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Crutzen +10: Reflecting upon 10 years of geoengineering research

Was breaking the taboo on research on climate engineering via albedo modification a moral hazard, or a moral imperative?

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Abstract The topic of increasing the reflectivity of the Earth as a measure to counteract global warming has been the subject of high-level discussions and preliminary research since several decades, though prior to the early 2000s there was only very limited research on the topic. This changed in the mid-2000s, particularly following the publication of a special section of *Climatic Change* with a lead paper by *Crutzen* [2006], which posited the idea of stratospheric aerosol injections as a possible solution to a policy dilemma. The discussions around the publication of *Crutzen* [2006] demonstrated how contentious the topic was at that time. The special section of *Climatic Change* contributed to breaking the "taboo" on albedo modification research that was perceived at that time, and scientific publications on the topic have since proliferated, including the development of several large national and international projects, and the publication of several assessment reports over the last decade. Here we reflect on the background and main conclusions of the publications in 2006, the developments since then, and on some of the main developments over the next decade that we anticipate for research and dialogue in support of decision-making and policy development processes.

Key Points:
- The 2006 *Climatic Change* special section facilitated opening up scientific research on climate engineering via albedo modification.
- The "policy dilemma" between air pollution and climate change posed by *Crutzen* [2006] was eventually resolved by a shift in politics.
- Attention is needed to limit the ethical risks like the moral hazard, for example, by embedding scientific research in broader societal dialogue.

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1. Introduction

Anthropogenic climate change poses vast and rapidly growing societal challenges, as described by the IPCC in their most recent assessment reports [*IPCC,* 2013, 2014a, 2014b]. While efforts to address climate change have sensibly primarily focused on mitigation and adaptation, over the last decades increasing attention has being given to various other possibilities, including

1. actively removing carbon dioxide from the atmosphere, and
2. cooling the Earth by either reflecting more sunlight back to space by various means, or by modifying cirrus cloud properties to allow more terrestrial infrared radiation to escape to space.

These two types of proposed techniques, though notably different, are often grouped together under terms like "climate engineering," "climate intervention," or "geoengineering." These techniques are rarely proposed as standalone replacements for mitigation, rather as supplemental possibilities to reduce the overall severity and impacts of climate change.

Here we focus on the second type of intervention noted above, which is commonly called either "albedo modification" (where the planetary albedo is defined as the fractional amount of sunlight reflected back to space) or "solar radiation management," or simply "radiation management." We employ the former term, which is also used in the two most recent major assessments. A wide range of techniques has been proposed for increasing the planetary albedo, ranging from painting surfaces white to placing mirrors in orbit between the Earth and the sun. The technique which has been most discussed is the possibility of injecting aerosol particles or their precursors into the stratosphere. This specific idea dates back over 40 years [*Budyko,* 1974, 1977], and for the more general issue of planetary albedo modification, high-level discussions and preliminary research date back to at least the early 1960s [*Keith,* 2000; *Fleming,* 2010]. However, prior to the early 2000s, research on this and other techniques for modifying the planetary albedo was very limited (see Figure 1), despite efforts to counteract this by raising awareness in the broader academic community of the issue and its complex facets. For instance, a special section of *Climatic Change* was published in 1996, featuring six papers by prominent researchers covering the scientific, economic, political, and ethical

