sary amount of sulfur injection would need to be estimated according to comprehensive forecast models, requiring extensive modeling capabilities. The total cost of SAM would also need to include compensation for potential side effects and would thus be much higher than the delivery costs (*16*).

Currently, a single person, company, or state may be able to deploy SAM without in-depth assessments of the risks, potentially causing global impacts that could rapidly lead to conflict. As such, it is essential that international agreements are reached to regulate whether and how SAM should be implemented (*3*). A liability regime would rapidly become essential to resolve conflicts, especially because existing international liability rules do not provide equitable and effective compensation for potential SAM damage (*17*). Such complexities will require the establishment of international governance of climate intervention, overseeing research with frequent assessments of benefits and side effects.

Climate intervention should only be seen as a supplement and not a replacement for greenhouse gas mitigation and decarbonization efforts because the necessary level and application time of SAM would continuously grow with the need for more cooling to counteract increasing greenhouse gas concentrations. A sudden disruption of SAM would cause an extremely fast increase in global temperature. Also, SAM does not ameliorate major consequences of the CO_2 increase in the atmosphere, such as ocean acidification, which would continue to worsen. ■

REFERENCES AND NOTES

1. R. Joeri *et al.*, *Nature* **534**, 631639 (2016).
2. K. Anderson, G. Peters, *Science* **354**, 182 (2016).
3. J. Pasztor, *Science* **357**, 231 (2017).
4. P. J. Crutzen, *Clim. Change* **77**, 211 (2006).
5. U. Lohmann, B. Gasparini, *Science* **357**, 248 (2017).
6. A. Robock, *Earth's Future* **4**, 644 (2016).
7. U. Niemeier *et al.*, *J. Geophys. Res.* **118**, 11905 (2013).
8. M. J. Mills *et al.*, *J. Geophys. Res.* **121**, 2332 (2016).
9. U. Niemeier, C. Timmreck, *Atmos. Chem. Phys.* **15**, 9129 (2015).
10. R. Moriyama *et al.*, *Mitig. Adapt. Strat. Global Change* **21**, 1 (2016).
11. D. Visioni, G. Pitari, V. Aquila, *Atmos. Chem. Phys.* **17**, 3879 (2017).
12. S. Tilmes, R. Müller, R. Salawitch, *Science* **320**, 1201 (2008).
13. D. Keith, D. K. Weisenstein, J. A. Dykemaa, F. N. Keutsch, *Proc. Natl. Acad. Sci. U.S.A.* **113**, 14910 (2016).
14. J. Dykema, D. Keith, J. G. Anderson, D. Weisenstein, *Philos. Trans. R. Soc. A* **372**, 20140059 (2014).
15. S. Tilmes, B. M. Sanderson, B. C. O'Neill, *Geophys. Res. Lett.* **43**, 8222 (2016).
16. J. Reynolds, A. Parker, P. Irvine, *Earth's Future* **4**, 562 (2016).
17. B. Saxler *et al.*, *Law Innov. Technol.* **7**, 112 (2015).

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GEOENGINEERING

A cirrus cloud climate dial?

Cirrus cloud seeding may help to reduce climate warming, but large uncertainties remain

By **Ulrike Lohmann** *and* **Blaž Gasparini**

Climate engineering is a potential means to offset the climate warming caused by anthropogenic greenhouse gases. Suggested methods broadly fall into two categories. Methods in the first category aim to remove carbon dioxide (CO_2) from the atmosphere, whereas those in the second aim to alter Earth's radiation balance. The most prominent and best researched climate engineering approach in the second category is the injection of atmospheric aerosol particles or their precursor gases into the stratosphere (*1*), where these particles reflect solar radiation back to space. Climate engineering through cirrus cloud thinning, in contrast, mainly targets the long-wave radiation that is emitted from Earth.

