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TITLE OF PROPOSED PROJECT **Introducing a design element into stratospheric aerosol geoengineering**

REQUESTED AMOUNT	PROPOSED DURATION (1-60 MONTHS)	REQUESTED STARTING DATE	SHOW RELATED PRELIMINARY PROPOSAL NO. IF APPLICABLE
$ 299,529	24 months	04/01/18	

THIS PROPOSAL INCLUDES ANY OF THE ITEMS LISTED BELOW

- ☐ BEGINNING INVESTIGATOR
- ☐ DISCLOSURE OF LOBBYING ACTIVITIES
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- ☒ COLLABORATIVE STATUS **Not a collaborative proposal**

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CERTIFICATION PAGE - CONTINUED

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AUTHORIZED ORGANIZATIONAL REPRESENTATIVE	SIGNATURE	DATE
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PROJECT SUMMARY

Overview:

The National Academies of Science recommended in 2015 that more research be undertaken to understand solar geoengineering; approaches such as stratospheric aerosol injection that would cool the climate by reflecting some sunlight back to space. Reducing CO2 emissions is essential to manage the long-term risks of climate change, but mitigation alone may not be sufficient. Given this context, it is both necessary and urgent to assess the projected climate impacts of geoengineering. These impacts, however, will depend on choices, such as the latitude and season in which to inject aerosols. Thus rather than asking "What will geoengineering do", one should instead ask "Given a set of objectives, how can one design an intervention to best meet those goals, and how well can they be met?" It is only in the context of a well-designed approach that the impacts of geoengineering can be fully assessed. The key step in this reframing is to explore the design space to understand how much control one could have over outcomes; this is only now possible with the availability of the latest climate models.

The starting point for this research is a recent ground-breaking study conducted in collaboration between the PI and researchers at NCAR and PNNL. Using a state-of-the-art chemistry-climate model, the team demonstrated that injecting stratospheric sulfate aerosols at different latitudes results in different climate responses, evaluated what could be achieved with combined injections at multiple latitudes, and then wrapped a feedback loop around the climate model to simultaneously manage three degrees of freedom of the climate response. This research explored one of the key design variables: the latitude of aerosol injection. However, there is strong reason to presume that the season of injection is an equally important design variable. The stratospheric Brewer-Dobson Circulation is seasonally-dependent, so material injected at one latitude might be transported northwards in part of the year and southwards the rest of the year. Furthermore, varying injection seasonally might enable better ability to influence regional precipitation patterns; a critical concern in evaluating the impacts of geoengineering. Finally, stratospheric aerosols provide no benefit in the polar winter, and injecting aerosols only when they are useful can minimize both the required mass and other effects of aerosols such as stratospheric heating.

This proposal builds on the initial proof-of-concept to more comprehensively address how one can design a geoengineering intervention to meet desired goals, and hence assess what can and cannot be achieved, including exploring the design space, designing injection strategies to meet different goals, and validating predictions through a simulation of the best strategy. Uncertainties and nonlinearities will require feedback to adjust the strategy in response to observations, though it is currently unclear whether existing feedback approaches will suffice; this research will identify these feedback design needs.

Intellectual Merit:

Solar geoengineering is no longer purely a scientific endeavor, but also an engineering one. Introducing a design element into solar geoengineering research provides a critical shift in perspective that will fundamentally alter the conversation surrounding geoengineering, and inspire further research. Only recently have models been able to simultaneously capture the full coupling between aerosol microphysics, chemistry, and stratospheric dynamics. By taking advantage of this state-of-the-art capability, this research will enable a better assessment of what can and cannot be achieved through an intentionally designed stratospheric aerosol injection strategy. This proposal is appropriate for EAGER funding as it takes a novel interdisciplinary perspective, and is exploratory but with the potential for high payoff, including opening up new avenues for future research.

Broader Impacts:

It is plausible that temporary and limited geoengineering deployment could be used to reduce climate risks, but making such an assessment requires understanding projected impacts. This proposal aims to take a major step forwards towards that objective by developing a well-designed strategy based on an exploration of the design space. This is essential to ensure that future decisions regarding these approaches are well-informed. Furthermore, the multidisciplinary perspective gained by applying engineering optimization, dynamic systems, and feedback design to climate science provides an opportunity to broaden both communities with the potential to spark additional insights and research.

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Appendix Items:

*Proposers may select any numbering mechanism for the proposal. The entire proposal however, must be paginated. Complete both columns only if the proposal is numbered consecutively.

1 Project Description

1.1 Motivation and Background

The Paris climate accord reaffirmed the goal of limiting global mean temperature rise to well below 2°C above preindustrial, while stressing the importance of a more aggressive 1.5°C target (UNFCCC, 2015). However, even a 2°C target cannot easily be achieved with mitigation alone (Fuss et al., 2014; Fawcett et al., 2015; Rogelj et al., 2016), nor has the requisite "negative emissions" technology been demonstrated at sufficient scale (National Academy of Sciences, 2015). This has prompted questions about the potential role of solar geoengineering in policies addressing climate change (e.g., MacMartin et al., 2017b). By analogy with large volcanic eruptions, stratospheric aerosol injection (SAI; e.g., Crutzen, 2006) would clearly "work" in the sense that it would cool the planet by reflecting some sunlight back to space. However, there are many reasons for concern, ranging from uncertainty in the climate response, to regional disparities in climate outcomes, to concern over the effect on mitigation decisions, and ethical and governance concerns (e.g., Robock, 2008; Gardiner, 2016). However, provided that geoengineering is considered only *in addition* to mitigation, rather than instead of mitigation (Wigley, 2006; Long and Shepherd, 2014; Tilmes et al., 2016), modeling results to date (e.g., Kravitz et al., 2014b; Keith and Irvine, 2016; MacMartin et al., 2017b) suggest that it is plausible that some amount of solar geoengineering might lead to less climate damage than no geoengineering.

One of the key questions is what the climate impacts would be; how well could SAI compensate for the climate changes due to increased atmospheric CO_2 and other greenhouse gas concentrations? While the impacts of CO_2 can be studied as a "science" question – specifying the concentrations and then evaluating the impacts – understanding geoengineering is a different type of problem because the response depends on choices regarding how it is implemented. Instead of asking what geoengineering would do, we need to instead ask how well we can design geoengineering to do what we want it to do.

