like, exponentially decaying attractive forces between neighboring filaments (*9*).

Most experimental data on nonspecific bundling interactions appear to be consistent with theoretical predictions of densely packed bundles resulting from counterion-induced attractive forces, but substantial discrepancies remain. Microtubules can form various bundling architectures, from tight hexagonal bundles to loose two-dimensional necklace-like morphologies with linear, branched, and loop morphologies (*10*) that are not predicted by theory.

In contrast to the filament bundling described so far, which typically arises from attractive forces, long-range electrostatic repulsion appears to play the dominant role in inducing the formation of widely spaced, stable hexagonal filament bundles reported by Cui *et al*. The authors hypothesize that x-ray irradiation induces a reversible chemical reaction, with deprotonation of carboxyl groups on glutamic acid residues leading to highly charged filaments (see the figure). Their observation that the induced ordered phase occurs only above a certain x-ray dose rate rather than accumulated dose is consistent with a reversible switching process (see the figure). The large equilibrium spacing observed by the authors seems to result from repulsive filaments in a confined geometry, reminiscent of a two-dimensional Wigner crystal [where minimization of potential energy at low concentration leads to a two-dimensional crystal (*3*)].

Radiation-induced structural changes are usually detrimental. The term "radiation damage" is widely used to describe the resulting structural degradation. What is unusual and interesting in Cui *et al*.'s study is that x-ray irradiation induces rather than destroys ordering. The system seems to be highly susceptible to hexagonal order due to the built-in electrostatic repulsive force; above a critical concentration, bundles form spontaneously without x-ray radiation. By increasing the charge of the filaments, irradiation tips the transition point to much lower concentrations, where spontaneous bundling does not occur.

Further studies are needed to clarify the detailed x-ray–induced ionization process responsible for the ordering observed by Cui *et al*. Nevertheless, the x-ray switch introduced by this study opens up entirely new directions in nanoscale assembly. We expect that future work will extend the discovery to other systems, such as other peptide-based geometric shapes, including sheets and spheres. Other new directions may involve using grazing-incidence x-ray irradiation for the controlled growth of ultrathin ordered phases at interfaces.

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ATMOSPHERIC SCIENCE

A Test for Geoengineering?

Stratospheric geoengineering cannot be tested in the atmosphere without full-scale implementation.

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Scientific and political interest in the possibility of geoengineering the climate is rising (*1*). There are currently no means of implementing geoengineering, but if a viable technology is produced in the next decade, how could it be tested? We argue that geoengineering cannot be tested without full-scale implementation. The initial production of aerosol droplets can be tested on a small scale, but how they will grow in size (which determines the injection rate needed to produce a particular cooling) can only be tested by injection into an existing aerosol cloud, which cannot be confined to one location. Furthermore, weather and climate variability preclude observation of the climate response without a large, decade-long forcing. Such full-scale implementation could disrupt food production on a large scale.

We use the term "geoengineering" to refer to solar radiation management (SRM), particularly the injection of aerosols into the stratosphere to emulate volcanic emissions. We consider the best case for conducting experiments in the atmosphere, putting aside some of the worst-case reservations that have been raised about the atmospheric risks of geoengineering (*2*, *3*).

If ongoing climate modeling and limited experiments to test insertion methodology were to indicate that SRM would reverse many negative aspects of global warming, could these results be validated with in situ experiments to test the creation of a stratospheric aerosol cloud and the resulting climate response? Some authors have argued that the effects of polar testing could be confined to the Arctic (*4*). However, we have shown (*5*), on the basis of analogs from past volcanic eruptions and climate model experiments, that Arctic injection would cool the atmosphere down to latitude 30°N, weakening the summer monsoon over Africa and Asia and reducing precipitation, just like tropical injections of stratospheric aerosols. Indeed, any high-latitude sulfate aerosol production would affect large parts of the planet.

Even if insertion does indeed have to end up as planetwide, it might be thought that one could at least proceed at low rates of insertion and look for any untoward side effects before increasing the dose. But two major issues prevent useful testing of stratospheric aerosol injection with small amounts.

First, to produce an aerosol cloud of sufficient thickness that lasts long enough to detectably cool Earth's surface, regular injections would be needed into air that already contains an aerosol cloud. One can fly aircraft or balloons into the stratosphere and test nozzles and injection of material into the wake of the planes (see the figure) (*6*), and thereby measure the creation of aerosols in the first minutes or hours into a pristine stratosphere. However, current theory tells us that continued emission of sulfur gases or sulfate particles would cause existing particles to grow to larger sizes, larger than volcanic eruptions typ-