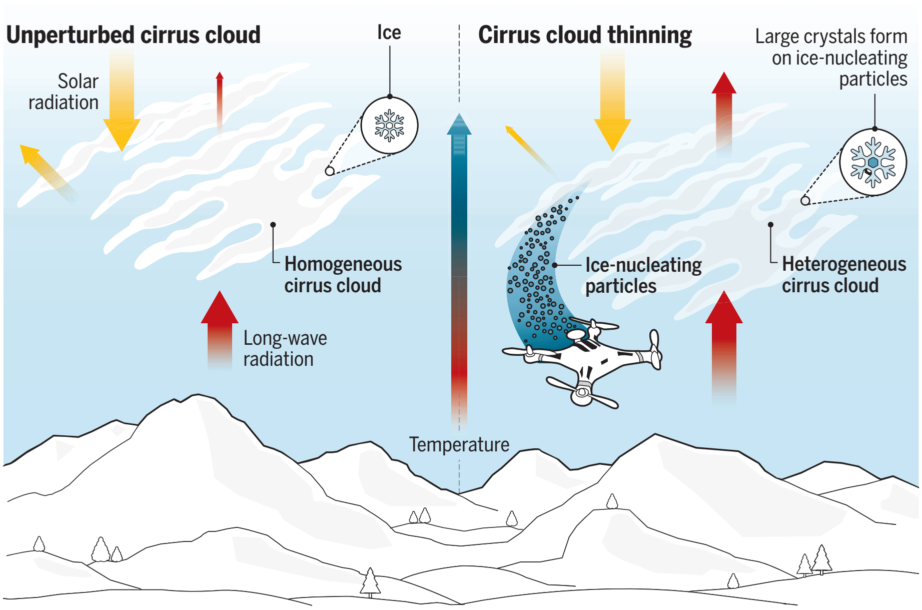
Wispy, thin, and often hardly visible to the human eye, cirrus clouds do not reflect a lot of solar radiation back to space. Because they form at high altitudes and cold temperatures, cirrus clouds emit less long-wave radiation to space than does a cloud-free atmosphere. The climate impact of cirrus clouds is therefore similar to that of greenhouse gases. Their long-wave warming (greenhouse) effect prevails over their reflected solar radiation (cooling) effect, causing a net-positive radiative effect of 5 to 6 W m^{-2} in the present-day climate (*2*, *3*).

However, the long-wave radiative effect of cirrus clouds depends on their optical depth and on the altitude at which they form. Two cirrus clouds of the same optical thickness formed at different altitudes will have different radiative effects. The higher and therefore colder one will have a larger warming effect on climate because of the larger temperature difference to the mid-troposphere from where cloud-free radiation is emitted to space. In a warmer climate, cirrus clouds will form at higher altitudes, increasing their warming effect (*4*).

The effect of cirrus cloud thinning would be opposite in sign to that of contrails in present-day climate. Because of increases in air traffic, contrails and the associated increase in cirrus cloud cover caused a positive radiative forcing (climate warming) of 0.05 W m^{-2} between 1750 and 2011. This forcing is negligible in magnitude compared with the radiative forcing of 2.83 W m^{-2} from green-

How seeded cirrus clouds could cool the climate

Cirrus clouds reflect some sunlight and absorb long-wave radiation; on balance, they warm the climate. Cirrus cloud thinning aims to change the radiative properties of cirrus clouds by reducing their lifetime and the altitude at which they form.



GRAPHIC: G. GRULLÓN/SCIENCE

house gases (*5*) but is of the same sign. Cirrus cloud thinning tries to achieve the opposite by reducing the coverage and optical thickness of cirrus clouds.

Cirrus clouds frequently form through homogeneous nucleation of liquid aerosol particles such as sulfuric or nitric acid. Alternatively, they can form through heterogeneous nucleation with the help of solid aerosol particles such as desert dust, pollen, or other biological particles, which act as ice-nucleating particles (INPs). The cirrus cloud thinning concept is based on the assumption that most cirrus clouds in the present climate nucleate homogeneously. Homogeneously formed cirrus clouds occur in regions that are cold and/or have high relative humidities. If suitable INPs are injected into cirrus levels, cirrus clouds would form via nucleation on these INPs at lower relative humidity and higher temperature, preventing the formation of cirrus clouds through homogeneous freezing (*6*). Paradoxically, seeding cirrus clouds in this way decreases their radiative impact and their lifetime, therefore reducing the overall warming effect compared with that of "natural" cirrus clouds.

The cooling effect of seeded cirrus clouds has three contributions. First, the cirrus clouds form at lower relative humidities that occur at lower altitudes in the atmosphere (see the figure), where they have a smaller warming effect. Second, because the number concentration of INPs is much lower than that of solution droplets, heterogeneously formed cirrus clouds contain fewer ice crystals. These ice crystals can grow to larger sizes and sediment more readily from cirrus levels, reducing the lifetime and optical thickness of cirrus clouds and hence their warming potential. Third, sedimenting ice crystals remove water vapor, the most important natural greenhouse gas, from the upper troposphere.

If cirrus thinning works, it should be preferred over methods that target changes in solar radiation, such as stratospheric aerosol injections, because cirrus thinning would counteract greenhouse gas warming more directly. Solar radiation management methods cannot simultaneously restore temperature and precipitation at present-day levels but lead to a reduction in global mean precipitation because of the decreased solar radiation at the surface. This adverse effect on precipitation is minimized for cirrus seeding (*7*) because of the smaller change in solar radiation.

The maximum cirrus seeding potential would be achieved by removing all cirrus clouds. The resulting radiative forcing of 5 to 6 W m^{-2} (*2*, *3*) would more than offset the radiative forcing of a CO_2 doubling. More realistically, the upper limit of cirrus seeding is given by the difference in radiation between a climate model simulation in which all cirrus clouds freeze homogeneously and one in which all cirrus clouds form through heterogeneous nucleation. This difference is on the order of 2 to 3 W m^{-2} (*8*, *9*), which corresponds to 50 to 80% of a doubling of CO_2 (*5*). Yet, even this is an overestimate, given that already in the present-day climate, cirrus clouds form both through homogeneous and heterogeneous nucleation (*10*).