This idea was first explored using idealized patterns of solar reduction (Ban-Weiss and Caldeira, 2010; MacMartin et al., 2013; Kravitz et al., 2016). However, the extent to which one can manage the climate response through SAI design choices is fundamentally determined by the stratospheric transport that relate these choices – principally aerosol injection location and season – to the resulting spatio-temporal distribution of aerosol optical depth (AOD) and in turn the radiative forcing. Climate models such as CESM1(WACCM) (Mills et al., 2016, 2017) are now capable of simulating the relevant physical processes involved, including aerosol microphysics, interactive stratospheric dynamics (at sufficient spatial resolution to capture modes of variability), and interactive ozone chemistry. Using this model, the PI in collaboration with NCAR and PNNL recently demonstrated that by injecting at different latitudes (Tilmes et al., 2017), three different degrees of freedom can be achieved (MacMartin et al., 2017a), and that these could be used to independently manage three degrees of freedom of the climate response in order to improve how well SAI can compensate for the climate changes due to increased CO_2 (Kravitz et al., 2017). Figure 1 illustrates the importance of using the available degrees of freedom, comparing the response with multiple injection locations to a case where only equatorial aerosol injection is used.

The most fundamental question in undertaking a design perspective on SAI is to understand the design space: how many independent degrees of freedom do we have? While the initial work explored the impact of choosing the latitude of injection, the season of injection is almost certainly an equally-important design variable. First, the stratospheric Brewer-Dobson circulation varies seasonally (see Figure 2), so that even with constant injection at a fixed latitude, the spatial pattern of AOD varies with season, as shown in Figure 2. Conversely, a desired AOD pattern will require different injection latitudes at different times of year. Second, the desired AOD to best match the forcing from climate change also varies with time of year; varying the forcing throughout the year can provide some ability to separately influence regional temperature and regional precipitation changes. And finally, there is no value in having aerosols at high latitudes in the polar winter. Modulating the injection rate over the year may lead to less total injection required, which in turn will lead to less impact on stratospheric chemistry and dynamics.

The primary purpose of this proposed research is thus to conduct an initial exploration into the impact of the season of injection in order to determine how important this design choice is, whether it indeed leads to additional design degrees of freedom, and how much of an improvement may be possible in compensating for the pattern of climate change due to increased CO_2.

Taking an engineering design perspective on geoengineering requires not just understanding the design space and optimizing for different goals, but also requires a strategy for managing inevitable uncertainty. This is needed to assess what might realistically be achieved in the presence of uncertainty and nonlinearities, by validating optimized injection strategies in simulation. By monitoring observations, the injection strategy can be adjusted in response, avoiding the need to accurately know the climate response. This was first demonstrated for geoengineering by adjusting a solar reduction to manage either one (MacMartin et al., 2014b) or three degrees of freedom (Kravitz et al., 2016), and used by Kravitz et al. (2017) to adjust aerosol injection rates each year in response to the climate model output from the previous year. Relatively simple feedback algorithms have been used to date to manage up to three degrees of freedom. These rely on decoupling the problem, but it may be less straightforward to do so when seasonal injection strategies are also used. Thus while feedback will still be necessary to manage uncertainty and nonlinearity, it may be necessary to develop more advanced feedback algorithms. A better understanding of the algorithmic requirements can only be obtained after initial research into the response patterns has been conducted.

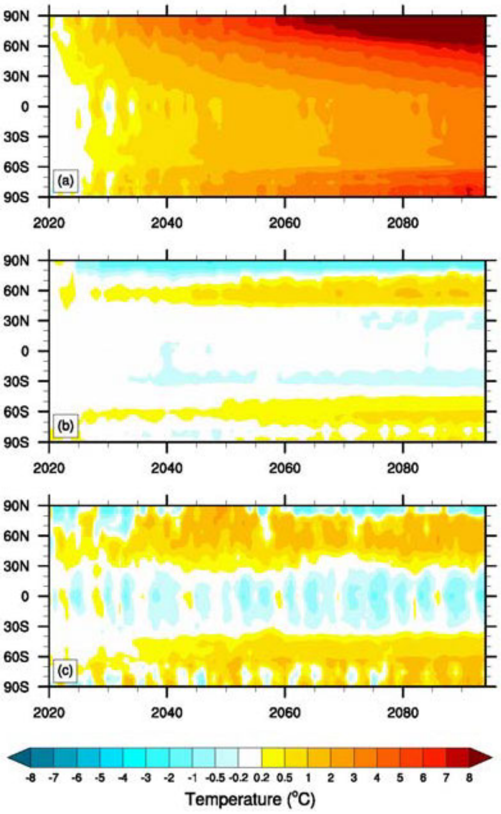

Figure 1: Zonal mean temperature anomaly relative to 2020 for (a) RCP8.5, (b) with SAI using multiple injection latitudes to manage multiple degrees of freedom (see Kravitz et al., 2017, for full description) and (c) with SAI but only using equatorial injection to maintain global mean temperature (unpublished).

1.2 Objectives

This research can be broken down into three questions:

1. What different climate effects can be achieved by choosing different injection strategies? This research will explore the design space for stratospheric aerosol geoengineering, focusing on the previously unexplored design space associated with the season of injection.

