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Needed: Research Guidelines for Solar Radiation Management

As this approach to geoengineering gains attention, a coordinated plan for research will make it possible to understand how it might work and what dangers it could present.

Emissions of carbon dioxide (CO_2) and other greenhouse gases (GHGs) continue to rise. The effects of climate change are becoming ever more apparent. Yet prospects for reducing global emissions of CO_2 by an order of magnitude, as would be needed to reduce threats of climate change, seem more remote than ever.

When emissions of air pollutants, such as sulfur dioxide and oxides of nitrogen, are reduced, improvements occur in a matter of days or weeks, because the gases quickly disappear from the atmosphere. This is not true for GHGs. Once emitted, they remain in the atmosphere for many decades or centuries. As a result, to stabilize atmospheric concentrations, emissions must be dramatically reduced. Further, there is inertia in the earth-ocean system, so the full effects of the emissions that have already occurred have yet to be felt. If the planet is to avoid serious climate change and its largely adverse consequences, global emissions of GHSs will have to fall by 80 to 90% over the next few decades.

Because the world has already lost so much time, and because it does not appear that serious efforts will be made to reduce emissions in the major economies any time soon, interest has been growing in the possibility that warming might be offset by engineering the planet: a concept called geoengineering. The term solar radiation management (SRM) is used to refer to a number of strategies that might be used to increase the fraction of sunlight reflected back into space by just a couple of percentage points in order to offset the temperature increase caused by rising atmospheric concentrations of CO_2 and other GHGs. Of these strategies, the one that appears to be most affordable and most capable of being quickly implemented involves injecting small reflective particles into the stratosphere.

There is nothing theoretical about whether SRM could cool the planet. Every time a large volcano explodes and injects tons of material into the stratosphere, Earth's average temperature drops. When Mount Pinatubo exploded in

Berndnaut Smilde

Dutch artist Berndnaut Smilde is interested in the ephemeral, impermanent state of being. In his *Nimbus* series, he creates Nimbus clouds in indoor spaces. To do so, he carefully regulates the temperature and humidity of the space, ensuring that the conditions are perfect, and then sprays a burst from a fog machine to create a cloud suspended in the middle of the room. The clouds disappear so quickly that they are mainly experienced through photographs. Smilde chooses empty spaces, including galleries and churches, as his settings. He describes his inspiration for this series: "I imagined walking into a classical museum hall with empty walls. The place even looked deserted. I wanted to create an ominous situation. You could see the cloud as a sign of misfortune. You could also read it as an element out the Dutch landscape paintings in a physical form in a classical museum hall."

Based in Amsterdam, Smilde holds an MA in Fine Arts from the Frank Mohr Institute, Groningen, The Netherlands. An international artist, Smilde has recently exhibited at the Land of Tomorrow gallery in Louisville, Kentucky, the Juming Museum in Taipei, Platform 57 in The Hague, and the Ronchini Gallery in London. He is the recipient of a start stipend award from The Netherlands Foundation for Visual Arts, Design and Architecture and was resident artist at the Irish Museum of Modern Art, Dublin, in 2008.

Photos courtesy of the artist and the Ronchini Gallery.

1991, the result was a global-scale cooling that averaged about half a degree centigrade for more than a year.

So SRM could work. As undesirable impacts from climate changes mount up, the temptation to engage in SRM will grow. But what if someone tries to do it before we knew if it will work, or what dangers might come with it? The time has come for serious research that can get the world answers before it is too late. To that end, we offer a plan.

Variable effects—and benefits

SRM could be designed to bring average temperatures around the world back to something close to their present levels. But because particles injected into the stratosphere distribute themselves around the planet, it is doubtful whether strategies can be found to cool just some vulnerable region, such as the Arctic. Even with a uniform distribution of particles, the spatial distribution of the temperature reductions will not be uniform. For example, work by Katharine Ricke, then at Carnegie Mellon University and now at the Carnegie Institution for Science, has shown that over many decades the level of SRM that might be optimal for China will move further away from the level that might be optimal for India, although in both cases the regional climates would be closer to today's climate than they would have been without SRM.

Change in precipitation patterns induced by climate change might present a particularly strong inducement to undertake SRM. But here again, there are some variables and some unknowns. Although the best current estimates suggest that SRM, on average, could probably restore precipitation patterns to approximately those of today, the ability of climate models to predict the details of precipitation is still not very good. Also, some parts of the world are likely to find at least a little bit of warming or other climate change to be beneficial, and so later in this century countries in those regions might not want to return to the climate of the past few centuries, even if they could. In the short term, modest warming and elevated CO_2 will probably enhance

BERNDNAUT SMILDE, *Nimbus Platform57*, Inkjetprint on bubond, 49 x 78 inches, 2012.

some agricultural production, although with further warming most agriculture will suffer.