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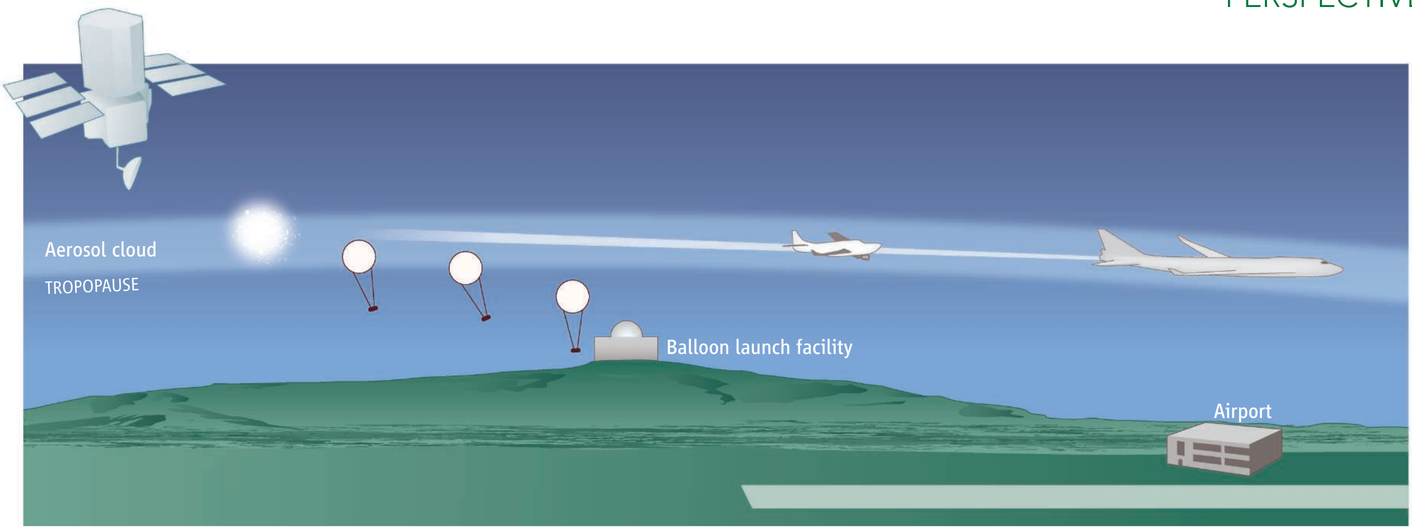

ically produce. These larger particles would be less effective at cooling Earth, requiring even more injections (*7*). Such effects could not be tested except at full scale.

Second, the signal of small injections would be indistinguishable from the noise of weather and climate variations. The only way to separate the signal from noise is to get a large signal from a large forcing, maintained for a substantial period. Different model simulations [e.g., (*5*)] have shown that injection of 5 Tg (5×10^{12} g) of SO_2 into the tropical lower stratosphere every year—the equivalent of one 1991 Mount Pinatubo eruption every 4 years—could lower global average surface air temperature, but African and Asian summer precipitation would also be reduced, potentially affecting the water and food supplies of more than 2 billion people. If much less SO_2 were injected, any potential effect on the monsoon would be indistinguishable from climate noise.

Volcanic eruptions serve as an excellent natural example of this. In 1991, the Mount Pinatubo volcano injected 20 Tg of SO_2 into the stratosphere (*8*). The planet cooled by ~0.5°C in 1992 and then warmed back up gradually as the volcanic cloud fell out of the atmosphere over the next year or so. There was a large reduction of the Asian monsoon in the summer of 1992 (*9*) and a measurable ozone depletion in the stratosphere (*10*). The eruptions of the Kasatochi volcano in 2008 (1.5 Tg of SO_2) and the Sarychev volcano in 2009 (estimated 2 Tg of SO_2) did not produce a climate response that could be measured against the noise of chaotic weather variability.

Climate model simulations suggest that the equivalent of one Pinatubo every 4 years would be required to counteract global warming for the next few decades. The cloud would have to be maintained in the stratosphere to allow the climate system to cool in response, unlike for the Pinatubo case, when the cloud fell out of the atmosphere before the climate system could react fully. Such an experiment would essentially be implementation of geoengineering. No matter what the results, it would be difficult to stop such an experiment quickly. First, all model simulations conducted so far, starting with Wigley (*11*), show that upon cessation of geoengineering, the climate would warm much more rapidly than if no geoengineering had been conducted. This rapid warming would be much more disruptive than the gradual change we are experiencing now. Second, the geoengineering infrastructure, including different industrial interests involving many jobs, would lobby to keep the program going.

Furthermore, no stratospheric aerosol observing system exists to monitor the effects of any in situ testing. After the 1991 Pinatubo eruption, data from the Stratospheric Aerosol and Gas Experiment II (SAGE II) instrument on the Earth Radiation Budget Satellite showed how the aerosols spread. A limb-scanning design such as that of SAGE II is optimal for measuring the vertical distribution of aerosols. SAGE III flew from 2002 to 2006, but there are no plans for a follow-on mission. A spare SAGE III sits on a shelf at a NASA lab and could be used now. The only limb-scanner currently in orbit, the Optical Spectrograph and Infrared Imaging System (OSIRIS) on the Odin satellite, is not used to regularly monitor stratospheric aerosols. These current and past successes could serve as a model for a robust stratospheric observing system, which could also be used to measure the effects of episodic volcanic eruptions.

Finally, local impacts are particularly difficult to predict. Modeling to date has raised concerns that large-scale sulfur insertion might produce untoward local climate responses affecting both temperature and moisture. Global climate models simulate monsoon circulation at a fairly large scale. The more local the interest, the longer an experiment would have to run to rule out adverse side effects. In a 10-year experiment to test for a climate signal over noise, the chance of a local adverse response could not be ruled out prior to the experiment. As such, a prudently designed experiment would have to make provision for such outcomes. Although even a major disruption of agricultural output would be difficult to attribute to geoengineering, were such outcomes to occur, necessitating an end to the experiment, the sulfate aerosol density would need to be decreased slowly to avoid ecological shocks. All these issues will need to be considered in policy and governance deliberations (*1*).

Potential techniques for producing aerosols in the stratosphere. The effects of creating aerosols in a pristine stratosphere can be tested, but longer-term effects as the particles grow to larger sizes are difficult to predict and attribute.

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