2. What is the optimal SO_2 injection strategy for different climate goals? If the strategy is opti-

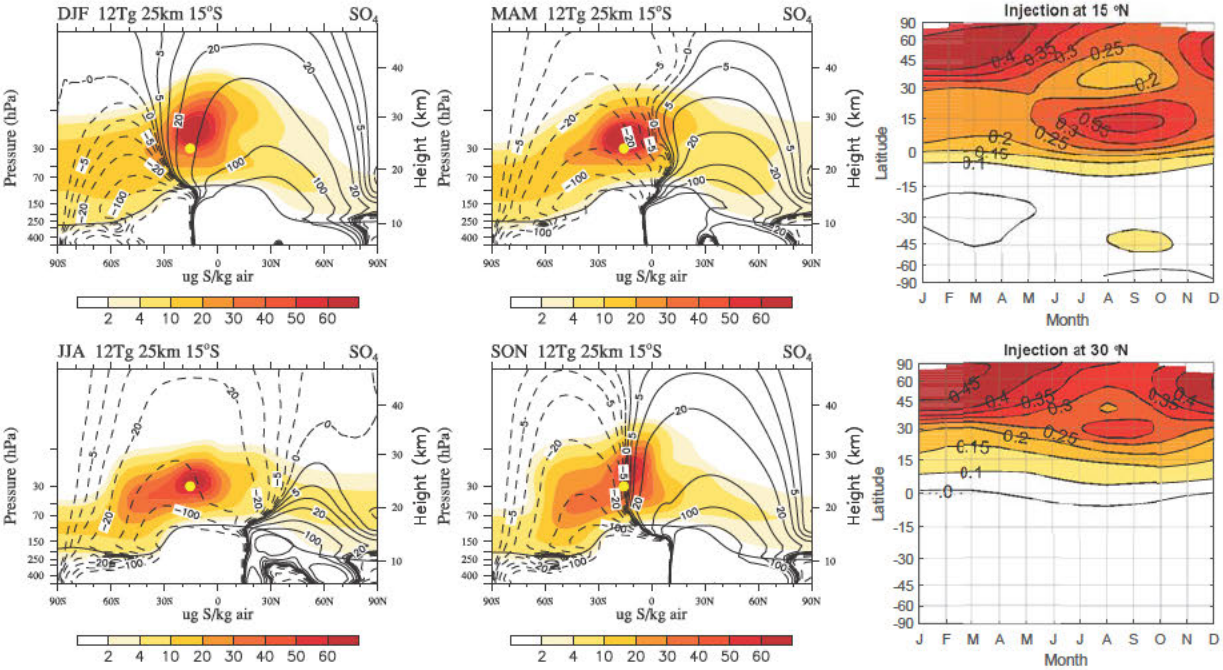

Figure 2: Left set of panels: Seasonal dependence of stratospheric Brewer-Dobson circulation (contours indicate streamlines; solid northwards and dashed southwards), and total sulfur concentration (shading) in four different seasons due to continuous injection at 15°S, from Tilmes et al. (2017). Right: resulting aerosol optical density (AOD) as a function of latitude and season for continuous injection of 12 Tg SO_2/yr at 15° and 30°N.

mized for one set of goals, what is the expected impact on other variables? This research will validate different strategies projected to optimize different goals in a final model simulation, using feedback to maintain desired goals.

3. What complexity of feedback algorithms is necessary to robustly achieve climate goals in the presence of inevitable uncertainty? This research will determine whether a decoupling approach can be developed (as in MacMartin et al., 2017a) that can manage more degrees of freedom or whether a coupled model-predictive framework is required.

1.3 Technical Approach

1.3.1 Climate Model: CESM1(WACCM)

Assessing the ability to design SAI to meet specified climate goals requires a sufficiently accurate assessment of what spatial patterns of radiative forcing result from different choices of injection strategy (different latitudes and seasons of injection). The radiative forcing and its spatial pattern depend on a variety of inter-related factors, including aerosol size distribution, spatial distribution, ozone concentrations, and water vapor concentrations, and these result from a complicated interplay between aerosol microphysics, stratospheric dynamics, and stratospheric chemistry. Different models conducting initial GeoMIP simulations, for example, each included only a subset of these (see Table 2 in Pitari et al., 2014). Obtaining a better estimate of how the spatial pattern of forcing changes as the injection strategy changes requires a climate model that includes all of these features simultaneously.

The primary tool that will be used in this study is the Community Earth System Model (CESM), version 1, with the Whole Atmosphere Community Climate Model (WACCM) as its atmospheric component. Simulations will be conducted on NCAR's petaflop high-performance cluster Cheyenne. CESM1(WACCM) is a fully coupled, community, global climate model that includes atmospheric, ocean, land, sea ice, and land ice components, with a horizontal resolution of 0.95° in latitude by 1.25° in longitude. The vertical domain is extended relative to CESM, with 70 levels up to 145 km; this is required to represent atmospheric dynamics and chemistry throughout the entire stratosphere. The model also simulates the microphysical evolution of stratospheric aerosols resulting from SO_2 injection, including particle growth, coagulation, and sedimentation, and matches observed stratospheric aerosol optical depth (AOD) for volcanic eruptions both during the peak after the 1991 Pinatubo eruption, and during the recent period of moderate volcanic activity since 2005 (Mills et al., 2016, 2017).

Stratospheric aerosols impact ozone (e.g., Tilmes et al., 2012; Solomon et al., 2016), which in addition to the impact on surface ultraviolet light, can have radiative effects that can influence stratospheric dynamics and potentially change surface climate. This latter effect is expected to be small, and initial simulations will be conducted with specified chemistry to reduce computational burden, while a final validation simulation will be conducted with interactive chemistry.

1.3.2 Simulations and Response Analysis

Figure 2 shows the aerosol spatial distribution at different times of year using a constant injection rate, illustrating the importance of the season of injection for influencing the resulting spatial pattern of aerosols. For example, it appears likely that winter injection at either 15° or 30°N will lead to aerosols transported quickly poleward, where they will have minimal climatic impact; achieving high aerosol concentrations at high latitudes in Northern hemisphere summer likely requires either injection at 15°N in spring (when aerosols are still transported northward) or at 30°N in the summer. Because the lifetime of aerosols in the stratosphere is longer than the seasonal timescale associated with changes in the circulation patterns, these constant-injection cases are neither sufficient to determine the relationship between injection at different times of year and the resulting spatio-temporal pattern of AOD, nor the relationship between that and the resulting climate response.

To assess the impact of seasonality, a total of 20 cases can be considered, corresponding to each season of injection at each of 5 latitudes: 30°S, 15°S, equatorial, 15°N, and 30°N; these were the locations considered in the seasonally-constant injection simulations in Tilmes et al. (2017). Not all 20 cases need to be simulated, as some will clearly not lead to useful outcomes (e.g., winter injection at 30°N). Additional computational savings can be obtained by considering some non-interacting cases simultaneously (e.g., injection at 30°N and 30°S), leading to an estimated 12 cases. These simulations will use raised-cosines centered on each season (as in MacMartin et al., 2013) to avoid sudden changes in injection rate that could have additional impacts on climate response. The exploratory work with CESM1(WACCM) indicates that with 6 Tg SO_2 per year injected, the signal-to-noise ratio is high enough, and the temporal pattern establishes quickly enough, that 5-year simulations are sufficient to estimate the stratospheric AOD response to any injection scenario (MacMartin et al., 2017a). Ten-year simulations are sufficient to give an estimate of the temperature response, though 15–20 years will be needed to estimate the precipitation response. To make the best use of finite computation time, the spatio-temporal AOD patterns from 5-year simulations will be evaluated, and only a subset of these simulations that lead to notably distinct AOD patterns will be extended to improve estimates of the climate response. Estimates of computational resources required are shown in Table 1.

