Statement to the Committee on Science, Space and Technology
of the United States House of Representatives

Hearing on

Geoengineering: Innovation, Research, and Technology

November 8, 2017

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Major points:

- The context for considering geoengineering is the fact that human emissions of greenhouse gases are warming the Earth's climate and creating risks for the United States and other nations.
- Because of the long lifetime of CO_2 in the atmosphere, the more we put in, the larger the impacts will be. Reducing greenhouse gas emissions remains the most important component of a strategy to respond to climate change.
- Geoengineering, including carbon dioxide removal (CDR) and sunlight reflection methods (SRM), could be an additional and valuable part of an integrated strategy for managing climate change. CDR is the only way to achieve negative emissions, while SRM can act quickly to cool the climate.
- Sunlight reflection cannot be a *substitute* for cutting emissions for several reasons:
    - Counteracting rising greenhouse gas concentrations would require continually increasing the amount of geoengineering, leading to increased side effects and rapid warming if deployment were ever interrupted.
    - A significant fraction of the CO_2 we add to the atmosphere remains for more than 1000 years, requiring a practically indefinite commitment for future generations to either maintain SRM or accept the consequences of higher CO_2.
    - SRM cannot compensate all impacts of climate change, e.g., it cannot reverse the ocean acidification caused by increased atmospheric CO_2 concentrations.
- Based on research to date, it is *plausible* that a *limited* amount of SRM, *in addition* to cutting emissions, could reduce some of the impacts of climate change. There is considerable uncertainty about the viability, impacts and risks; research to reduce this uncertainty could take decades.
- A coherent, prioritized geoengineering research effort would be valuable, to support informed decisions regarding these approaches (including possibly abandoning the idea), and would need to include natural sciences, social sciences, and explicit attention to research governance. Such a program would need to be integrated into the overall US climate science research effort.
- Near-term research for stratospheric aerosol injection should be primarily model-based, to characterize model uncertainty and understand the potential to improve outcomes. Marine cloud brightening would benefit from limited field experiments, which would also inform critical uncertainties in climate change science. The first step is to better define research needs.
- Conducted at sufficient scale, carbon dioxide removal would direct address the mechanism of climate change. Research is needed to find approaches that are sufficiently scalable, cost-effective, and without significant local impacts.

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1. Introduction and context

Chairman Biggs, Chairman Weber, Ranking Members Bonamici and Veasey, and members of the subcommittees, thank you for the opportunity to provide testimony regarding the status of geoengineering research in the United States. I hold research appointments in both the Department of Mechanical and Aerospace Engineering at Cornell University and the Computing + Mathematical Sciences Department at the California Institute of Technology. My research lies at the intersection between engineering and climate science, and geoengineering has been my primary research focus for the last ten years.

There are three areas I will briefly address. The first is the role that geoengineering might be able to play in managing climate change. Second, I will make a few comments regarding the current status of research that are relevant for considering the path forward. And third, I will discuss future research needs.

Geoengineering, or climate engineering, refers to two broad categories of technologies. First, carbon-dioxide removal (CDR)[1], including technologies such as burning bio-energy and capturing and storing the carbon underground (BECCS), or direct air capture (DAC) of CO_2, which would reduce atmospheric CO_2 concentrations and directly address the cause of climate change. Second, sunlight reflection methods (SRM), also known as solar geoengineering or albedo modification[2], would involve either adding aerosols to the stratosphere or brightening marine boundary layer clouds, these would cool the climate by reflecting a small portion of sunlight back to space. I will address both but focus on the latter, both because it is the more novel and potentially disruptive of the two, and because I am more knowledgeable about SRM. Both topics were recently addressed by the US National Academies[1,2].