One problem with cirrus seeding is overseeding, which occurs if too many INPs are injected. In overseeding, the cirrus clouds become optically thicker, leading to warming. Current models give different critical INP concentrations (INP*) at which overseeding starts (*2*, *11*, *12*). INP* depends on the fraction of cirrus clouds that nucleates heterogeneously in the present climate (*11*) as well as on the chemical composition (*12*) and the size of the injected INPs (*13*). In addition, seeding needs to be avoided in cloud-free regions with high relative humidities where no cirrus clouds form. Here, seeding with INPs could lead to cirrus clouds that cause a warming effect on the climate, same as that from contrails.

"If cirrus thinning works, it should be preferred over methods that target changes in solar radiation…"

Unintended cirrus formation is especially pronounced if the seeded INPs start to nucleate ice at very low relative humidities (*2*). Because of the competition of these various factors, the radiative forcing of cirrus cloud seeding varies between –1.8 and +2.1 W m^{-2}. Thus, if cirrus seeding is not done carefully, the effect could be additional warming rather than the intended cooling. If done carefully, the negative radiative effect from cirrus seeding should be stronger in a warmer climate, in which the overall radiative effect of cirrus clouds will be larger.

The results from model studies of cirrus thinning suggest that the perfect seeding INPs should be large and that seeding could be geographically or temporally limited. Bismuth triiodide (BiI_3) has been suggested as a nontoxic and affordable substance for cirrus seeding (*6*); other substances such as mineral dust should work as well. However, further research is needed to investigate which particles would be good seeding agents. It is also important to determine whether these INPs also influence lower-lying clouds, and if so, whether this enhances or dampens the effect of cirrus thinning (*13*).

If the time and place of seeding is selected with care, the climate effect of cirrus thinning can be enhanced. For that, only the long-wave warming effect of cirrus clouds should be targeted, and their solar effect should be avoided. This can be achieved if seeding is limited to high-latitude winters (*11*) or to nighttime seeding (*13*). Contrary to solar radiation management methods, cirrus seeding is more effective at high than at low latitudes. A small-scale deployment of cirrus seeding could therefore be envisioned—for instance, in the Arctic to avoid further melting of Arctic sea ice. Governance of such local climate engineering might be easier to achieve than for solar radiation management, especially if substantial climate effects outside the targeted region could be avoided.

The climatic side effects of cirrus thinning have yet to be explored in larger detail. Intensification of tropical convection and changes in the tropical circulation seem likely if cirrus thinning is applied globally. Ideal target regions, seeding frequency, and transport mechanisms of seeded INPs also remain to be identified. Only after these questions are addressed could one move further to explore the costs and feasibility of cirrus cloud thinning. It is also important to remember that, like solar radiation management, cirrus thinning cannot prevent the CO_2 increase in the atmosphere and the resulting ocean acidification. For the time being, cirrus cloud thinning should be viewed as a thought experiment that is helping to understand cirrus cloud–formation mechanisms. ■

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REFERENCES AND NOTES

1. U. Niemeier, S. Tilmes, *Science* **357**, 246 (2017).
2. B. Gasparini, U. Lohmann, *J. Geophys. Res*. **121**, 4877 (2016).
3. Y. L. Hong, G. S. Liu, J. L. F. Li, *J. Climate* **29**, 7651 (2016).
4. O. Boucher *et al.*, in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, T. F. Stocker *et al.*, Eds. (Cambridge Univ. Press, 2013), pp. 571–657.
5. T. F. Stocker *et al*., in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, T. F. Stocker *et al.*, Eds. (Cambridge Univ. Press, 2013), pp. 33–115.
6. D. L. Mitchell, W. Finnegan, *Env. Res. Lett*. **4**, 045102 (2009).
7. J. E. Kristjansson, H. Muri, H. Schmidt, *Geophys. Res. Lett.* **42**, 10807 (2015).
8. U. Lohmann, P. Spichtinger, S. Jess, T. Peter, H. Smit, *Env. Res. Lett*. **3**, 10.1088/1748 (2008).
9. T. Storelvmo *et al*., *Geophys. Res. Lett*. **40**, 178 (2013).
10. D. J. Cziczo *et al.*, *Science* **340**, 1320 (2013).
11. T. Storelvmo, N. Herger, *J. Geophys. Res*. **119**, 2375 (2014).
12. J. E. Penner, C. Zhou, X. Liu, *Geophys. Res. Lett*. **42**, 8775 (2015).
13. B. Gasparini, S. Münch, L. Poncet, M. Feldmann, U. Lohmann, *Atmos. Chem. Phys.* **17**, 4871 (2017).

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