Although SRM could offset future warming, it does nothing to slow the steadily rising atmospheric concentrations of CO_2. The higher concentration of CO_2 in the atmosphere is already having notable effects on terrestrial and oceanic ecosystems. Some plant species are able to metabolize CO_2 much more efficiently than others, giving them a comparative advantage in a high-CO_2 world. This is beginning to disrupt and shift the makeup of terrestrial ecosystems.

Over a third of the CO_2 that human activities are adding to the atmosphere is being absorbed by the world's oceans. Today the oceans are roughly 30% more acidic than they were in preindustrial times. Sarah Cooley and colleagues at the Woods Hole Oceanographic Institution have estimated that by late in this century, there will be a dramatic drop in harvest yields of molluscs, resulting in a serious decline in the protein available to low-income coastal populations. Also, acidification is already affecting the ability of many coral species to make reef structures. Many marine experts believe that if emissions and ocean acidification continue to increase, most coral reefs will be gone by the end of this century. In addition to being aesthetically and economically important, reefs (along with coastal mangroves) provide the breeding grounds for many oceanic species and form the base of many oceanic food chains.

Political landscape

Today in the United States, there are many people who doubt that climate change is occurring, or if it is, that those changes result from human action. Congress is no longer pursuing legislation to mandate reduced emissions of GHGs, and many political leaders have been avoiding the issue.

Federal regulatory actions to advance energy efficiency and reduce emissions from coal-fired power plants are making modest contributions to reducing emissions of GHGs, as is the tightening of the Corporate Average Fuel Economy, or CAFE, standards covering vehicles. Indeed, as Dallas Burtraw and Matthew Woerman of Resources for the Future recently observed, these regulations, together with the dramatic growth in the use of natural gas, have placed the United States on a path to achieve President Obama's goal for reducing U.S. emissions of GHGs. The goal calls for cutting emissions by 2020 to a level that is 17% below levels emitted in 2005. Of course, a 17% reduction does not come close to the U.S. share of reductions needed to stabilize the climate. A few states, most notably California and some in the northeast, are taking direct steps to reduce emissions. Overall, however, the United States shows no signs of being ready to adopt policies to implement the large economy-wide emission reductions necessary to deal with climate change.

Explicit climate policy has progressed further in Europe, where there is a widely shared understanding of the reality of climate change and the risks that it holds. But even as Europe has taken steps to begin reducing emissions of GHGs, these efforts also remain modest when compared with what will be needed to stabilize climate. In the 27 nations that comprise the European Union, per capita CO_2 emissions are roughly half those of the United States. However, Europe's present economic difficulties, together with Germany's growing dependence on coal as it moves to abandon nuclear power, have resulted in a rate of emissions reduction that now lags that of the United States.

Across the major developing nations—China, India, and Brazil—the primary focus is, of course, on economic growth. China is actively developing wind and solar power, as well as technologies for carbon capture and sequestration. China is doing this because it faces local and regional air pollution that is prematurely killing millions of people, because the government realizes that the country will need to wean itself from coal, and because the government assumes that sooner or later the rest of the world will get serious about reducing emissions and, when that happens, China wants to be a strong player in the international markets.

A tempting quick fix

Although subtle impacts from climate change have been apparent for decades, it is only recently that changes have become more obvious and widespread. Over the next few decades, such changes will become ever more apparent. Because reducing atmospheric concentrations of GHGs is inherently slow and expensive, as more and more people and nations grow concerned, SRM could become a tempting quick fix.

SRM is a technology that has enormous leverage. Recent analysis by a university/industry team of researchers, led by Justin McClellan of the Aurora Flight Science Corporation, suggests that a small fleet of specially designed aircraft could deliver enough mass to the stratosphere in the form of small reflecting particles to offset all of the warming anticipated by the end of this century for a cost of less than $10 billion per year, or roughly one ten-thousandth of today's global gross domestic product of $70 trillion (in U.S. dollars). In contrast, estimates by the Intergovernmental Panel on Climate Change in its fourth assessment report suggest that the annual cost of controlling emissions of GHGs to a level sufficient to limit warming will be between half a percent and a few percent of global gross domestic product.