For each simulation, analysis will include aerosol spatial distribution and size distribution, changes to stratospheric heating and winds, and changes to surface air temperature and precipitation patterns. One of the first questions will be linearity; whether the annually-constant injection results can be predicted from the sum of seasonally-constant injection rates. Note that linearity might not be satisfied if, for example, ceasing injection over the winter leads to decreased coagulation/condensation onto existing aerosols when injection resumes in the spring; this could be an additional benefit of seasonally-modulated injection strategies.

1.4 Optimization and Feedback

It is clearly not the job of scientists to define what the "right" set of goals for geoengineering might be, but rather to inform: e.g., to be able to tell policy makers that for some particular choice of goals, what the best strategy is to meet those, how well they can be met, and what the implications are for other relevant variables. This process will be illustrated for several plausible goals, such as (i) minimizing the zonally-averaged and seasonally-averaged temperature residuals when compensating for CO_2-induced climate change, while (ii) maintaining Arctic sea ice and/or (iii) minimizing changes in tropical precipitation.

The first challenge is the previous step of estimating the climate responses (or influence functions) corresponding to different injection choices. Given these, it is in principle straightforward to optimize for different metrics, while including the constraint that injection at any location or time of year is non-negative. Previous research (e.g., MacMartin et al., 2013; MacMartin and Kravitz, 2016; MacMartin et al., 2017a) suggest that linearity is a reasonable starting point for assessing the climate response; an initial assessment is therefore a relatively straightforward task given the climate responses. The concept is similar to the optimization of spatio-temporal patterns of solar reduction by MacMartin et al. (2013), or the optimization of the amount of mass injected at each of four latitudes to best match different spatial patterns of stratospheric aerosol optical depth, as in MacMartin et al. (2017a).

A second challenge arises because the influence functions are only estimates of how the climate model responds to forcing. These estimates are uncertain due to climate variability present in the simulations, uncertain at time-scales longer than the simulation length used in estimating them, and subject to nonlinearities. Furthermore, even if these problems were all resolved, any climate model will never match reality. This implies that any attempt to include design principles in an exploration of what geoengineering could do must also include some approach for managing uncertainty. Not only is this a capability required for any ultimate deployment, but it is necessary to assess a geoengineering strategy in a model and evaluate what can and cannot be expected to be achieved in the presence of uncertainty, nonlinearity, and climate variability.

Previous work with the PI and collaborators used a proportional-integral feedback algorithm (MacMartin et al., 2014b; Kravitz et al., 2014a, 2016, 2017), potentially improved with a feedforward or "best-estimate" (MacMartin et al., 2014a). The feedforward defines the initial estimate $\hat{S}$ of the inputs required in year $k+1$ to meet the objectives, in the absence of new information (where the input here will be SO_2 injection rate). This amount is then adjusted in response to the simulated climate response T_k from the previous year using the feedback algorithm:

$$S_{k+1} = \hat{S}_{k+1} - K_P(T_k - T_{\text{goal}}) - K_I \sum_{j=0}^{k} (T_j - T_{\text{goal}})$$

where K_P scales the correction *proportional* to the error and K_I proportional to the *integral* of the error over time. Despite uncertainty, this algorithm converges to the desired goals over time. This process has been extended to multiple degrees of freedom by decoupling the problem into separate single-input, single-output problems (Kravitz et al., 2016; MacMartin et al., 2017a); for example using the difference in injection between hemispheres to control the interhemispheric temperature gradient and the total injection rate to control the global mean temperature.

These prior results demonstrate that including feedback is essential in assessing whether geoengineering can or cannot meet specific climate goals – without feedback the goals will almost certainly not be met. More specifically, "what can geoengineering do, and what can it not do" cannot be fully answered without research to understand what degree of uncertainty and nonlinearity can be compensated for with feedback. The simple algorithm described above may not be sufficient for managing more complex multivariate goals, and thus one of the goals of this project is to identify future research needs in this area.

1.5 Statement of Work

Consistent with the objectives described earlier, this reesearch can be broken into three tasks:

1. *What different climate effects can be achieved by choosing different injection strategies?* Using CESM1(WACCM), vary the season of SO_2 injection for five different injection latitudes; 30°S, 15°S, equatorial, 15°N and 30°N. For each case evaluate the climate response to assess how many independent patterns of climate response can be obtained. Assess linearity by comparing the response to continuous injection to the sum of the responses to injection occurring only over a single season.

2. *What is the optimal SO_2 injection strategy for different climate goals? If the strategy is optimized for one set of goals, what is the expected impact on other variables?* By combining different amounts of injection in different seasons and at different latitudes, optimize the combination for achieving different climate objectives. Goals to be considered include different combinations of (i) compensating zonal-mean temperature, (ii) minimizing changes in precipitation patterns, and (iii) maintaining summer Arctic sea ice extent. Identify combinations of input degrees of freedom used in meeting climate objectives. Validate projected strategies in a longer (20+ year) model simulation using feedback to maintain goals.

3. *What complexity of feedback algorithms is necessary to robustly achieve climate goals in the presence of inevitable uncertainty?* Assess whether a decoupling approach can be developed (as in MacMartin et al., 2017a) that can manage more degrees of freedom or whether ultimately a coupled model-predictive framework will be required.

4. Communicate and disseminate research results through presentations at conferences, publication in archival journal articles, and presentations in geoengineering policy meetings.

The proposed research will require computing resources on the NCAR supercomputer Cheyenne, and will be conducted primarily by a graduate student in engineering at Cornell, with initial short-term assistance from a postdoctoral associate with a climate science background.

Simulation	years	number	total
Multiple seasons & latitudes of injection	5	12	60
Extended climate response simulations	15	6	90
Final validation using feedback	20	2	40
Total	190 years		

Table 1: Simulations required; all except the final assessment will be conducted with specified chemistry to reduce the computational burden signficantly relative to CESM1(WACCM). Specific cases will be repeated with interactive chemistry if computational allocations permit. Requirements are consistent with a large academic allocation on Cheyenne.

1.6 Suitability for EAGER funding

The proposed research is well-aligned with the objectives of the EAGER program for four reasons:

- Potentially game-changing through the introduction of novel disciplinary perspectives. The challenge of understanding geoengineering is fundamentally different from that of understanding the response to climate change, because at its core it involves an engineering design element. Nonetheless, research to date has typically simulated ad hoc strategies rather than designed strategies. Introducing an engineering perspective into geoengineering can fundamentally reshape research in this field.