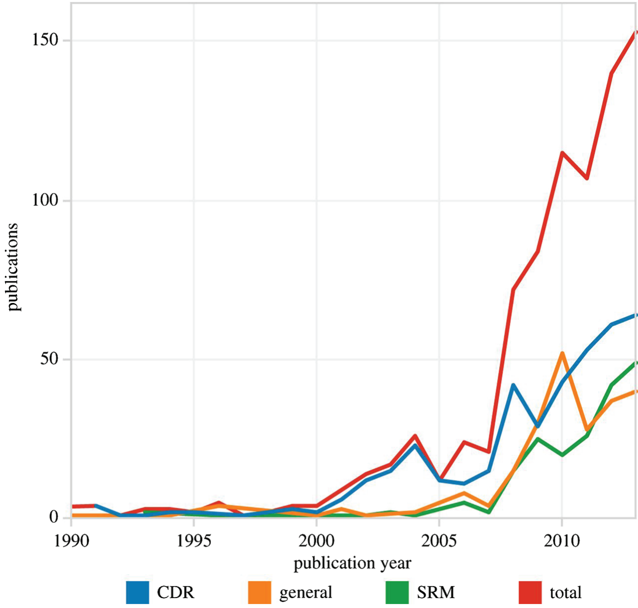

Figure 1. Trends in scientific publications on climate engineering (number of publications per year, indexed in Web of Science). Source: *Oldham et al.* [2014]

dimensions of the issue [*Bodansky,* 1996; *Dickinson,* 1996; *Jamieson,* 1996; *Marland,* 1996; *Schelling,* 1996; *Schneider,* 1996].

Figure 1 shows how this changed in the 2000s, with a very rapid increase in the number of publications during the course of the decade. In the middle of this, and perceived as one of the key factors leading to the more open discourse was the publication of a second special section in *Climatic Change* in 2006, 10 years after the first. This special section again included six papers [*Bengtsson,* 2006; *Cicerone,* 2006; *Crutzen,* 2006; *Kiehl,* 2006; *Lawrence,* 2006; *MacCracken,* 2006] (noteworthy is that this time all were natural scientists), in the form of editorial essays covering roughly the same wide range of issues as in the first special section. Nearly all the authors concluded that it is sensible to conduct research on this topic, though all expressed considerable caution, for various reasons. Several authors also noted a sense of "taboo" toward research which had been apparent in the broader climate and atmospheric science communities; for example, *Cicerone* [2006] noted: "I am aware that various individuals have opposed the publication of Crutzen's paper, even after peer review and revisions, for various and sincere reasons that are not wholly scientific," and *Lawrence* [2006] noted that "… serious scientific research into geoengineering possibilities, such as discussed in the publications by *Crutzen* [2006] and *Cicerone* [2006], is not at all condoned by the overall climate and atmospheric chemistry research communities."

This sense of taboo was based on a range of arguments against research on albedo modification that have been raised by the broader scientific community, including:

1. the so-called moral hazard issue, that is, the possibility that research on climate engineering could be perceived as an implicit legitimization, and thus reduce the motivation for mitigating anthropogenic emissions;
2. the concern that reducing temperatures by albedo modification could distract from other impacts of a fossil-fuel-based economy and the resulting CO_2 emissions, such as ocean acidification;
3. the "slippery slope" concern that research into understanding the potential effectiveness could cascade toward the development and deployment of the techniques under investigation; and
4. contention about the perceived "techno-fix" approach to address environmental challenges, that is, the notion that technology-caused problems can simply be fixed with more and better technology.

In the 10 years since these publications, although climate engineering remains a very controversial issue, the sense of a taboo has largely disappeared in the broader Earth sciences research community, evidenced not only by the numerous publications (Figure 1), but also by the participation of nearly all major climate modeling centers in the climate engineering simulations of the Geoengineering Model Intercomparison Project (GeoMIP, see Section 3). This leads us to pose the question: was the 2006 special section in *Climatic Change*—which helped break the perceived taboo on the topic of climate engineering via stratospheric aerosol particle injections—at risk of leading to the moral hazard and other ethical concerns discussed above, or was it a moral imperative?

2. The Framing in 2006

2.1. The Policy Dilemma Framing

Although the essay by *Crutzen* [2006] was quite influential, the primary line of argumentation that was employed has largely been forgotten, and has hardly been used since then. At that time, which was during the run-up to the fourth assessment report of the *IPCC* [2007], with the rapidly growing awareness and acceptance of the seriousness of global warming and its anticipated impacts, policy makers were hesitant to do anything that would exacerbate global warming. At the same time, there was a growing realization of the significant role that lower tropospheric reflecting aerosol particles played in cooling the climate. Reflecting particles are composed of sulfate, nitrate, organic carbon, and other compounds; only black carbon, a primary component of soot, is strongly absorbing, and has a significant warming effect on the climate. The reflecting particles not only directly reflect sunlight, but they also affect clouds, generally causing them to also be more reflective of sunlight. Overall, the reflecting particles cool the climate on average by a similar magnitude to the warming by carbon dioxide (nearly 1.5 $W\,m^{-2}$), and thus they partially "mask" global warming. Reducing the emissions of reflecting particles and their precursor substances (such as sulfur dioxide, from which sulfate particles form) would thus partially "de-mask" the cooling effect, exacerbating global warming. However, at the same time, these particles contribute substantially to negative impacts on human health and ecosystems (as well as reducing visibility, damaging monuments and other structures, etc.).