Clearly, given this enormous cost difference, as the impacts of warming and other climate change become more apparent, SRM is going to look increasingly tempting to countries and policymakers who face serious adverse impacts from climate change. Adding to this temptation is the fact that implementing SRM could be done unilaterally by any major nation, which is far from the case with reducing global emissions of GHGs, which would require cooperation among a number of sovereign nations around the world.

Planning a research agenda

Although it is well established scientifically that adding fine particles to the stratosphere would, on average, cool Earth, science cannot be at all sure about what else might happen. For example, science cannot be confident about the fate and transport of particles (or precursor materials) once they are injected. It is unknown whether and how the distribution of particles could best be maintained. The surfaces of some types of particles could provide catalytic reaction sites for ozone depletion, but again details are uncertain. Researchers have documented the transient effects of large volcanic injections, but it is not known whether a planned continuous injection of particles might produce large and unanticipated dynamic effects. In short, if the United States or some other actor were to undertake SRM today, it would be "jumping off a cliff" without knowing much about where it, and the planet, would land. Humans have a long tradition of overconfidence and hubris in considering such matters. In our view, anyone who undertook SRM based on what is known today would be imposing an unacceptably large risk on the entire planet.

The climate science community has been aware of the possibility of performing SRM for decades. However, most researchers have shied away from working in this area, in part because of a concern that the more that is known, the greater the chance that someone will try to do it. Although such concerns may have been valid in the past, we believe that the world has now passed a tipping point. In our view, the risks today of not knowing whether and how SRM might work are greater than any risks associated with performing such research.

We reach this conclusion for two reasons. First, the chances are growing that some major state might choose to embark on such a program. If science has not studied SRM and its consequences before that happens, the rest of the world will not be in a position to engage in informed discourse, or mount vigorous scientifically informed opposition if the risks are seen as too great. Second, given the slow pace at which efforts to abate global emissions of GHGs have been proceeding, the chances are growing that when the world does finally get serious about abatement, the United States and other nations may in fact need to collectively engage in a bit of SRM, if it can be done safely, in order to limit damages, while simultaneously scrambling to reduce emissions rapidly and perhaps also scrub CO_2 from the atmosphere.

There have been several calls for a significantly expanded research program on SRM. For example, the House Science Committee and an analogous committee in the UK's Parliament have explored the issue. The United Kingdom has also undertaken a modest program of research support. A task force of the Bipartisan Policy Center, an independent think tank based in Washington, DC, recently developed recommendations for a program of research by the U.S. government. However, most of the limited research now under way in the United States is occurring as part of existing programs that focus on climate and atmospheric science more generally.

Because SRM could rapidly modify the climate of the entire planet at a very modest cost, and because it holds the potential to have profound impacts on all living things, we believe that there is an urgent need for research to clarify its potential impacts and consequences and to provide sufficient reliable information to enable the establishment of appropriate regulatory controls. Building on the work of the Bipartisan Policy Center, the scientific community needs to develop a robust SRM research agenda and obtain the public and private funding necessary to carry it out. In parallel, the community needs to develop guidelines that ensure that such research is responsibly carried out. Finally, as we discuss in detail below, SRM research should be conducted in an open and transparent manner by providing public notification of proposed field experiments and providing decisionmakers and the public with full access to the results of the research.

Except for limited U.S. authority under the National Weather Modification Reporting Act to require notification and reporting of "weather modification" activities, neither U.S. nor international law provides readily useable authority to prohibit, regulate, or report on the conduct of SRM research or field experiments. Our recommendation is to develop and implement a voluntary research code before attempting to impose any regulatory mandates with respect to SRM research, for two reasons. First, a voluntary code can address and work out the various definitional and policy questions we discuss below. Second, a clumsy U.S. attempt to require notice and reporting of SRM research may simply delay or drive that research abroad, frustrating the ultimate objective of open access to responsibly conducted SRM research. A voluntary code, in our view, is the most sensible first step. The United States should take the lead by developing and implementing a code of best SRM research practices and a set of rules governing federally funded SRM research. After doing that, it should then undertake formal governmental steps and informal steps through scientific channels to urge other international players to promptly do the same.

A key component of a significant SRM research program is to develop a fully articulated research agenda. This might be done under the auspices of the U.S. National Academies, drawing on researchers from major universities, national laboratories, and federal agencies, with input from the international research community.