- High pay-off. Future decisions about this technology will be strongly influenced by the expected climate impacts. There is a risk of poorly informed decisions if research does not distinguish impacts that are an inevitable consequence of any deployment strategy or simply a consequence of a particular strategy. Understanding the extent to which well-designed geoengineering can or cannot compensate for climate change impacts due to increased atmospheric greenhouse gases is essential; this requires introducing this design perspective.

- Fundamentally exploratory. While there is good reason to presume that modulating the injection rate for SAI seasonally would increase the number of degrees of freedom available, and increase the space of possible outcomes, no simulations have yet been undertaken to explore this potential. This makes some of the final steps of the proposed research less well-defined than would be appropriate for a regular proposal.

- Opens up new space for future research. If successful, this program will lead to further research to optimize injection strategies for SAI, and in turn assess climate impacts due to well-designed SAI. In addition, while it is clear that feedback will be required to manage uncertainty and nonlinearity, it is unclear what the algorithmic requirements will be without first understanding the available degrees of freedom and the coupling between them. Future research will be required to further develop control algorithms, but that research cannot yet be defined until the research proposed herein is conducted.

2 Broader Impacts

The international community has agreed to avoid “dangerous” climate intervention, with a goal of keeping global-mean temperature increases well-below 2°C, and ideally below 1.5°C. While solar geoengineering should never be considered as a substitute for mitigation, mitigation alone is unlikely to succeed in limiting temperature rise even to 2°C. A limited solar geoengineering deployment might reduce many climate risks, though clearly more research is needed. One critical concern, for example, is regional disparities in outcomes. However, climate model simulations to date have primarily just evaluated how the climate responds to some specific aerosol injection strategy, rather than asking whether it is possible to intentionally design an intervention strategy that would achieve desired outcomes, and minimize undesired effects. Introducing this “engineering” or design component into geoengineering research is essential to provide the broader climate-policy community with the information they need to support future decision-making regarding geoengineering – in particular, addressing the question of what is our best understanding of how well geoengineering could compensate for climate change due to increased greenhouse gases. Climate model output will be made available to the broader community to engage other researchers in evaluating different climate impacts from these geoengineering strategies.

In addition to supporting a graduate student that will conduct the bulk of the research, this project will also provide an opportunity for undergraduate research involvement. Undergraduate engineering students at Cornell can fulfill design requirements for their degree through additional for-credit design-related activity connected with coursework; one undergraduate student is currently working with the PI to re-design feedback control parameters in previous geoengineering simulations. The project PI teaches the undergraduate/graduate feedback design class, providing an opportunity for involving undergraduates. Specifically, potential seniors design projects associated with this research include (i) optimization of climate impacts, given simulated climate response functions, (ii) constructing low-order dynamic models from system identification simulations, (iii) design of feedback algorithms based on dynamic models.

Finally, this research integrates an engineering perspective into climate science research. One of the outputs, therefore, is not simply the research knowledge itself, but the ideas and engineering tools, that have the potential to impact not only how the scientific community thinks about geoengineering, but could potentially impact climate science more broadly. Training a truly interdisciplinary graduate student, integrated into a network of expert collaborators, is thus a valuable output of this work in itself.

3 Results from prior NSF support:

No prior NSF support in preceding five years.

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COVER SHEET FOR PROPOSAL TO THE NATIONAL SCIENCE FOUNDATION

PROGRAM ANNOUNCEMENT/SOLICITATION NO./DUE DATE: **PD 20-7643**

☐ Special Exception to Deadline Date Policy

FOR NSF USE ONLY

NSF PROPOSAL NUMBER: **2038246**

FOR CONSIDERATION BY NSF ORGANIZATION UNIT(S) (Indicate the most specific unit known, i.e. program, division, etc.)

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☐ IF THIS IS A PRELIMINARY PROPOSAL THEN CHECK HERE

TITLE OF PROPOSED PROJECT: **What are the fundamental limits / trade-offs of stratospheric aerosol geoengineering?**

REQUESTED AMOUNT	PROPOSED DURATION (1-60 MONTHS)	REQUESTED STARTING DATE	SHOW RELATED PRELIMINARY PROPOSAL NO. IF APPLICABLE
$ 398,143	36 months	01/01/21	

THIS PROPOSAL INCLUDES ANY OF THE ITEMS LISTED BELOW
☐ BEGINNING INVESTIGATOR
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☐ HUMAN SUBJECTS Human Subjects Assurance Number ______
Exemption Subsection ______ or IRB App. Date ______
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☒ INTERNATIONAL ACTIVITIES: COUNTRY/COUNTRIES INVOLVED
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☒ COLLABORATIVE STATUS
Not a collaborative proposal

PI/PD DEPARTMENT: **Mechanical and Aerospace Engineering**

PI/PD FAX NUMBER: **626-395-6170**

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CERTIFICATION PAGE

Certification for Authorized Organizational Representative (or Equivalent)

By electronically signing and submitting this proposal, the Authorized Organizational Representative (AOR) is: (1) certifying that statements made herein are true and complete to the best of his/her knowledge; and (2) agreeing to accept the obligation to comply with NSF award terms and conditions if an award is made as a result of this application. Further, the applicant is hereby providing certifications regarding conflict of interest (when applicable), flood hazard insurance (when applicable), responsible conduct of research and organizational support as set forth in the NSF Proposal & Award Policies & Procedures Guide (PAPPG). Willful provision of false information in this application and its supporting documents or in reports required under an ensuing award is a criminal offense (U.S. Code, Title 18, Section 1001).

Certification Regarding Conflict of Interest

The AOR is required to complete certifications stating that the organization has implemented and is enforcing a written policy on conflicts of interest (COI), consistent with the provisions of PAPPG Chapter IX.A.; that, to the best of his/her knowledge, all financial disclosures required by the conflict of interest policy were made; and that conflicts of interest, if any, were, or prior to the organization's expenditure of any funds under the award, will be, satisfactorily managed, reduced or eliminated in accordance with the organization's conflict of interest policy. Conflicts that cannot be satisfactorily managed, reduced or eliminated and research that proceeds without the imposition of conditions or restrictions when a conflict of interest exists, must be disclosed to NSF via use of the Notifications and Requests Module in FastLane.