This contrast between beneficial and harmful effects was the main premise for *Crutzen* [2006]: "This creates a dilemma for environmental policy makers, because the required emission reductions of SO_2, and also anthropogenic organics (except black carbon), as dictated by health and ecological considerations, add to global warming and associated negative consequences, such as sea level rise, caused by the greenhouse gases." Looking back, it is now known that the dilemma was actually considerably worse than was realized at that time, since many of the health impacts of air pollution were not yet known then. *Crutzen* [2006] relied on studies available at that time that indicated air pollution contributed toward approximately 500,000 premature deaths annually. Studies since then have shown that that number was likely underestimating the impacts by about a factor of 10, with current estimates being that air pollution contributes to about 6–7 million premature deaths annually [*United Nations Environmental Programme [UNEP],* 2011*; Leliveld et al.,* 2015]. Air pollution is now recognized as the single largest environmental cause of premature death [Lim *et al.*, 2012]. But even with the factor of 10 underestimate of the health impacts in 2006, the situation was sufficient for *Crutzen* [2006] to propose that " … although by far not the best solution, the usefulness of artificially enhancing earth's albedo and thereby cooling climate by adding sunlight reflecting aerosol in the stratosphere [*Budyko,* 1977; *National Academy of Sciences [NAS],* 1992] might again be explored and debated as a way to defuse the Catch-22 situation just presented and additionally counteract the climate forcing of growing CO_2 emissions."

This main aspect of *Crutzen* [2006]—considering the contrast between the health impacts and the "masking" of global warming, and thus the concomitant policy dilemma—was hardly addressed in the accompanying editorials published in the *Climatic Change* special section. It has also hardly been used since then as a line of argumentation in the discourse around albedo modification (we are not aware of it being brought into any substantial discussions in at least the past 5 years). The impacts of air pollutants on climate and on health and ecosystems and other sectors are still getting increasing international attention, for example, in the context of the so-called short-lived climate-forcing pollutants, or SLCPs [*Ramanathan and Feng*, 2009; *Shindell et al.,* 2012; *Schmale et al.,* 2014], which has led to the development of a rapidly growing international consortium to address these issues, the "Climate and Clean Air Coalition" (http://www.ccacoalition.org). In this context, the attention has turned primarily toward the opportunities for rapidly reducing climate impacts by reducing the emissions of the short-lived warming pollutants. The role of the cooling pollutants is acknowledged, but has generally left the focus of the discussions. This is especially due to results showing that the warming pollutants are apparently playing a significant role in climate change [*Ramanathan and Feng*, 2009]*,* with a recent major review [*Bond et al.,* 2013] indicating the warming effect is perhaps much larger than previously acknowledged in many studies. Warming short-lived pollutants thus present a much more appealing "solution" to the policy dilemma discussed by *Crutzen* [2006] than consideration of albedo modification: if the warming pollutants can be reduced at the same rate or faster than the cooling pollutants, then the impacts on health will be substantially reduced, and the net impact on the climate would remain neutral or cooling, rather than warming. Thus, in the years since the 2006 special section, the discussions of climate-cooling and climate-warming pollutants have ended up usually being kept very distinct from discussions of albedo modification.