The context for considering these ideas is the fact that human emissions of heat-trapping greenhouse gases (GHG), principally CO_2, are altering Earth's climate, as reiterated in the recent US Fourth National Climate Assessment (2017)[3], which notes that in addition to warming, "Thousands of studies conducted by researchers around the world have documented changes in surface, atmospheric, and oceanic temperatures; melting glaciers; diminishing snow cover; shrinking sea ice; rising sea levels; ocean acidification; and increasing atmospheric water vapor". CO_2 has a long lifetime in the atmosphere, with a significant fraction remaining even after 1000 years[4]; as a result the planet will still be warmer in 1000 years due to the CO_2 we add today[5]. The more CO_2 we add, the greater the warming. It is thus not possible to limit climate change without ultimately reducing net carbon emissions to zero; reducing emissions must therefore be a central element of any meaningful climate change strategy.

The United States is already experiencing impacts of a warmer world, from increased tidal flooding in the Atlantic and Gulf states, increases in heavy rainfall, increased heatwaves, increased large forest fires, and reduced snowpack that affects water resources (see the US National Climate Assessment, 2017 for further details). Additionally, unusually strong hurricanes have likely been amplified by higher than normal sea surface temperatures that are a result of climate change. These impacts are a result of roughly 1.8°F (1°C) of warming. However, without any policy to reduce emissions of greenhouse gases, the warming could reach 9°F (5°C) or more by the end of century, leading to far more extreme impacts and greater risk of crossing irreversible "tipping point" thresholds in the climate system such as triggering significant sea level rise from the Antarctic and Greenland ice sheets. Flooding, heat waves, and forest fires will be greatly exacerbated relative to today, while the risk of chronic long-duration drought is expected to rise. Sea level rise under such a scenario is expected to be at least 1-4 feet by the end of the century, while a rise of as much as 8 feet cannot be ruled out[3].

To avoid these impacts from "business as usual", almost every nation has voluntarily chosen nation-specific targets for reducing their individual greenhouse gas emissions; taken together these commitments have been estimated[6] to lead to end-of-century warming near 3°C. This is far lower than the 5°C that could occur without any agreement to act[3], but still substantially higher than the 1.5 – 2°C level of warming deemed "safe" by the international community[7,8].

Geoengineering technologies may be able to reduce climate impacts in two ways. First, CDR is the only way to achieve net-negative emissions, ultimately reducing the atmospheric CO_2 concentrations and reducing the long-term impacts that our emissions are imposing on future generations. Second, because it acts quickly to cool the planet, SRM could limit the amount of climate damage that would otherwise result from higher atmospheric CO_2 concentrations.

An overall strategy for reducing climate change risks may involve four elements:

- Accept higher levels of warming; some impacts may be reduced through adaptation, e.g., by building sea-walls or relocating some urban areas.
- Increase the speed at which new technologies are adopted to reduce emissions, by earlier adoption of renewable energy, earlier transitions to electric vehicles, etc.
- Large-scale deployment of CDR approaches; to be a relevant component of a strategy the rate of removal needs to be at a sustained level of at least several billions of tons of CO_2 every year.
- Limited use of solar geoengineering approaches.

Neither of the last two options exist today. We do not know whether it will be possible to develop CDR approaches that can be scaled up to the necessary levels at reasonable cost, and without having substantial local impacts such as loss of food production. We do not know whether the risks of solar geoengineering would outweigh the benefits even in a limited deployment scenario. Research into geoengineering could thus add to the portfolio of options available for managing climate change.

Figure 1 (from MacMartin et al 2017[9], adapted from Long and Shepherd 2014[10]) illustrates how these elements might be integrated into an overall strategy to manage climate change: (i) anthropogenic emissions of greenhouse gases are eventually brought to zero, (ii) excess atmospheric concentrations are reduced through CO_2 removal, and (iii) solar geoengineering might be used to limit climate impacts in the interim. Note that while SRM could reduce the global mean temperature, it will not reduce ocean acidification and resulting impacts on ocean ecosystems, and it will also have other effects on the climate system. However, unlike mitigation, solar geoengineering would affect the climate quickly, and thus could provide a unique additional tool for managing climate change.