Certification Regarding Flood Hazard Insurance

Two sections of the National Flood Insurance Act of 1968 (42 USC §4012a and §4106) bar Federal agencies from giving financial assistance for acquisition or construction purposes in any area identified by the Federal Emergency Management Agency (FEMA) as having special flood hazards unless the:

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(2) for other NSF grants when more than $25,000 has been budgeted in the proposal for repair, alteration or improvement (construction) of a building or facility.

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(This certification is not applicable to proposals for conferences, symposia, and workshops.)

By electronically signing the Certification Pages, the Authorized Organizational Representative is certifying that, in accordance with the NSF Proposal & Award Policies & Procedures Guide, Chapter IX.B. , the institution has a plan in place to provide appropriate training and oversight in the responsible and ethical conduct of research to undergraduates, graduate students and postdoctoral researchers who will be supported by NSF to conduct research. The AOR shall require that the language of this certification be included in any award documents for all subawards at all tiers.

Certification Regarding Organizational Support

By electronically signing the Certification Pages, the Authorized Organizational Representative (or equivalent) is certifying that there is organizational support for the proposal as required by Section 526 of the America COMPETES Reauthorization Act of 2010. This support extends to the portion of the proposal developed to satisfy the Broader Impacts Review Criterion as well as the Intellectual Merit Review Criterion, and any additional review criteria specified in the solicitation. Organizational support will be made available, as described in the proposal, in order to address the broader impacts and intellectual merit activities to be undertaken.

Certification Regarding Dual Use Research of Concern

By electronically signing the certification pages, the Authorized Organizational Representative is certifying that the organization will be or is in compliance with all aspects of the United States Government Policy for Institutional Oversight of Life Sciences Dual Use Research of Concern.

AUTHORIZED ORGANIZATIONAL REPRESENTATIVE	SIGNATURE	DATE
NAME **Tammy J Custer**	**Electronic Signature**	**Jun 18 2020 9:31AM**

TELEPHONE NUMBER	EMAIL ADDRESS	FAX NUMBER
607-255-5066	**tjb3@cornell.edu**	**607-255-5058**

PROJECT SUMMARY

Overview:

Reducing net emissions of CO2 and other greenhouse gas (GHG) is an essential part of any response to climate change, but is unlikely to occur fast enough to avoid significant climate impacts, leaving open the possibility of significant future climate impacts. Model projections of stratospheric aerosol geoengineering suggest that it could reduce some climate impacts, and thus could potentially become an additional element of a comprehensive climate change strategy. However, current knowledge is insufficient to support informed decisions. A key issue is that geoengineering would not affect the climate the same way as increased atmospheric GHG, leading to residual differences. However, these differences depend strongly on how geoengineering is deployed, making analysis of geoengineering fundamentally different in character from analysis of GHG-driven climate change as it necessitates an engineering-design perspective. A critical question in evaluating geoengineering is thus, what are the fundamental limits or trade-offs in how well geoengineering can manage the climate response from increased GHG? That is, what can geoengineering do, and what can it not do? Building on recent research, we propose to address this essential question. Specifically, we will generate a set of climate model simulations that each make different choices for which climate goals to prioritize relative to others, and use this to identify potential tradeoffs (sets of objectives that are mutually exclusive) and boundaries (which objectives are achievable and which are not). Throughout this process, we will engage policy and governance experts, regarding the potential range of climate goals that might motivate different actors, and on the governance implications of identified trade-offs.

Intellectual Merit:

The full range of possible strategies has never been explored, in part because optimization over the space of available degrees of freedom – primarily latitudes and seasons of aerosol injection – is complicated by uncertainty and nonlinear interactions (from both microphysics and aerosol-heating-induced changes in stratospheric circulation), and compounded by combinatorial computational complexity. To address these challenges, we combine three innovations. First, the key enabler to this research is an initial assessment on the "size" of the design space; how many usefully-independent degrees of freedom are there? This reduces the combinatorial problem. Second, the computational burden can be reduced by separating the simulations needed to understand the spatial- and seasonal- distribution of stratospheric aerosol optical depth (AOD), which can be short but require a complete stratosphere model, from those needed to assess the climate response to a specified aerosol distribution, which require multi-decadal simulations but not an accurate stratosphere. And third, nonlinearities and uncertainty can be managed through feedback that adjusts injection rates; this enables comparing simulations based on specified objectives rather than specified injection rates. We will design a suite of simulations that individually meet different objectives and collectively span the space of possible outcomes. From this, the key tool in evaluating and visualizing trade-offs is through Pareto-optimal surfaces: how do strategies and their responses change as a function of the optimization criteria. By combining these novel contributions, we can begin down a path toward a "holy grail" of geoengineering research: assessing what geoengineering can and cannot do.

Broader Impacts:

The fundamental motivation for this research is to understand a potential option to reduce future climate impacts. Better information is needed both to support future decisions around deployment, and support the development of governance capacity that will be needed to make these decisions. This research will enable a more complete view of the impacts of deploying geoengineering than has previously been possible, by generating simulations that capture a more comprehensive set of deployment options rather than just one or two; and furthermore will assess the extent to which different objectives can or cannot be simultaneously met. Although our simulations are focused on understanding physical science tradeoffs, the social and governance dimensions play a critical role in understanding which objectives may be most important to achieve or which strategies are simply politically infeasible, thus limiting the space in ways not revealed by climate modeling. We will interface with governance experts throughout to ensure research informs policy. Simulations will also be made available to the wider international community, including developing world researchers funded through DECIMALS. Finally, integrating an engineering design perspective into climate science can broaden both communities and spark new insights.

TABLE OF CONTENTS

For font size and page formatting specifications, see PAPPG section II.B.2.

Appendix Items:

*Proposers may select any numbering mechanism for the proposal. The entire proposal however, must be paginated. Complete both columns only if the proposal is numbered consecutively.

What are the fundamental limits / trade-offs of stratospheric aerosol geoengineering?

1 Introduction and motivation

Reducing CO_2 and other greenhouse gas (GHG) emissions is an essential part of any response to climate change, but it is unlikely that this will occur fast enough to avoid significant climate impacts [41, 49]. Negative emissions technologies may be able to reduce long-term warming [13, 35], but there is no guarantee that these largely untested ideas can be developed and scaled up quickly enough [10, 9], leaving open the possibility of significant future climate impacts. Model projections of stratospheric aerosol geoengineering suggest that it could reduce some climate impacts [34, 14], and thus future decision-makers might consider this as an additional element of a comprehensive climate change strategy [30]. However, current knowledge is insufficient to support informed decisions about whether to deploy geoengineering (hereafter, geoengineering is used interchangeably with stratospheric sulfate aerosol geoengineering) and, if so, what it can be relied upon to do [27].