Code of best practices

In parallel with, or even before, developing a full research agenda, there is a pressing need to develop what we will call a code of best SRM research practices. This code will need three components. The first would comprise guidelines to provide open access to SRM knowledge by making research results available to decisionmakers and the public. The second would be the delineation of categories of field experiments that are unlikely to have adverse impacts on health, safety, or the environment (that is, experiments conducted within an agreed-upon "allowed zone" of experimental parameters and expected effects on the stratosphere.) The third component would be agreement that any field research to be conducted outside the allowed zone will not be undertaken before a clear national and international governance framework has been developed.

The development of this code will require a convening entity and sufficient resources to support activities. Federal funding through an Executive Branch agency might be secured for such an undertaking. For example, Congress could fund a National Research Council study to develop a set of clear definitions and research norms. Perhaps a faster way to get this done would be to persuade a well-respected private foundation to provide the necessary resources. The National Academies or the National Research Council would be appropriate organizations to convene the effort. Alternatively, the American Geophysical Union might do this as part of its recently expanded set of activities in public policy.

Formulating guidelines for SRM research and a policy to advance open access to SRM research must address a set of key issues of definition and scope:

- First we need to define what counts as SRM. Is the technology to be deployed only for SRM, such as a specific type of specially engineered reflective particle, or does it also include multiuse technology, such as high-altitude aircraft designed to deliver mass to the stratosphere but also capable of performing a variety of other missions that are completely unrelated to SRM? To the extent that SRM overlaps with fields of use that do not raise concerns, non-SRM commercial activity might be affected by efforts to single out SRM activity for special attention. What about research on "incidental" SRM? Such current or proposed research might include, for example, geophysical studies of future volcanic eruptions; studies of the atmospheric effects of "black carbon," the strongly light-absorbing particulate matter emitted by the incomplete combustion of fossil fuels; and studies of the behavior of sulfur dioxide emitted from stationary industrial sources. Any SRM open-access program must define SRM in order, among other things, to minimize its impact on related but uncontroversial commercial activity.
- Next we need to agree on what constitutes SRM research. Does it include theoretical research, literature searches, term papers, and legal memoranda, or should it be limited to experimental research, and if so, does it extend to laboratory research or should it be limited to only field experiments? If the focus is limited to field experiments, how should (and could) basic studies in atmospheric science be differentiated from studies that are more specifically focused on improved understanding of SRM? Trying to make such a demarcation on the basis of experimenters' intent strikes us as deeply problematic; objective criteria will be needed.
- Activities that should be subject to a requirement of prior notification of SRM research need to be defined. At what stage of a project (planning, approval, or funding) should public notification occur, and in how much detail? Also, what medium or media (for example, a dedicated public Internet site, a Federal Register notice, or a proposal submitted to a designated governmental entity) should be used?
- Any policy respecting public access to SRM research needs to spell out the type of research it covers. Does it cover only completed peer-reviewed research? What about studies whose results are not published or that are in progress but have not reached the stage of publication? What about industry research and abandoned or unsuccessful projects? How can public access be bounded in such a way as to preserve valid commercial interests while providing the appropriate level of public disclosure?
- The allowed zone stipulated for experiments will have to be defined, based on results of existing scientific knowledge. This will include careful delineation of areas of permissible field studies and of a protocol for determining that a proposed field study lies within the allowed zone.
- Finally, there are a series of important policy questions that must be addressed. Should an open-access policy be a voluntary undertaking by researchers? Should the policy be incorporated into federal grants and contracts? Is it feasible to prescribe regulations that require open access to SRM research? Do any of these policies interfere with academic freedom or intellectual property rights?

Importance of open access

As part of the effort to develop a code of best SRM research practices, the United States should develop strategies that ensure that the knowledge developed through SRM research is available to the general public and to national and international policymakers to support informed policy discourse and decisionmaking. The creditability and usefulness of a research program can best be advanced by providing the public with advance notice of SRM field experiments and public access to research results.

The SRM research code of best practices should include a commitment to make public the existence of all SRM research activities, perhaps through a mechanism as simple as posting to a common Web site. It should include an agreement that results from prescribed types of research will be made public (preferably through publication in refereed journals). It should provide guidance on the types of field studies that can be undertaken without any special oversight or approval. And it should express an understanding with respect to privately held intellectual property, as discussed below.

Because most federally funded research would probably already have been described in publicly assessable proposals, posting announcements with an abstract of plans to conduct specific field studies on a common public Web site is not likely to present a significant problem for most investigators. However, asking investigators to post preliminary findings on such a site could be more problematic. This is because some leading journals adopt a strict interpretation with respect to the definition of "prior publication." We be-

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lieve that in the interests of promoting open access to SRM knowledge, an effort should be made to induce several top journals to adopt a more lenient policy in the case of work related to SRM.