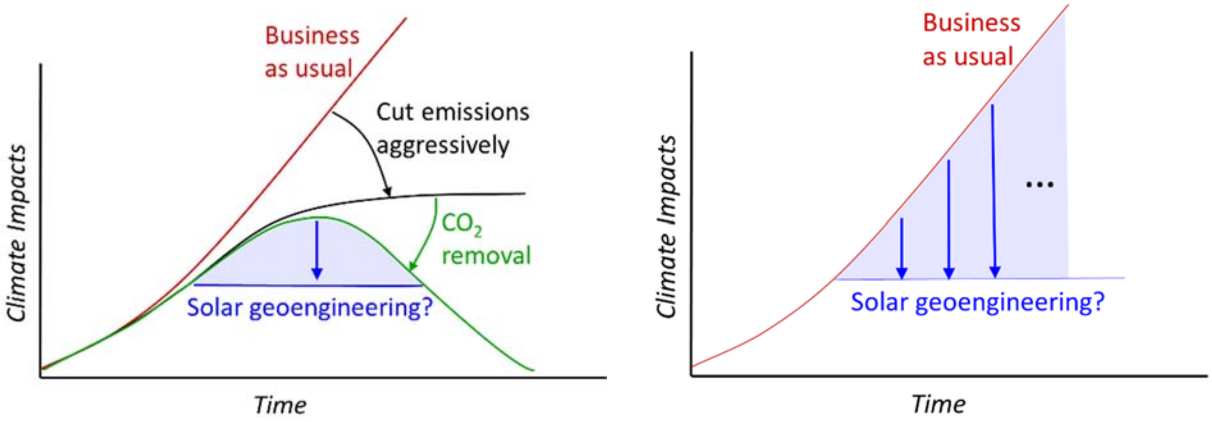

Figure 1. (left) Reducing greenhouse gas emissions, combined with future large-scale atmospheric CO_2 removal, may lead to long-term climate stabilization with some overshoot of desired temperature targets. There is a plausible role for temporary and limited SRM (solar geoengineering) as part of an overall strategy to reduce climate risks during the overshoot period. (right) SRM instead of mitigation would require large and increasing forcing, sustained for millennia, and is thus not realistic. This graph represents climate impacts conceptually, not quantitatively

SRM cannot be an alternative to reducing greenhouse gas emissions. This is a conclusion that has been reached by every assessment that has been conducted of these technologies, including by the US National Academies in 2015. If emissions are not reduced then atmospheric greenhouse gas concentrations continue to grow as illustrated in Figure 1, requiring continuous increases in the amount of reflecting stratospheric aerosols or the amount of cloud brightening to maintain a stable temperature. This is not a viable solution for at least four reasons. First, undesired side-effects of geoengineering (e.g., stratospheric ozone depletion) would increase with the amount used. Second, increased atmospheric CO_2 also results in ocean acidification that would not be counteracted by SRM. Third, because of the long lifetime of CO_2 in the atmosphere, geoengineering would need to be maintained for a practically indefinite time period, imposing a commitment on future generations to either maintain the deployment or accept the consequences of high CO_2; if the deployment were ever terminated there would be a sudden rapid warming[11] that could have impacts worse than if SRM were never initiated. Finally, while we are confident that several degrees of cooling could be achieved, it is not clear how much cooling might be possible[12], and it would be risky to assume that sufficient cooling could be obtained to offset the warming from un-mitigated CO_2 emissions.