Geoengineering would not affect the climate the same way as increased atmospheric GHGs affect the climate, leading to residual differences. However, these differences depend strongly on how geoengineering is deployed [19, 50], meaning that the climate effects of geoengineering have an important engineering-design component [23, 26]. This makes analysis of geoengineering fundamentally different in character from analysis of GHG-driven climate change. Given this potential for making deliberate choices based on desired outcomes, one of the critical questions in evaluating geoengineering is thus: what are the fundamental limits or trade-offs in how well geoengineering can manage the climate response from increased GHG? That is, ***what can geoengineering do, and what can it not do***? Building on recent research, we propose here to provide an answer to this long-standing essential question, focusing exclusively on stratospheric aerosol geoengineering.

This design perspective is important for interpreting past conclusions and making new ones. For example, from energetic arguments, it is not possible to simultaneously maintain global mean temperature and global mean precipitation [2, 17, 43, 16]. However, other early simulations suggested geoengineering would overcool the tropics and undercool the poles, which we now know is due to how geoengineering was simulated in those studies [19]. Similarly, several past studies have shown that geoengineering reduced monsoonal rain in India, but it appears that this depends on the season of stratospheric aerosol injection [50]. These last two examples involve introducing additional *degrees of freedom.* Rather than just injecting SO_2 into the stratosphere at the equator, as in many early simulations, one can inject at different latitudes [47, 6], and combine injection at different latitudes to simultaneously achieve multiple climate goals [29, 22]. Rather than injecting the same amount every day of the year, adjusting the injection rate seasonally can also alter climate outcomes [51, 50]. However, we don't yet fully understand the limits of these sorts of activities: how big is the space of achievable climates? A crucial barrier to answering these questions is that just because one can choose different latitudes and seasons, those different choices may not yield usefully different outcomes. We have started down the path of addressing that question (Section 2.2 below); this is a fundamental enabler to addressing what can and cannot be achieved.

The space of available degrees of freedom can be described by the latitudes and seasons of aerosol injection, or equivalently the resulting spatiotemporal patterns of stratospheric aerosol optical depth (AOD). Our ultimate vision is to learn how to achieve particular climate objectives by adjusting these degrees of freedom. Understanding this design space is complicated by uncertainty and by nonlinear interactions arising from both microphysics (e.g., [37, 8, 36]) and aerosol-heating induced changes in stratospheric circulation [1, 42]. Moreover, simulating every combination of these degrees of freedom in expensive, state-of-the-art models is computationally infeasible. To address this challenge, our proposal combines three innovations/observations:

1. The computational burden can be greatly reduced by observing that the problem can be separated into two pieces: which injection strategies lead to which spatial- and seasonal- distributions of stratospheric AOD, and which AOD distributions lead to which climate effects? The first part can be done with short simulations but requires a complete stratosphere model, whereas the second requires multi-decadal simulations but not as accurate a stratosphere.
2. Not all combinations of degrees of freedom are independent – some combinations may achieve the same climate impacts as others (see Section 2.2).
3. Nonlinearities and uncertainty can be managed through feedback that adjusts injection rates (associated with the degrees of freedom) to achieve some set of desired outcomes [28, 23] (see Section 2.4).

Ultimately there are more climate variables that “matter” than there are degrees of freedom that can be adjusted, and there will inevitably be trade-offs - not all objectives can be simultaneously met by any given strategy. An important tool in evaluating and visualizing trade-offs is Pareto-optimal surfaces, which describes how strategies and their responses change as a function of the optimization criteria (Section 2.3).

By combining these novel innovations, we can begin down the pathway toward a “holy grail” of geoengineering research - assessing what geoengineering can and cannot do.

Specific Objectives

We will generate a set of climate model simulations that, taken collectively, describes the space of achievable climate goals. This will be a set of case studies that each make different choices for which climate goals to prioritize relative to others, and which degrees of freedom to use in doing so. These simulations will be made available to the broader community for impact analysis.

We will use this set of simulations to (a) identify potential tradeoffs (sets of objectives that are mutually exclusive) and (b) boundaries (which objectives are achievable and which are not). This will provide an initial answer to a central question in geoengineering research: what can geoengineering do, and what can it not do?

Throughout this process, we will engage policy and governance experts, first regarding the potential range of climate goals that might motivate different actors, and then on the governance implications of identified trade-offs. Although our simulations are focused on understanding physical/natural science tradeoffs, the social and governance dimensions play a critical role in understanding which objectives may be most important to achieve or which strategies are simply politically infeasible, thus limiting the space in ways not revealed by climate modeling.

Achieving these objectives will significantly advance our understanding of the range of plausible geoengineering strategies and their trade-offs, feeding into a more holistic impacts assessment than has previously been possible, and informing governance and ultimately policy in this area.

2 Technical Background

There are a number of elements on which the proposed effort builds; many of these have only recently been demonstrated through an NSF EAGER award.

2.1 Climate model and simulations to date

The ability to assess different injection strategies rests in part on having a climate model that captures stratospheric dynamics, aerosol microphysics and chemistry. The prior research that enables the proposed work was conducted with the Community Earth System Model version 1, with the Whole Atmosphere Community Climate Model as its atmospheric component; CESM1(WACCM). This model has been validated against observations after volcanic eruptions [32] and used in a number of subsequent geoengineering studies (e.g., [47, 46, 29, 22, 19, 42, 51, 50]. Research conducted herein will use the updated version CESM2(WACCM6) [7, 11, 44].

Simulations exploring different injection strategies were originally conducted with annually-constant injection rates at 30°N, 15°N, 0°, 15°S, and 30°S, as well as 50°N and 50°S, all ∼5km above the annual mean tropopause [47]. (The effect of altitude will not be explored herein both to bound scope and because it is expected from past work to primarily affect efficiency [48, 6].) Early analysis discarded the higher-latitude 50°N/50°S cases because the annually-averaged AOD was similar to the 30°N and 30°S cases but with lower efficiency. Ref. [51] repeated the cases from 30°N to 30°S, but also simulated cases in which injection was restricted to a single season; March-April-May (MAM), June-July-August (JJA), September-October-November (SON), and December-January-February (DJF). In addition, we have now simulated injection at 45°N, 60°N, 45°S, and 60°S: while annually-constant injection at these latitudes is not very efficient in terms of AOD produced per unit injection, injection in spring (MAM in Northern Hemisphere, SON in Southern) produces a peak in AOD at high latitudes aligned with the summer peak in insolation; this is indicative of higher efficiency in affecting Arctic sea ice for example [50]. Furthermore, injection at 60°N/60°S is poleward of the stratospheric polar jet that acts as a transport barrier to aerosols. These additional cases thus provide potentially valuable additional degrees of freedom that expand the design space.