2.2. The Research Needs and Hazards Framing

However, while the article by *Crutzen* [2006] did not end up contributing directly to solving the particular policy dilemma that was specifically addressed, it did contribute substantially to opening up the other part of the discourse that it was focused on, which was already pointed out by *Dickinson* [1996], 10 years before in the previous special section: “As global greenhouse warming continues to intensify, it is likely that demands to employ technologies of climate engineering will become increasingly insistent.” In this context, *Crutzen* [2006] posited: “Given the grossly disappointing international political response to the required greenhouse gas emissions … research on the feasibility and environmental consequences of climate engineering of the kind presented in this paper, which might need to be deployed in future, should not be tabooed.”

It is interesting to ask would a manuscript of the nature of *Crutzen* [2006] nevertheless have been written, even if the policy dilemma discussed in the previous section had not existed? Given the recognition already by *Dickinson* [1996], and by *Crutzen* [2006] and many others of the impending situation of increasing political relevance of alternate methods for reducing climate change, beyond mitigation (and removing carbon dioxide), it seems probable that such a manuscript would have eventually been written. This is more relevant than ever with the unanimous agreement in the Paris Agreement to try to keep global temperature increase well below 2°C. In light of that, the motivation to write such a paper would still exist if a lasting, broad taboo on the topic of albedo modification were evident within the research community, since breaking that taboo would help ensure that political discussions and decisions could be based on good scientific knowledge, rather than an unnecessarily high degree of uncertainty and speculation.

Whether or not to break the perceived taboo at that time—and how to go about this responsibly—was the primary focus of the five commentaries that were published along with *Crutzen* [2006]. These give a cross-section of some of the key perspectives that were shaping the discourse at that time. We thus summarize here some of the main points in each of these commentaries, in the order of publication.

Cicerone [2006] was primarily concerned with supporting research, and in the process making sure to adequately address the “moral hazard” issue by imposing a moratorium on implementation, so that research could be conducted in a framework that would be intended to decouple it from concerns about premature implementation or reducing motivation for mitigation: “Here, I write in support of his [Crutzen’s] call for research on geoengineering and propose a framework for future progress in which supporting and opposing viewpoints can be heard and incorporated. I also propose that research on geoengineering be considered separately from actual implementation, and I suggest a path in that direction.”

Kiehl [2006] was also in support of research, but with a substantial concern about whether or not we could adequately judge the quality of model simulations used as a basis for that research: “For this reason, I support Crutzen’s argument that more detailed and comprehensive modeling studies be carried out with regards to experiments. But my concern is that all models have their limitations (e.g. note the inability of models to predict the appearance of the Antarctic ozone hole before it was observed). When will we know a model is ‘good enough’ to go out and perform a real experiment?”

Bengtsson [2006] was the most skeptical of all about prospects of future research, not so much from the perspective of objecting to research on the topic due to the moral hazard or other concerns about the impacts of research, but rather because of a strong notion that albedo modification will likely prove to be ineffective, and even if it did work, would present major societal challenges, in particular maintaining it over the long timescales that carbon dioxide would remain in the atmosphere: “So in conclusion, I do consider it more feasible to succeed in solving the world’s energy problem, which is the main cause to the present concern about climate change, than to successfully manage a geo-engineering experiment on this scale and magnitude, which even if it works is unable to solve all problems with the very high concentration of greenhouse gases in the atmosphere.”

MacCracken [2006], in contrast, was relatively strongly in support of research, with a primary focus more on alleviating regional than global climate change effects (e.g., reducing polar ice sheet melting): “… continued and increasing emissions of greenhouse gases merit very serious control efforts. In addition, however, as Crutzen suggests, research would be a prudent option, both on the globally uniform approach to geoengineering proposed by Crutzen and, in my view, on dealing with specific changes, some of which have already begun, in a way that might benefit the world community of nations."

Finally, *Lawrence* [2006] focused on the responsibility of the scientific community in the face of a potentially urgent future political need for knowledge: " … we may eventually reach the state of extreme climate change where the overall international sentiment is in favor of applying geoengineering. If we do not conduct careful research now, we will not be prepared to advise politicians on how to best approach large-scale geoengineering applications—including providing sound information on the various risks involved, and on which ideas should not be pursued further." Going beyond this impression of a fundamental moral imperative is the concern about potential "covert," "clandestine," or "uni-lateral" applications of climate engineering, which makes research even more imperative. Nevertheless, concern about the moral hazard and other risks of climate engineering research were noted to be significant, and in order to address these it was concluded that " … the pertinent question is not 'To speak or not to speak?', but rather 'How to speak?' about geoengineering," with a focus on care in using accurate scientific terminology, and explicit discussion of values and norms behind assessments and recommendations.