Reducing emissions of greenhouse gases is the most urgent and essential response to climate change. However, while every reduction in emissions leads to lower climate impacts and risks, a rapid reduction in emissions will still result in a world that may be substantially warmer than today with correspondingly larger impacts from climate change. While solar geoengineering is not a substitute for cutting emissions, climate modeling research suggests that it is plausible that a limited deployment, in addition to mitigation and CO_2 removal, would reduce many climate risks. However, the current state of knowledge is insufficient to assess whether the risks of deploying geoengineering outweigh the risks of not deploying it. Developing the required knowledge demands a strategic *goal-oriented* research program. This knowledge base could take decades to develop, as some research will require small-scale outdoor experimentation. Meanwhile climate change impacts will continue to grow in severity. The worst-case outcome is that we find ourselves in a climate crisis in 20 years and face the need to make decisions without knowledge; needing to decide whether to deploy SRM without knowing enough to ensure that it will do what we want it to do, safely. In order to support informed decisions, strategic research needs to be initiated soon and conducted with some degree of urgency.

The next section briefly summarizes the status of geoengineering research, highlighting some recent results. Building on current status, Section 3 then addresses research needs.

2. Status of Geoengineering Research

2.1 Carbon dioxide removal

Various approaches have been suggested for deliberately removing CO_2 from the atmosphere; see for example the 2015 National Academies Report[1]. In the near-term, CDR is equivalent in outcome to cutting emissions, but likely at higher cost. In the long-term CDR allows net-negative emissions that would compensate for our current positive emissions; this effectively makes future generations pay for reducing our current emissions. Current human emissions of CO_2 are of order 40 billion tons per year; to make a useful contribution to the problem, CDR would need to be undertaken at least at a fraction of that scale, 10-20 billion tons per year or more. Not all of the ideas that have been suggested are capable of being scaled up sufficiently. While there are no direct climate risks from removing CO_2 from the atmosphere, anything conducted at the massive scale required could have other negative impacts.

The capacity for large-scale CDR later in the century will not materialize without near-term investments to learn whether and how solutions can be scaled up at reasonable cost.

Possible approaches include:

- Bio-energy with carbon capture and storage (BECCS). This involves growing biofuels, burning them in a power plant, capturing the CO_2 before it is released to the atmosphere, and storing it underground. Because the plants absorb CO_2 as they grow, this would both create energy and sequester CO_2, and is likely to be technically possible. However, implementing this on a sufficient scale to be useful would create competition for land use with food crops if terrestrial biofuels were used; using oceanic biofuels might also be possible.
- Direct air capture involves using chemical means to extract CO_2 directly from the atmosphere, and then sequester the CO_2 underground. This is certainly technically possible, and scalable, but there is currently high uncertainty on what the costs are likely to be.
- Enhanced mineral weathering accelerates natural CO_2 removal processes that would otherwise occur on geological timescales.
- Planting trees would reduce atmospheric CO_2 as the trees grow. This is limited by land availability, and while it could contribute, is not sufficient to address the scale of CO_2 removal required.
- Soil management, including biochar: there is significant carbon stored in soils today, and better land management might increase this amount. Estimates suggest that like afforestation it has the potential to contribute but is unlikely to be able to address the full scale of the problem
- Ocean iron fertilization could increase marine phytoplankton, increasing CO_2 uptake through photosynthesis, some unknown fraction of which may ultimately be sequestered in the deep ocean by settling of biological detritus. At scale this approach would have significant implications for ocean ecosystems.

2.2 Sunlight reflection methods

Methods for reflecting some incoming solar radiation could rapidly cool the Earth; for recent reviews see MacMartin et al (2017)[9], or the 2015 US National Academies report[2]. Two principle approaches have been suggested:

- Stratospheric aerosol injection, or SAI. Large volcanic eruptions can introduce significant amounts of sulfate aerosols (an aerosol is a small liquid or solid particle) into the upper atmosphere, where the residence time can be 1-2 years; this results in temporary cooling of the planet by reflecting some sunlight back to space. By analogy, mimicking this natural process by deliberately adding sulfate aerosols to the stratosphere is certain to cool the planet, although it will have other effects on the climate system as well. This is nearly certain to be technically feasible (e.g. by designing suitable aircraft; none currently exist). The direct cost of delivering material to the stratosphere is not likely to be an important factor in deployment decisions.
- Marine cloud brightening (MCB) involves injecting sea-salt aerosols into low clouds in appropriate regions of the ocean; with more cloud-condensation nuclei, the clouds are expected to be “brighter” and reflect more sunlight. A similar phenomenon is observed with ship tracks; the pollution from ship smokestacks results in a cloud that can persist for days. Cloud-aerosol interactions are highly uncertain, and so the feasibility of this approach is less certain.

