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Special Section:

Crutzen +10: Reflecting upon 10 years of geoengineering research

Key Points:

- Paul Crutzen warned the world about dangerous global warming and inspired important geoengineering research in 2006
- Stratospheric geoengineering could present a number of risks and concerns as well as benefits, but there are still many issues to address
- More research on geoengineering is needed so that if society is tempted to implement geoengineering, it will be an informed decision

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Albedo enhancement by stratospheric sulfur injections: More research needed

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Abstract Research on albedo enhancement by stratospheric sulfur injection inspired by Paul Crutzen's paper a decade ago has made clear that it may present serious risks and concerns as well as benefits if used to address the global warming problem. While volcanic eruptions were suggested as innocuous examples of stratospheric aerosols cooling the planet, the volcano analog also argues against stratospheric geoengineering because of ozone depletion and regional hydrologic responses. Continuous injection of SO_2 into the lower stratosphere would reduce global warming and some of its negative impacts, and would increasing the uptake of CO_2 by plants, but research in the past decade has pointed out a number of potential negative impacts of stratospheric geoengineering. More research is needed to better quantify the potential benefits and risks so that if society is tempted to implement geoengineering in the future it will be able to make an informed decision.

At the Fall American Geophysical Union Meeting in 2005, the buzz going around was, "Did you hear about the paper that Paul Crutzen is writing about geoengineering?" My first reaction was, "What is geoengineering?" I wrote to Paul for a copy of the draft, found the idea very interesting, and after reading it, asked him if he was sure he wanted to publish this. Of course, the answer was "Yes" and of course he was right to do it [*Crutzen*, 2006]. Crutzen stimulated many, including myself, to get involved in geoengineering research. I was intrigued and began working on it, specifically the idea of the creation of an artificial stratospheric sulfate aerosol cloud to emulate those created by large volcanic eruptions.

At my first meeting on this topic, the Managing Solar Radiation Workshop at NASA Ames Research Center, Moffett Field, California, November 18–19, 2006, I was amazed and shocked to find so many engineers and physicists enamored of this idea, and ended up writing down 20 reasons why it might be a bad idea [*Robock*, 2008]. The hubris of some, who thought that this was just a mechanical or physical problem to solve, and the lack of awareness of the science of climate change and the natural chaotic variability of climate, was very scary. A number of those potential risks were already understood 10 years ago, and were discussed by Crutzen and in the accompanying essays, particularly by *MacCracken* [2006], but work in the past decade has produced much better understanding and identification of those risks, in particular that temperature and precipitation cannot both be controlled at the same time [e.g., *Jones et al.*, 2013], that summer monsoon precipitation would be reduced [*Tilmes et al.*, 2013], that even if global average temperature could be kept from increasing, there would be cooling and warming in different places [*Kravitz et al.*, 2013a], and that ice sheets melt from the bottom, and changing insolation would not be very effective at slowing their melting [*McCusker et al.*, 2015]. The history of past weather and climate modification attempts provides strong lessons about the difficulty of governance and the dangers of military applications [*Fleming*, 2010].

My research has led me to summarize what we know, as a list of five potential benefits of stratospheric geoengineering and 27 concerns and risks, and is shown in Table 1, updated from *Robock* [2008, 2014]. The number of items on each side of the list was never meant to be a metric for deciding whether to ever implement stratospheric geoengineering. It would be possible to produce a list with an equal number of benefits and risks, but each would have different levels of importance. In the current list, items listed under both benefits and risks differ in specificity, scope, and granularity.

In fact, item number 1 on the benefits side, that stratospheric geoengineering could reduce global warming and many of its negative impacts, may be so important that society in the future may decide to implement stratospheric geoengineering to reduce some amount of warming and live with and adapt to the negative

Table 1. Risks or Concerns and Benefits of Stratospheric Geoengineering, Updated From *Robock* [2014]

