Climate engineering: exploring nuances and consequences of deliberately altering the Earth’s energy budget

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Our planet is warming, largely from the ever-increasing burning of fossil fuels. If this continues, serious consequences to our planet are likely to occur within the second half of this century. The objective of Climate Engineering (hereafter CE, but also referred to as ‘Geoengineering’, and sometimes as ‘Solar Radiation Management’) is to offset the warming and some other climate consequences that would otherwise result from increasing greenhouse gas concentrations by reducing the amount of sunlight reaching the Earth’s surface or by increasing the outward transmission of long-wave radiation from the Earth. These strategies might be used throughout the period required to replace fossil-fuel burning with globally distributed clean energy and even be continued while CO\textsubscript{2} concentrations remained too high.

Five years ago, the Royal Society published a report titled \textit{Geoengineering the Climate} [1] summarizing many of the issues associated with CE. The Society’s article-tracking software records a large number of downloads and citations to an earlier \textit{Phil Trans A} theme issue on \textit{Geoengineering} [2] (to which a significant number of the authors involved in this Theme Issue also contributed). This fact underlines the wide scientific concern about the issues raised by global warming, and an appreciation of the urgency of charting a credible path to avoid some of its worst consequences, should efforts to shift to a very-low-carbon society progress too slowly (as appears...
likely). There is not yet, however, a good understanding of CE and the nuances which need to be explored.

To have any chance of developing and—should it ever be necessary—deploying a globally acceptable CE technique for temporarily countering the rising temperatures induced by continually increasing levels of atmospheric CO₂ (and other contributors), there needs to be open, continuous and concerted discussion between experts and interested groups from many fields. An optimal assessment of any CE method requires a dialogue between three communities: (i) leading scientists and engineers from the arenas of meteorology, physics, chemistry, mathematics, engineering and the biological sciences to evaluate the issues from a physical point of view; (ii) experts in governance, ethics, sociology, psychology and related topics who focus on societal issues and (iii) citizens and policymakers who, in the end, must be involved in the decision on whether to deploy or not. These communities must understand the impacts, trade-offs, risks and benefits, both to the planet and to society, of the effects of CE compared with those of other choices in dealing with climate change.

This Theme Issue explores details of (i) the fundamental physics and chemistry of what we (the editors) perceive to be the most feasible of the announced CE methods; (ii) possible field experiments that can be used to examine science’s understanding of those processes and (iii) societal issues associated with the testing of CE and its impact on the planet. Indeed, the issue seeks to draw together research relevant to these disparate areas. Our primary focus is on global issues, but attention is also given to possible amelioration of significant regional-scale problems.

One important concern is that if research indicates that one or more of the CE techniques are capable of producing sufficient global cooling to offset additional heating resulting from maintaining or increasing the burning of fossil fuels, there could be a reduction of interest in reducing fossil-fuel burning. In that circumstance, climate engineering would simply be postponing the day of reckoning, with the potential for a much higher risk situation in which increasingly strong CE is required to compensate for increasingly strong CO₂ forcing. Another danger is that the deployment of CE measures, while capping and perhaps reducing global temperature levels, could cause drastic and negative changes in the local weather patterns, leading, for example, to rainfall reduction in regions where precipitation levels were already marginal.

Each of the 14 articles contributing to this Theme Issue were chosen to provide readers with an overview of leading edge research over many (but by no means all) of the topics germane to CE. The overall theme of each paper is briefly provided in the paragraphs immediately below, and more substantial summaries are to be found in the abstracts that preface each of the papers.

Papers 1–5 are all concerned with issues associated with Marine Cloud Brightening (MCB), that is, climate engineering methods designed to increase the reflectivity of marine boundary-layer clouds by increasing the number density of cloud droplets. The first, by Maalick et al. [3], explores the efficacy of brightening clouds composed of liquid drops, by employing a higher resolution model of the physics than has hitherto been attempted with a comprehensive representation of aerosol processes. This enables its authors to explore consequences of the negative buoyancy caused by water evaporation from aerosols and—at a very high resolution—to capture aerosol coagulation effects near the source point. Paper 2, by Kravitz et al. [4], explores the interactions between aerosols, cloud liquid and ice particles, and cloud dynamical features, in a series of eight simulations for a meteorological regime (the Arctic) that has not previously been carefully treated. Seeding is limited to open ocean areas as sea ice already has higher albedos than low marine clouds. The paper by Latham et al. [5] investigates potential benefits of MCB for a variety of regional phenomena important to the climate system: the restoration of polar sea-ice, as well as reductions in hurricane intensity and the elimination of or, at least, the reduction in tropical coral-reef bleaching. The paper by Cooper et al. [6] presents preliminary results exploring practical mechanisms (via an effervescent spray-atomization technique) for the production of the copious quantities of sub-micrometre sea-salt aerosol particles needed to act as cloud condensation nuclei, that would serve to increase the cloud reflectivity and thus produce a cooling effect. To conclude this group, Connolly et al. [7] provide a numerical exploration of the
effects of various characteristics of the salt-particle spray (particle size and number density) on
the increase in the cloud albedo and also on the power required to generate the spray using three
alternative strategies.