In developing a voluntary code for research conduct, comment and advice should be sought from federal agencies, universities and other research institutions, and nongovernmental organizations and companies likely to conduct SRM research. To maximize its acceptance, the code should probably draw a line between research results that are to be publicly disclosed and those that do not need to be publicly disclosed so as to protect the commercial interests of technologies with multiple non-SRM uses. The expectation is that once the code is finalized, its recommendation could be incorporated into approval requirements in government and private nonprofit funding arrangements for SRM research and promoted as a model for industrial researchers and non-U.S. researchers.

U.S. government support

Although there has already been some modest support of SRM research from private sources, if a concerted SRM research program is undertaken in the United States, it most likely will involve funding by the federal government as well as some use of the unique capabilities of federal equipment and laboratories. Federal research activities that meet the definition of SRM research should include provisions requiring that an abstract describing the research to be performed be made publicly available upon execution of the underlying agreement. In the case of research involving field experiments, the National Environmental Policy Act may require an Environmental Impact Assessment, unless the proposed project fits into a category excused from such assessment. If an assessment if required and prepared, the public will have ample notice and opportunity for comment.

Federal research agreements should include provisions requiring delivery to the government of publicly releasable research results, commensurate with the SRM research code of best practice. Federal agencies have experience in negotiating lists in each of their research agreements of specifically identified publicly releasable data that would meet the standards set by the SRM code while at the same time, in appropriate agreements, excluding data whose restriction on public release would not be inconsistent with the SRM research code.

Federal research agreements also typically include a patent rights clause that usually provides that the agreement awardee has the option to elect to retain title to its new inventions made under the agreement. In order to lessen the incentive for private commercial interests to influence the direction of the pursuit of SRM, it would be desirable to restrict the assertion of such private intellectual property rights to technical fields other than SRM. Federal agencies already have statutory authority to take prescribed action to restrict or partially restrict the patent rights of awardees. For example, in order to control commercialization, the Department of Energy has provided for federal government ownership of inventions made by its research contractors in the field of uranium enrichment.

A uniform standard can be applied across transactions involving multiple agencies, through mechanisms such as Federal Acquisition Regulations, Office of Management and Budget circulars, and presidential executive orders. Because the promulgation of government-wide guidance may take some time, individual agencies can act on their own initiative if they feel that their mission justifies such action. Individual agency action may lay the groundwork for broader action across the government. If a lead agency is identified to conduct SRM research, that agency should take such an initiative, in the same way that the National Institutes of Health required that investigators who received its support to conduct analysis of genetic variation in a study population submit descriptive information about their studies to a publicly accessible database. The United States could also use international cooperative research agreements as a means to encourage other countries to follow the code of best SRM research practices.

Action by the U.S. government would set a powerful precedent by a major player in the world economy and world research community, giving the nation better standing to advocate for international action in SRM research. Specific U.S. action, developed with input from stakeholders including public interest groups, would establish a model that ensures appropriate public availability of information without unnecessarily affecting commercial interests.

Understand before regulating

The approach we have advocated would have the United States take the lead in developing a set of norms for good research practice for SRM. We have proposed that once developed, these norms should be adopted by federal research programs and urged upon all privately funded research. Once the norms are developed and implemented, it should be possible to persuade others across the international research community to adopt similar norms. Organizations such as the International Council of Scientific Unions and the national academies of science in various countries are well positioned to promote such adoption.

As we noted above, the U.S. National Weather Modification Reporting Act provides a statutory framework for making an SRM open-access research policy mandatory in the United States, at least insofar as the research entails field experiments that are conducted domestically and are of such a scale that they could actually affect climate or weather. Our recommendation, however, is to develop and implement a voluntary research code before attempting to use this authority to implement federal rules governing SRM research.

There is also the question of whether considerations should attempt to go beyond open-access policies for SRM research (that is, notice and reporting) and impose substantive regulation, such as permit requirements or performance or work practice standards. We believe that it is premature today to embark on the development and implementation of substantive regulatory requirements. But as the prospect of large-scale field studies—or actual implementation—of SRM becomes more real, the need for and pressure to develop such regulation will grow. Because future regulations should be based on solid well-developed science, the creation of a serious program of SRM research, combined with procedures to ensure open access to SRM knowledge, is now urgent.

Recommended reading

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