Benefits	Risks or Concerns
1. Reduce surface air temperatures, which could reduce or reverse negative impacts of global warming, including floods, droughts, stronger storms, sea ice melting, and sea level rise	*Physical and biological climate system*
2. Increase plant productivity	1. Drought in Africa and Asia
3. Increase terrestrial CO_2 sink	2. Perturb ecology with more diffuse radiation
4. Beautiful red and yellow sunsets	3. Ozone depletion
5. Unexpected benefits	4. Continued ocean acidification
6. Prospect of implementation could increase drive for mitigation	5. May not stop ice sheets from melting
	6. Impacts on tropospheric chemistry
	7. Rapid warming if stopped
	Human impacts
	8. Less solar electricity generation
	9. Degrade passive solar heating
	10. Effects on airplanes flying in stratosphere
	11. Effects on electrical properties of atmosphere
	12. Affect satellite remote sensing
	13. Degrade terrestrial optical astronomy
	14. More sunburn
	15. Environmental impact of implementation
	Esthetics
	16. Whiter skies
	17. Affect stargazing
	Unknowns
	18. Human error during implementation
	19. Unexpected consequences
	Governance
	20. Cannot stop effects quickly
	21. Commercial control
	22. Whose hand on the thermostat?
	23. Societal disruption, conflict between countries
	24. Conflicts with current treaties
	25. Moral hazard—the prospect of it working could reduce drive for mitigation
	Ethics
	26. Military use of technology
	27. Moral authority—do we have the right to do this?

Please also see *Robock* [2008] for explanations of most items.

consequences of geoengineering. (The only rational way to do this would be for a limited amount of time while mitigation and carbon dioxide removal from the atmosphere reduce the radiative forcing from greenhouse gases.) Each of the potential benefits and risks needs to be quantified so that society can make informed decisions in the future about how much and what type of geoengineering to implement and for how long.

Some of the topics in Table 1 can be addressed by climate modeling. With Ben Kravitz and others, I have started the Geoengineering Model Intercomparison Project [GeoMIP, http://climate.envsci.rutgers.edu/GeoMIP/; *Kravitz et al.*, 2011, 2013b, 2013c, 2015; *Tilmes et al.*, 2015], in which various scenarios of anthropogenic stratospheric aerosols, marine cloud brightening, and cirrus thinning are being evaluated with climate model experiments as a response to global warming. So far we have had six annual international workshops [*Robock et al.*, 2011; *Kravitz et al.* 2012, 2013d, 2014, 2016a, 2016b], produced a special section of

Table 2. All Core GeoMIP Experiments up to This Point, Including the Additional Proposed GeoMIP6 Experiments

Experiment Name	Description	References
G1	Balance 4 ∝ CO_2 via solar irradiance reduction	*Kravitz et al.* [2011]
G1ext	Same as G1 but extended an extra 50 years	*Kravitz et al.* [2015]
G1ocean-albedo	Balance 4 ∝ CO_2 via global ocean albedo increase	*Kravitz et al.* [2013b]
G2	Balance 1% CO_2 increase per year via solar irradiance reduction	*Kravitz et al.* [2011]
G3	Keep top of atmosphere radiative flux at 2020 levels against RCP4.5 via stratospheric sulfate aerosols	*Kravitz et al.* [2011]
G4	Injection of 5 Tg SO_2 into lower stratosphere per year against a background of RCP4.5	*Kravitz et al.* [2011]
G4cdnc	Increase cloud droplet number concentration in marine low clouds by 50% against a background of RCP4.5	*Kravitz et al.* [2013b]
G4sea-salt	Inject sea salt aerosols into tropical marine boundary layer to achieve effective radiative forcing of $-2.0\ \mathrm{W\ m^{-2}}$ against a background of RCP4.5	*Kravitz et al.* [2013b]
G4-SSA	Use Specified Stratospheric Aerosols from an annual 8 Tg SO_2 injection into the lower stratosphere against a background of RCP6.0	*Tilmes et al.* [2015]
G5	Identical setup as G3 but using sea salt injection into marine low clouds [Implications and risks of engineering solar radiation to limit Climate Change (IMPLICC) experiment; named SALT in *Niemeier et al.*, 2013]	*Alterskjær et al.* [2013], *Niemeier et al.* [2013]
G6sulfur	Reduce forcing from RCP8.5 to RCP4.5 with stratospheric sulfate aerosols	*Kravitz et al.* [2015]
G6solar	Reduce forcing from RCP8.5 to RCP4.5 with solar irradiance reduction	*Kravitz et al.* [2015]
G7cirrus	Reduce forcing by constant amount via increasing cirrus ice crystal fall speed	*Kravitz et al.* [2015]

G4-SSA and G5 are not core experiments but are included for completeness. Updated from Table 1 from *Kravitz et al.* [2015]. New experiments are shaded yellow.