The next pair of papers explores the use of a second method for increasing the reflectivity of the
planet, by increasing the number of sulfate aerosols in the stratosphere. In most respects, however,
the issues examined by MacMartin et al. [8] are generic and are equally relevant to other strategies
for reducing solar radiation reaching the Earth’s surface. In contrast to many previous studies that
explore the consequences of strong CE employed to counter high (doubling or quadrupling of pre-
industrial) CO2 concentrations, this paper notes that other implementation strategies are possible
and examines the implied consequences of using SRM simply to limit the rate of temperature rise
to a fixed number (say, 1°C per century) rather than to hold the global annually averaged surface
temperature fixed at some predetermined level. The paper by Dykema et al. [9] provides for
the first time a careful (although, inevitably, imprecise) estimate of a major physical experiment
conceived to provide detailed data on the physics and chemistry of stratospheric aerosols using a
high-altitude balloon (rather than aircraft) to gather data.

While marine-cloud brightening and stratospheric aerosols are well-established proposals for
limiting the level (or growth rate) of the Earth’s temperature, Storelvmo et al. [10] report progress
with a quite different and relatively novel approach first aired by Mitchell & Finnegan [11]. Rather
than reflecting incoming sunlight, the paper explores the outcome of seeding cirrus clouds to thin
or eliminate them thus increasing the efficacy of emission of outgoing long-wavelength radiation.
Their computational simulations suggest that the method may be especially effective at higher
latitudes. The study suggests that the method may well have a safer impact on climate, with
fewer side effects, than the strategies that increase planetary reflectivity.

The theme issue considers just these three broad classes of CE methods that appear potentially
feasible, i.e. that are possibly quantitatively adequate, technically achievable and affordable.
Other CE techniques have been proposed, but founder on one or other of those criteria. The
ingenious mirrors-in space [12] (or the conceptually similar light-diverting lenses in space [13]),
for example, appear to be technically feasible and sufficiently powerful in their effect to be
important, but their costs and huge logistical demands remove them from serious consideration
at the present time.

Of course, it is likely that potential dangers (some as yet unrecognized) are attached to all
three of the strategies classified above as ‘feasible’. For all three strategies, however, it is crucially
important to devote major efforts both to identifying unacceptable dangers and to searching
for techniques and pathways that may provide significant operational improvements. If, in the
course of that research, serious operational weaknesses become apparent with no evident route
to circumvent them, then equally, that would be a signal to abandon further research on the
 technique in question.

The paper by Keith et al. [14] summarizes the outcomes of a workshop at which 27 researchers
thrashed out, collectively, a range of experiments that might be used to advance understanding
of the effectiveness and cost of the three broad approaches noted above. The paper provides
concrete examples of the type of experiments that are being considered and the motivation for
those experiments. As the authors point out, some of the nine experiments tabled while focusing
on understanding relevant to CE may also provide strong ‘co-benefits’ for climate science more
generally, contributing to basic scientific knowledge about key components of the climate system
(e.g. clouds and aerosols) that are critical in understanding climate and climate change even in
the absence of CE.

Since the publication of the Royal Society report on geoengineering [1], there has been an
appreciable surge of research activity into the very important ‘non-scientific’ aspects of CE, which
include ethical, moral, technical, societal and related issues. The final section of this Theme
Issue, comprising Papers 10–14, thus connects the physical aspects of CE to societal issues and
consequences. We believe these issues are relevant not only to social scientists, but must also
be considered by scientists and engineers, because societal and scientific issues are so strongly
coupled. It is clear that choices made by a few scientists to proceed without regard for societal
concerns might poison the opportunity for scientific research and understanding in this area; and it is equally clear that society might needlessly suppress scientific progress through governance in situations where such control is not needed. An explicit consideration of the trade-offs (risks and benefits) and governance mechanisms is needed.

In the first of these papers on societal issues, Parker [15] begins by noting that a range of prominent commentators, citing numerous risks and concerns, have called for field experiments to be delayed until there is formalized research governance, such as an international agreement. As a piece of pragmatic policy analysis, this paper explores the practicalities and implications of demands for ‘governance before research’. It concludes that while such a policy is a highly desirable goal, the resultant delay in experimentation—a moratorium—would probably be an ineffective and counterproductive way to achieve it. Both Morrow [16] and Corner & Pidgeon [17] explore ‘moral hazard’, i.e. whether consideration of CE as a solution to climate change might affect society’s willingness and motivation to make the hard decisions needed to reduce GHG emissions. These two papers reject the notion that geoengineering may be defined as a typical moral hazard situation. Moreover, Morrow [16] also identifies the most important mechanisms by which society might perceive CE as a means to reduce or delay mitigation efforts and concrete steps that geoengineering researchers could take to avoid those mechanisms, i.e. steps whose importance may be missed if researchers incorrectly identify the issues as a moral hazard problem. The final two papers introduce the reader to the complex issues of governance of CE. Schäfer & Low [18] consider the issue for small field experiments, in situations where there will be no perceptible impact on climate. They point out similarities to the issues raised with recombinant DNA during its formative period in the late 1960s. Oldham et al. [19] consider the issue from another point of view, noting that research on climate engineering could itself be a step onto a slippery slope, making development and eventual deployment of a technology more likely; where social and technological choices are constrained by pre-existing technological commitments, and norms, standards and technologies may develop a momentum that proves hard to govern. In the absence of an established governance framework, the practices of scientific research and intellectual property tend to shape the field and set trajectories for the future. These issues make it important to expose and document the emerging patterns of research and patenting. Their study outlines a methodology for describing the evolution of these patterns and summarizes the evolution to date.

Overall, these papers just scratch the surface of the challenges of understanding CE, and its possible role in addressing climate-change issues, but we hope they stimulate more research, understanding and dialogue among scientists and society more generally. We hope you enjoy and learn from them.

References