global implications shouldn’t require global consensus. “Things should be done safely at a national level, modeling good behavior,” he says. “It’s premature to have international governance.”

Cloudy approaches

Another approach to climate intervention is marine-cloud brightening, which entails adding particles to clouds to make them optically thicker and more reflective. The effect lasts a day or two. It occurs when vessels spew pollution and form so-called ship tracks (see the image on page 24; see also PHYSICS TODAY,

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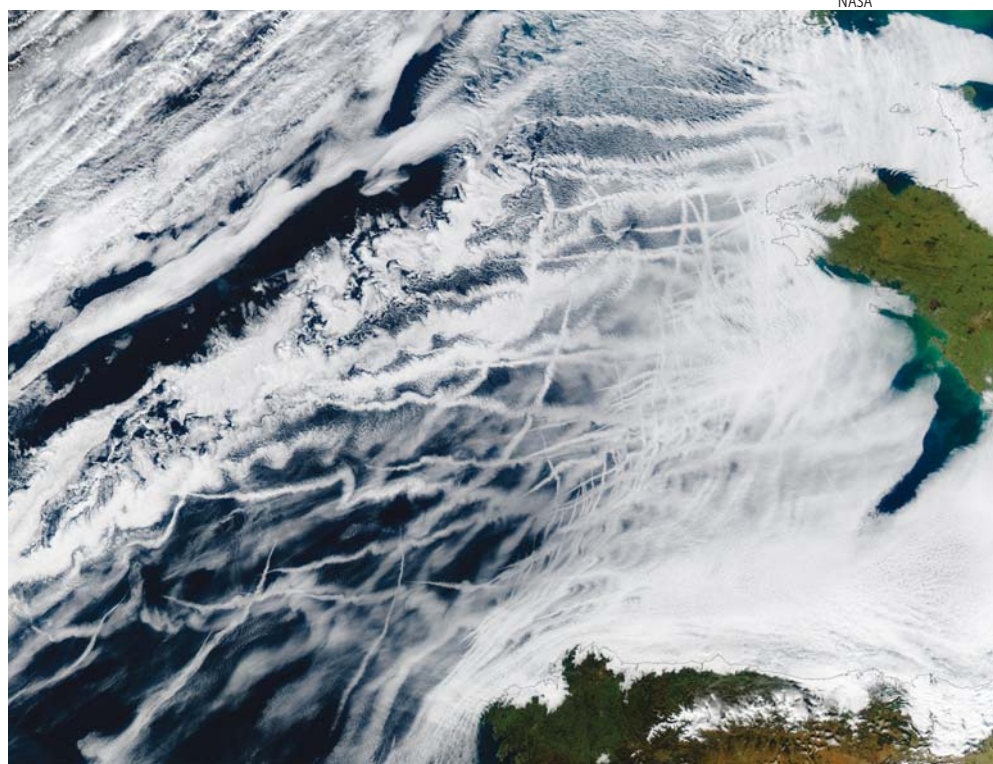
November 2017, page 80). The optimal clouds for marine-cloud brightening are typically no higher than 3 km and are found off the west coasts of California, South America, and South Africa. Lynn Russell, an atmospheric chemist at the Scripps Institution of Oceanography and a member of the NASEM committee, notes that the effect is dampened when the particle density gets too high. “A lot of the processes involved in marine-cloud brightening we know about only theoretically.”

The marine-cloud brightening project at the University of Washington runs simulations varying, for example, the size and concentration of the particles. The project team hopes to collect supporting data by spraying salts from a ship into the air and measuring the clouds and resulting change in reflection. Such experiments would be small scale, says project leader Sarah Doherty. “At most, it might change the distribution of drizzle from the clouds within about 10 km downstream but would have no measurable impact on climate or ecosystems.”

Both approaches would have global effects, although marine-cloud brightening might also be able to target extreme weather events through regional cooling. In Australia, scientists are using marine-cloud brightening to try to cool the area near the Great Barrier Reef to protect its corals.

The third approach to climate intervention that the NASEM report tapped for further study is cirrus-cloud thinning. Unlike stratospheric aerosol injection and marine-cloud brightening, which would cool Earth by reflecting sunlight, cirrus-cloud thinning would work by removing IR-absorbing clouds from the atmosphere and thus reducing trapped heat. Compared with the other intervention approaches, it’s a more direct analogue to removing greenhouse gases—although no greenhouse gases are removed in the process. “If you got rid of all cirrus clouds, you could negate the warming from doubling CO_2 ,” says Ulrike Lohmann, an environmental scientist at ETH Zürich in Switzerland.