Other approaches have also been suggested. Cirrus clouds result in a net warming of the planet, and thus deliberately thinning cirrus cloud cover has been suggested as a way of providing some cooling; the viability of this approach is highly uncertain.

To date, research on sunlight reflection methods has relied on climate modeling. References 13 and 14 illustrate the capability of state of the art climate models to capture observed stratospheric aerosol concentrations after the Mt. Pinatubo eruption in 1991, as well as the recovery of the ozone hole. Consistency between model simulations and the observations made during and after an eruption builds confidence that the models can reasonably represent the relevant processes. There are, however, differences between continuously injecting aerosols for geoengineering and impulsively injecting them through an eruption, which leads to some uncertainty in model predictions that will be discussed in more detail below; there are similar uncertainties in model simulations for marine cloud brightening.

Deploying SRM would not simply reverse the heating caused by greenhouse gases, it would also change climate patterns. While a reduction in sunlight would cool the planet everywhere, the cooling would not have the same spatial or seasonal pattern as the greenhouse gas warming. The warming caused by increased greenhouse gases also influences precipitation (both rain and snowfall), while the cooling from SRM would not simply reverse these effects. Thus if CO_2 increases relative to today, and the resulting warming is then offset by a reduction in sunlight, the resulting climate will not be the same as the current climate. However, the resulting climate will be much more similar to the current climate than either would be to the high-CO_2 world without SRM (see MacMartin et al 2017[9], which compares both regional temperature and precipitation projections). Recent research with climate models suggests this may be true for many features of climate change: not only are annual mean temperature and precipitation closer to current conditions with some SRM than without, but that is also the case for high temperature extremes, soil moisture, ocean circulation patterns, Arctic sea ice, and hurricane strength, for example.

One recent development in SRM research worth highlighting comes from exploring how the resulting climate impacts depend on choices that can be made[15], such as the latitude at which to inject aerosols into the stratosphere, or where to deliberately brighten marine clouds. Combining aerosol injection at multiple different latitudes allows the climate response to be at least partially tailored[16], possibly improving outcomes[17]. While sulfate aerosols have often been assumed in simulations, different aerosols could also be chosen that have less stratospheric heating and associated impact on dynamics[18,19] or that might reverse the sign of the effect on ozone[20]. The extent to which SRM can be designed to better manage climate outcomes is as yet unknown, and thus how well it could compensate for the climate effects of increased atmospheric greenhouse gases is still uncertain. This is a promising avenue of research, and one reason why it is premature to assess climate impacts from any current simulations.

There is also significant research in geoengineering beyond the physical climate science described above. This includes evaluations of the ethics of climate intervention, social science to better understand how different publics might respond to the idea[21], and research aimed at building necessary governance.

As noted earlier, progress made to date with climate models suggests that it is at least plausible that a limited deployment (where the amount of cooling provided is no more than 1-2°C) used in addition to, rather than instead of, cutting greenhouse gas emissions would reduce many climate impacts. However, relatively limited research has been conducted to date, and significantly more research would be required to support informed decisions.