3. Resulting Developments

Since shortly after 2006, research and scientific publications on the topic of albedo modification have proliferated (see Figure 1). The 2006 *Climatic Change* special section was soon followed by the first major assessment report, conducted by the Royal Society [*Shepherd et al.,* 2009], as well as by a plethora of further assessment reports from various national and international perspectives and focused on various aspects of the topic [e.g., *Blackstock et al.,* 2009; *Gordon,* 2010; *UK House of Commons Science and Technology Committee,* 2010; *Ginzky et al.,* 2011; *Rickels et al.,* 2011; *Bodle et al.,* 2013; *Caviezel and Revermann,* 2014; *McNutt et al.,* 2015a, 2015b; *Schäfer et al.,* 2015; *Klepper et al.,* 2016]. The topic has also been addressed by all three Working Groups in the IPCC's Fifth Assessment Report [*IPCC,* 2013, 2014a, 2014b].

Numerous national and international projects have also developed. The majority of this work has been model based. Experimental work directly on albedo modification techniques and their effects and side effects has been very limited thus far, although considerable work has gone into conceiving possible future field experiments [*Keith et al.,* 2014]. Among the modeling studies, we would particularly like to highlight GeoMIP [*Kravitz et al.,* 2011], and a smaller predecessor, Implications and Risks of Novel Options to Limit Climate Change (IMPLICC) [*Schmidt et al.,* 2012], which was funded by the European Commission. The GeoMIP simulations build on CMIP, the Coupled Model Intercomparison Project, which provides the community simulations that are primarily employed in the IPCC Assessment Reports. The first phase of GeoMIP corresponded to the CMIP5 simulations for the Fifth Assessment Report, with nearly all of the CMIP5 models having completed the GeoMIP simulations by now. A second phase of GeoMIP is now being conducted corresponding to CMIP6 for the Sixth IPCC Assessment Report. IMPLICC and GeoMIP have contributed substantially to the understanding of how to set up useful CE simulations that are comparable across a wide array of models, helping to improve the robustness of the model results, and giving an initial sense of uncertainty in these results. The GeoMIP project shows the degree to which research on albedo modification has become "normalized" among the scientific research community, in contrast to having been perceived as a largely tabooed (or at least broadly avoided) topic prior to 2006, as discussed above. Interestingly, the GeoMIP project also, at least partly, addresses all of the primary concerns brought out by the articles published in the 2006 *Climatic Change* special section, corresponding to the main points noted above:

1. It provides for a substantial research platform and scientific exchange forum which is kept distinct from the research and development toward actual implementation.
2. It supports the call by *Kiehl* [2006] for "detailed and comprehensive modeling studies," while providing a forum for comparatively assessing model results as a valuable (though in itself inadequate) step toward assessing the model limitations and when models will be "good enough."
3. It shows, based on all simulations thus far, and in contrast to some initial expectations, that if the technology for aerosol injection or other forms of increasing the planetary albedo were to actually work, then albedo modification would indeed be effective in reducing the global mean surface temperatures, and although there would be significant regional variability in the climate response, it

appears that some techniques including stratospheric aerosol injection would be able to reduce the risk due to climate change in most regions of the world simultaneously. In addition, the GeoMIP protocol includes simulations to examine the effects of a potential, unintended abrupt termination of albedo modification, which was a major source of concern expressed by *Bengtsson* [2006].

4. It provides a forum in the second phase for encouraging the development community simulations of new focal topics, including those focused especially on alleviating regional climate change effects.
5. It encourages "careful research now … " in order to " … be prepared to advise politicians on how to best approach large-scale geoengineering applications—including providing sound information on the various risks involved, and on which ideas should not be pursued further," as recommended by *Lawrence* [2006].