Journal of Geophysical Research — Atmospheres with 15 papers, a current special combined issue of *Atmospheric Chemistry and Physics* and *Geoscience Modeling Development* that is now accepting submissions, and a robust international modeling community conducting standardized climate model experiments, with 36 peer-reviewed GeoMIP publications so far (http://climate.envsci.rutgers.edu/GeoMIP/publications.html). The new Coupled Model Intercomparison Project 6 [CMIP6; *Meehl et al.*, 2014] requested additional focused experiments, and in July 2015, GeoMIP6 (named to coincide with CMIP6 nomenclature) was formally made a CMIP6-Endorsed MIP. The GeoMIP6 experiments to be conducted are described by *Kravitz et al.* [2015] and *Tilmes et al.* [2015] and in Table 2, where the experiments that international modeling groups have agreed to carry out over the next several years are shaded in yellow. In addition to the standard experiments, GeoMIP6 also establishes a GeoMIP Testbed for new experiments to be conducted by one or a few climate models as demonstration projects for future possible model intercomparisons.

Some of the issues in Table 1 can be studied by looking at the analog of volcanic eruptions [*Robock et al.*, 2013], but some cannot be addressed at all by scientific investigation. In 2012, I thought that the governance problems, some of which were discussed by *MacCracken* [2006], would be insoluble and that stratospheric geoengineering will never be implemented by international agreement [*Robock*, 2012a], and have yet to change my mind. In fact the more we look at stratospheric geoengineering, the more unlikely implementation becomes because of the associated risks. In particular, risks associated with unknowns, governance, and ethics (18–27 in Table 1) will be very difficult to address. Nevertheless, much is still unknown, and we have an obligation to continue the research.

The ethics of doing geoengineering research also needs to be addressed. Both *Lawrence* [2006] and *Cicerone* [2006] made a clear case that we have an obligation to better understand the benefits and risks of potential geoengineering deployment so that policymakers in the future, should they be tempted, would be able to make informed decisions. I agree [*Robock*, 2012b], provided that outdoor small-scale experiments are subject to environmental regulation and governance. However, as discussed by *Robock et al.* [2010], large-scale experiments would have to be conducted for decades to distinguish the signal of small injections from the noise of weather and climate variations. This would be no different from actual geoengineering implementation. Furthermore, only by injecting SO_2 into an existing sulfate aerosol cloud could the growth of aerosols be studied. Perhaps, after the next large volcanic eruption, this could be tested on part of the cloud, but that would require development of monitoring equipment that could follow the air parcel.

The American Meteorological Society policy statement on geoengineering [*American Meteorological Society*, 2009], which was subsequently adopted by the *American Geophysical Union* [2009], recommends "Enhanced research on the scientific and technological potential for geoengineering the climate system, including research on intended and unintended environmental responses." Strong recommendations for geoengineering research have also come from *Keith et al.* [2010], *Betz* [2012], and *Government Accountability Office* [2011]. The recent U.S. National Academy of Sciences report [*McNutt et al.*, 2015] recommends "an albedo modification research program be developed and implemented that emphasizes multiple-benefit research that also furthers basic understanding of the climate system and its human dimensions." Yet a U.S. national geoengineering research program has yet to materialize. Now that the stigma of doing the research is over, it would be relatively cheap to evaluate the many suggested techniques, by continued computer modeling and study of analogs, and also by conducting small outdoor experiments, as recommended by Crutzen.

Crutzen started an international research effort on geoengineering, yet much more remains to be learned. All scientists working on geoengineering that I know of make a strong call for mitigation and adaptation to address global warming, and this is also the recommendation of the U.S. National Academy of Sciences report [*McNutt et al.*, 2015]. In fact, a rapid transition to solar and wind power can keep global warming close to the 2015 Paris goal of 2°C above pre-industrial levels [e.g., *International Energy Agency*, 2016]. So far geoengineering research concludes that there is no safe Plan B, and provides enhanced support for mitigation and adaptation. Additional research support for these efforts will make clear over the next decade whether this current understanding is robust, and it would be irresponsible for the United States and other nations not to make this investment in research.

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