3. Research Needs for Sunlight Reflection Methods

3.1 Questions

The goal of research into geoengineering is to support future decisions regarding this technology, i.e., what role, if any, SRM might play in addressing climate change. There are three overlapping sets of questions that will need to be addressed to support an informed decision:

1. What outcomes are and are not achievable through SRM? For example, different choices (such as the latitude of aerosol injection) will lead to different impacts; understanding the trade-offs is needed to define responsible options.
2. What are the impacts of different options for deployment? How would SRM affect the broad list of concerns regarding climate change? What additional concerns are associated with the specific approach (either SAI or MCB)?
3. What is our confidence in predicting outcomes? What uncertainties are there and how do these affect impacts; what is the range of plausible outcomes? What is the justification for our confidence? What research would be needed to further reduce uncertainty?

Research can be framed around these overarching questions. It is reasonable to expect that much of the research between now and any decision regarding deployment will ultimately revolve around how to reduce or manage uncertainty, but a thorough analysis of future research needs does not yet exist.

3.2 Uncertainty

While some progress has been made over the last decade in understanding how SRM might affect the climate system, there is still significant uncertainty[22] about how SRM would affect the climate. First, as noted earlier, there is some uncertainty in small-scale processes directly related to how SRM reflects sunlight, discussed in the next paragraph. Second, there are uncertainties about how the climate system responds to a reduction in sunlight as compared with a change in greenhouse gases, and how these affect the things society might care about, from the probabilities of heat waves or drought to ecosystem health or agricultural yields (which are influenced by a combination of CO_2 concentrations, temperatures, and precipitation), to how effective SRM would be at reducing the risks of sea level rise.

For stratospheric aerosols, process uncertainties in the upper atmosphere include aerosol microphysics (if we release sulfur dioxide, how large are the resulting aerosol droplets), stratospheric chemistry (e.g., what is the impact on ozone), and the impact on cirrus clouds. Stratospheric aerosols also heat the stratosphere and affect stratospheric dynamics and water vapor concentrations; these processes are also uncertain. Validation with existing observations after volcanic eruptions is not sufficient to constrain all of the parameters, as noted earlier. Marine-cloud brightening (MCB) involves injecting sea-salt aerosols into marine boundary layer clouds in order to increase cloud reflectivity. However cloud-aerosol interactions are one of the largest areas of uncertainty in climate change science, and it is thus unclear over what fraction of the ocean MCB might be effective. In addition, while stratospheric aerosols may be relatively uniformly distributed around the world, the regions in which clouds would be brighter would be more localized, potentially creating more regional variation in the climate effects.

3.3 Near-term research needs

Reducing uncertainty to acceptable levels will ultimately require a series of additional dedicated observations and (small scale) perturbative field experiments, each designed to reduce specific uncertainties.

However, for stratospheric aerosol geoengineering, we do not yet know which uncertainties are most important to reduce; that is, how sensitive are the outcomes we care about to uncertainty in some specific physical process? State of the art climate models are now capable of simultaneously capturing aerosol microphysics, interactions with stratospheric chemistry, and coupling with stratospheric dynamics in a fully coupled model[14], but there has not yet been a careful analysis to assess either how uncertain any one of these processes might be, nor how uncertainties in any of the above processes flow down into uncertainty in the outcomes that we care about. As a result, one of the important near-term goals would be to better characterize how much uncertainty there is and how it affects outcomes, in order to better define and prioritize a longer-term and larger-scale research effort in this area. A more thorough exploration of the design space – what can geoengineering do and what can it not do – can also be conducted using existing climate models. Thus for stratospheric aerosol geoengineering, near-term research is likely to be almost exclusively model-based.

This is not necessarily the case for marine cloud brightening, where small scale controlled experiments could inform the relevant cloud-aerosol interactions[23]; indeed, conducting these process experiments would also reduce important uncertainties in climate science[24].

3.4 Longer-term research

An example of a possible future field experiment would be a stratospheric balloon experiment to verify chemical reaction rates[25,26]. This experiment cannot be conducted indoors because of the difficulty in replicating all of the important features of the stratospheric environment in a laboratory setting. A small amount of material would be released, and then instrumentation would sample the ensuing plume to measure the chemistry; the information would then be used to better constrain uncertain parameters in a climate model. The direct environmental impact of such a test would be too negligible to detect. Nonetheless, any outdoor experiment raises some legitimate concerns with the public regarding the intent of research, and thus some level of governance is appropriate.