But how to rid the atmosphere of cirrus clouds is “a tricky question” and has so far been studied only with computer models, Lohmann says. Cirrus clouds occur naturally at altitudes of about 6–13 km in midlatitudes. Seeding the atmosphere with mineral dust, such as from the Sa-



SHIP TRACKS are clouds that form from the exhaust that ships spew. Marine-cloud brightening would be a purposeful analogue with the intention of reflecting sunlight to help cool the planet.

hara desert, could form them at warmer temperatures and lower altitudes. Consequently, they would contain fewer, larger ice crystals that would sediment faster, leading to shorter-lived cirrus clouds and reduced warming.

Cirrus-cloud thinning is the only climate intervention that targets IR radiation. It would change precipitation patterns less than the solar radiation modification methods, Lohmann says. One danger “would be if you put the material in the wrong place, you would form cirrus clouds where you don’t want them, and that could lead to warming.” But clouds are just around for hours to days, so you can easily stop the process, she says. Greenhouse gases, by contrast, remain for decades.

Still, like the other climate intervention approaches, cirrus-cloud thinning is a Band-Aid, not a solution. “Anything we do, short of removing CO_2 from the atmosphere, just addresses symptoms. That is doable for a limited time, but if greenhouse gases continue to rise and we need to offset to a larger and larger extent, that would be problematic,” says Lohmann. “I see climate intervention coming into effect for a limited time until we get rid

of CO_2 from the atmosphere and stop emitting greenhouse gases.”

The scientists researching climate intervention mostly do it on the side or with a primary goal—and funding—related to broader climate studies. “Understanding cloud feedback is important for climate change models,” Russell says. “There haven’t been enough observations to constrain models, and the effects of clouds on climate are still a big gap.” Addressing the many scientific and technical questions about climate intervention requires a combination of modeling, lab experiments, and field tests, notes Caltech’s Wennberg. “We don’t advocate for outdoor experiments unless lab tests are not possible.”

Most important to limiting the global temperature rise is tackling its causes, says Keutsch of SCoPEX. “I hope that stratospheric engineering will never be used. At the same time, I worry that humanity is cutting emissions and reacting too slowly to prevent severe climate impacts. If the impacts are severe, albedo modification is an action you can take quickly.” Climate intervention could become attractive to decision makers, he adds. “They may have no choice, to save lives and the planet. I hope we never reach that point.

But in case we do, we need to do research now so we are prepared.”

Global impact, global input

The sense that any deliberate tinkering with the environment that would have global implications should also have global consultation has inspired investment in climate intervention expertise. DECIMALS is a fund distributed by the UK-based Solar Radiation Management Governance Initiative. In 2018 DECIMALS supported eight research groups in low- and middle-income countries with a total of \$450 000 to model how solar radiation management could affect their respective regions. The groups are paired with collaborators in high-income countries, and they share information with each other. They access data from mainstream climate models to home in on local issues. A longer-term goal is for the researchers to become trusted experts who could advise policymakers in their own countries.

Izidine Pinto is part of a climate research team in South Africa that is studying how stratospheric aerosol injection will affect mean and extreme temperatures and rainfall throughout Africa. So far, he says, the models show a reduction in temperature but more complicated results for precipitation. “There are only winners when it comes to temperature. But there are both winners and losers when it comes to rainfall.” A future direction, he says, is to compare the effects on agriculture and animal species with increasing climate change and solar geoengineering.

Dust storms and storm tracks in the Middle East and North Africa are the focus of DECIMALS-funded research by Khalil Karami, an atmospheric scientist who splits his time between Leipzig University in Germany and the Institute for Advanced Studies in Basic Sciences in Iran. Dust storms result from interactions between precipitation, wind, temperature, humidity, and soil moisture, and dust is transported around the globe. Storm tracks, the paths along which storms are driven by winds, transfer moisture and heat over large distances. Both phenomena have implications for climate and human health, Karami says, “so it’s crucial to assess how stratospheric solar engineering affect them.”