On the whole, the GeoMIP simulations and numerous other separate studies conducted by the scientific modeling community in the last 10 years have given an initial impression which has been summarized by *Irvine et al.* [2014], who concluded that "Although the evidence from model studies about the impacts of SRM geoengineering is, at present, limited, the initial evidence broadly indicates that SRM deployed to cool the climate could potentially reduce many of the physical impacts of climate change as well as the risk of crossing tipping points," and furthermore that the GeoMIP results make it clear that "SRM is no panacea; it would introduce new risks and would shift the overall burden of risks, which might pose substantial political problems … ," and that " … to minimize the risks posed by climate change, mitigation will need to be pursued vigorously."

4. Future Developments

The last decade of intensifying investigation of albedo modification by the Earth system sciences community has thus provided very valuable information—but also challenging in many ways. First, the numerous studies conducted on the scientific and engineering aspects have not yet found a major fundamental scientific or engineering reason why stratospheric aerosol injections would definitely not work to cool the climate (albeit regionally unevenly, but—according to the model studies thus far—likely feasible in a way that could reduce the overall impacts and risks due to climate change nearly everywhere). Second, no side effects that would be a real "showstopper" have been uncovered yet. This is quite in contrast to the situation for some other proposed forms of climate engineering, especially ocean iron fertilization, for which the effectiveness and potential has been brought more and more into question through field experiments, and numerous potentially very detrimental side effects have been uncovered [*Lawrence et al.,* 2008]. Of course, still uncovering major side effects of albedo modification techniques cannot be ruled out, as was already pointed out by *Crutzen* [2006]: "The chances of unexpected climate effects should not be underrated, as clearly shown by the sudden and unpredicted development of the antarctic ozone hole." There is still much to be learned from model studies, and the second phase of GeoMIP and many other independent studies are expected to bring us further important insights. However, to us, going beyond further model studies, these results of the last decade point toward two main future developments:

1. First, a broad, well-informed sociopolitical dialogue is needed to determine whether humanity as a whole is likely to actually someday provide broad support for the pursuit of full-fledged climate engineering—and if so, in what forms, for what purposes, and for how long—or if it will be a topic like human cloning or genetic engineering, which is open for general discussion, but under a broad societal taboo for any form of experimental research or steps toward realization.
2. Second, depending partly on how the societal dialogue develops, and in support of a better information basis for what will potentially be a protracted international political debate, it is likely that the scientific community will pursue field experimentation to help clarify many uncertainties; if so, then an adequate public funding and governance framework (in soft and hard forms) urgently needs to be developed [*Morgan et al.,* 2013; *Parson and Keith,* 2013; *Schäfer et al.,* 2013; *Victor et al.,* 2013].

Here we posed the question: was breaking the perceived taboo on the topic of stratospheric aerosol particle injections at risk of leading to the moral hazard and other ethical concerns, or was it a moral imperative? The Paris Agreement has provided evidence that the overall international political intention to reduce greenhouse gas emissions has not diminished, and that while there may be an overoptimism about the possibilities of removing large amounts of carbon dioxide from the atmosphere via various means, there is no evidence of hope being built on employing albedo modification to achieve the Paris Agreement goals. Thus we generally conclude that the moral hazard risk has thus far largely been avoided on an international political scale. There is also no clear evidence that we are aware of that the other ethical concerns (e.g., the "slippery slope" and "techno-fix" arguments) are manifesting in the scientific literature or in climate policy. However, given the balance of results of model studies over the last decade, as discussed in the previous sections, and the challenging directions that this implies both for future research and also for sociopolitical aspects, especially public perception and the development of good governance principles, we have to conclude that the overall verdict is still out. The responsibility still resides with the scientific community to conduct research and engage in the broader dialogue in a responsible way, so that whatever the outcome, historians will hopefully look back and conclude that it was indeed of value—and in that sense a moral imperative—to begin carefully investigating this topic at this point in our history. Perhaps this will already be clear by the time of the next special section like this one, which, following those in 1996 and 2006, should be due in 2026.

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