While future experiments may be somewhat larger in scale than this balloon experiment ALL of the experiments that might ever be conducted on SRM over the coming decades will be relatively small scale in the sense that they will be designed not to have any detectable climate impact. The reason for this is that experiments will be designed to understand specific process uncertainties in models, and not to measure the climate response to geoengineering. An experiment to measure the regional climate response to geoengineering would require such substantial forcing levels[27] so that no such test would ever occur without society first having made an explicit decision to deploy. This both means that there will always be some uncertainty in the regional climate projections prior to deployment, but also that there will be a bright line between research activities and anything resembling deployment.

It is clear that no deployment should take place without adequate research. Since research will take considerably longer than it would take to develop the technical capacity for deployment, it would be inappropriate to develop any deployment capability today or soon.

3.5 Research governance

Research into geoengineering, and SRM in particular, raises important questions for society beyond typical scientific research. While model-based research does not need any unusual governance beyond normal scientific peer review, it would be appropriate to consider governance needs for any geoengineering research that involves outdoor experiments. This echoes the National Academies report[2], which recommended "the initiation of a serious deliberative process to examine: (a) what types of research governance, beyond those that already exist, may be needed for albedo modification research, and (b) the types of research that would require such governance," and that any new governance structure emanating from this deliberation should be transparent and broadly representative; similar observations have been made for high-level principles proposed for responsible geoengineering research[28].

3.6 The path forward

Given this context on research needs, it is appropriate to consider what a path forward might look like.

While I have given some observations on the type of research that is likely needed, a first step would be to conduct a more comprehensive assessment of research needs; this would benefit from involving an expert panel. In addition it would be valuable to put in place appropriate research governance in preparation for the expectation of likely future small-scale outdoor experimentation. Particularly for stratospheric aerosol geoengineering, additional model-based research would be valuable; in part this is needed because without this research it would be impossible to appropriately prioritize any larger research effort. Any research conducted in this space will need to be in coordination with existing climate science research, and will need to build on existing infrastructure for climate observations and US computing resources.

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Biography for Douglas MacMartin

Douglas MacMartin is a Senior Research Associate and Senior Lecturer in the Sibley School of Mechanical and Aerospace Engineering at Cornell University, and also a Visiting Scientist in the Department of Computing and Mathematical Sciences at the California Institute of Technology. Prior to his appointment at Cornell, he was a Research Professor at Caltech. From 1994 to 2000 he worked for United Technologies Research Center where he led the Active Control research activities. He holds a Ph.D. in Aeronautics and Astronautics from the Massachusetts Institute of Technology (1992), and a B.A.Sc. from the University of Toronto in Engineering Science (1987). He is a member of the American Geophysical Union and an Associate Fellow of the American Institute for Aeronautics and Astronautics.

While his original training is as an aerospace engineer, he has been working as a climate scientist since roughly 2002, and has been researching geoengineering since 2006. He has 61 peer-reviewed publications including 24 in geoengineering and another 10 in climate science (the rest in more traditional engineering fields), as well as 73 conference papers, 2 book chapters, and 5 patents. In 2017 he was co-chair of the first Gordon Research Conference on Climate Engineering, and he will be a chair (with Trude Storelvmo) of the second conference in 2020. He is also on the Board of Advisors for the Forum for Climate Engineering Assessment at American University, an informal international advisor for the climate engineering program at Beijing Normal University, and was a member of the Advisory Group for the second international Climate Engineering Conference (CEC17) in Berlin.

The combination of an engineering background and climate science gives him a unique perspective in the field of geoengineering, and he has published on dynamics, the use of feedback to manage uncertainty, treating geoengineering as a design problem, and uncertainty in geoengineering, among other contributions.