In Argentina, atmospheric scientist Inés Camilloni leads a group that is looking at possible impacts of stratospheric aerosol injection on water availability in the La Plata basin, among South America’s most populated regions. “We are looking at what we can expect in terms of river flow and expected impacts in the production of hydroelectric energy, floods, and droughts,” she says. “We found that the mean flow would increase by 15–30%.” More water is good, she says, but the maximum flow would also increase, so a possible negative consequence from solar radiation management compared with ongoing global warming would be more floods.

Youth are also involved in climate intervention. Gideon Futerman first learned about reflecting sunlight to cool the planet

in 2016 when he was 13 years old. “I had a geography teacher who was convinced that the only way to combat warming was through giant mirrors,” he says. Futerman rejected the space mirror idea but became interested in solar radiation management. “I’m not saying I’m in favor of deploying it,” he says, “but we need to be well informed to make that decision. If we get to a 3 or 4 °C increase, solar radiation management may look attractive.”

Now finishing his last year of secondary school near London, Futerman notes that “it will be my generation and the next generation who are burdened with the consequences of climate change. It’s a matter of intergenerational justice that young people be consulted in the decision-making process.”

Masahiro Sugiyama of the University of Tokyo’s Institute for Future Initiatives conducted surveys in six Asian Pacific countries about attitudes toward climate intervention. He found that people from low- and middle-income countries were more willing than those from high-income countries to entertain the idea. They were also more concerned about the effects of climate change, he notes, and their countries are generally more climate vulnerable.

“It’s essential in thinking about these technologies that we understand public perception,” says NASEM committee member Peter Frumhoff, chief climate scientist and director of science and policy at the Union of Concerned Scientists. “Social feasibility is as important as



GIDEON FUTERMAN AND BENJAMIN GOLDSTEIN

GIDEON FUTERMAN (right) and Benjamin Goldstein at a Global Youth Climate Strike in London in 2019.

technical feasibility.” Use of technologies cannot be decided by Bill Gates, Harvard University, or the US, he says.

Objections and controversy

A main objection to solar radiation modification is the unknown risks. It might, for example, disrupt precipitation on the planet. Those concerns can be explored at least partially through research. (See PHYSICS TODAY, November 2013, page 22, and August 2014, page 20.)

Another objection is the slippery slope—that having invested in research, people and governments would inevitably implement the fruits of those efforts. The NASEM report recommends building in exit ramps, criteria for terminating research programs or areas, if a research activity “is deemed to pose unacceptable physical, social, geopolitical, or environmental risks or if research indicates clearly that a particular [solar geoengineering] technique is not likely to work.”

Perhaps the most widespread concern is the so-called moral hazard: the notion that if people—and fossil-fuel interests—feel they can get by with, say, injecting aerosol into the stratosphere to cool the

planet, they would get lazy about addressing the root causes of global warming. None of the climate intervention approaches address ocean acidification, atmospheric greenhouse gas concentrations, or the underlying causes of climate change. Michael Mann and Ray Pierrehumbert, scientists who have long been vocal about their global warming concerns, detail their criticisms of solar geoengineering in a 22 April commentary in the *Guardian*.

And climate interventions would likely require a long-term commitment; once begun, they should continue until the greenhouse gas forcing they palliate has abated, says Caltech’s Wennberg. A premature, abrupt termination would lead to rapid warming, he explains, “which could expose the world to even higher risks than never having deployed solar radiation modification schemes in the first place.”

National security is another concern: Consider a scenario in which some country or rogue actor deploys climate intervention on its own. If some other country then suffers a catastrophic weather event and blames the deployment, it could lead

to political conflicts, or in the worst case, war, notes Cornell’s MacMartin. “That’s why everyone needs a seat at the table.”

Laying the groundwork so that decisions about climate intervention can be truly global may be at least as daunting as figuring out whether it is a safe and smart way to go. Janos Pasztor is executive director of the Carnegie Climate Governance Initiative (C2G). “Many fear the potential negative impacts of solar radiation modification,” he says. “How do we weigh the risks? Who should make decisions about where and when to use solar radiation modification?”

The Intergovernmental Panel on Climate Change’s sixth assessment report, slated to be available in late 2022, is expected to include new information on solar radiation modification, says Pasztor. He and his colleagues at C2G are working to get the topic taken up by the United Nations General Assembly in 2023. Says Pasztor: “Based on my personal intergovernmental work experience, it will take a minimum of 10 years to start developing a governance framework for solar radiation modification.”

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