2.2 Degrees of freedom

The total number of simulations described above is 35; see Figure 1. However, due to the aerosol lifetime and the constraints imposed by stratospheric circulation, the number of usefully independent degrees of freedom is considerably less than that. For example, the spatial- and seasonal-pattern of AOD of all of the simulations described previously can be represented as a linear combination of the following nine simulations (indicated in yellow in Figure 1) with a residual of only 2.5%:

1. Annually-constant equatorial injection
2. Summer injection in each hemisphere at 15°N and 15°S (JJA and DJF respectively)
3. Spring/fall injection (MAM and SON) in each hemisphere at 30°N and 30°S, and
4. Spring injection at 60°N and 60°S (MAM and SON respectively)

This set is not necessarily "optimal", in that there are other choices of 9 that yield similar results and a similar resulting subspace of achievable spatiotemporal AOD patterns. This set has the advantage that spring/fall injections have been demonstrated to have significantly distinct outcomes for Arctic sea ice, for Indian monsoon precipitation, and for Amazon dry-season precipitation [50], but different choices of degrees of freedom may better target different objectives.

Conclusions from these simulations indicate that, at least in this model,

1. Choosing alternate seasons at 30°N and 30°S introduces significant seasonal dependence to the resulting mid-latitude AOD, with potentially important surface climate responses [50].
2. The effect of injection season is less important at lower latitudes: a second season at 15°N, 15°S, or at the equator, provides less "new" capability than at 30°N and 30°S.
3. Adding high latitude injection of the appropriate season provides significantly unique spatiotemporal patterns of AOD, introducing the potential to increase summer AOD poleward of the stratospheric transport barrier that otherwise limits high-latitude AOD (see e.g., [47]); increased summer AOD increases Arctic sea-ice extent [50]. Most patterns of AOD introduced by high latitude injection are not expected to have significant advantages in climate response due to the timing of the high-latitude AOD peak relative to the peak in summer insolation.
4. 45°N and 45°S injection do not provide significantly "new" capability relative to 60°N/S.

The spatiotemporal patterns of AOD for each of the 9 injection choices described above are shown in Figure 2, along with a spider-plot that illustrates the additional flexibility in choosing the AOD that increasing sets of injection choices achieves. The AOD metrics shown include the achievable projection onto each of the first three Legendre polynomials L0, L1, L2 that have been used in many prior multi-degree-of-freedom studies [3, 23, 29, 22], as well as summer high-latitude AOD in each hemisphere, and seasonal modulation of the mid-latitude AOD. Not all of these may be important for achieving any particular climate objective, but each capability may expand the space of achievable objectives.

2.3 Pareto-optimality

The design space of SAI is spanned by all possible combinations of all available degrees of freedom. In CESM1(WACCM), we have quantified a portion of this space via five different simulations. These include (i) the 20-member ensemble of the Geoengineering Large Ensemble (GLENS), that used injection at 30°N, 15°N, 15°S, and 30°S to maintain three large-scale patterns of temperature change [22, 46], (ii) an equatorial-injection strategy [19], (iii,iv) two strategies employing different seasons of injection and similar goals to GLENS [50], and (v) a simulation using the same latitudes as GLENS but different objectives and thus different distribution of injection across the 4 latitudes (not yet published; see Fig. 4).

While these simulations do not span the full design-space, they are sufficient to illustrate the potential for trade-offs (see also [25]). Any objective, or set of objectives, will have a minimum set of usefully-independent degrees of freedom that meet that objective, or come as close as physically possible. Some objectives may be mutually exclusive – we already have the example of global mean temperature and global mean precipitation [43], and Figure 3 shows how SAI in the previously described simulations has different effects on precipitation over northern India vs Amazon.

This illustrates a fundamental purpose of the proposed research – to understand whether there are trade-offs such as this one that persist when considering the entire design space for SAI. Iden-

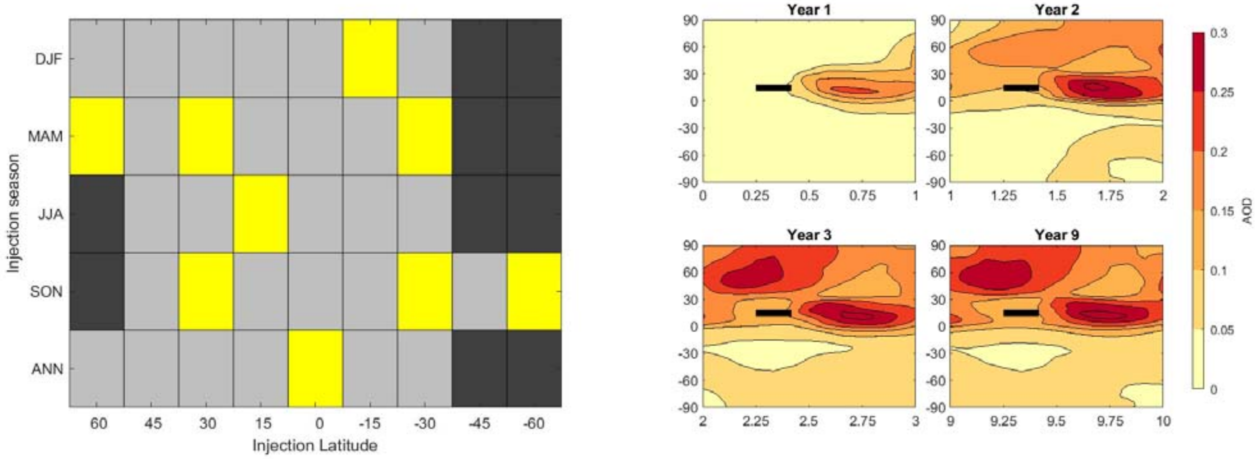

Figure 1: Left: Injection latitudes and seasons that have been simulated, with those considered in Section 2.2 highlighted in yellow. Right: An example showing convergence of the spatial- and seasonal- pattern of AOD (for injection at 15°N in MAM, indicated by the thick black line in each panel); by year 3 the pattern is established.

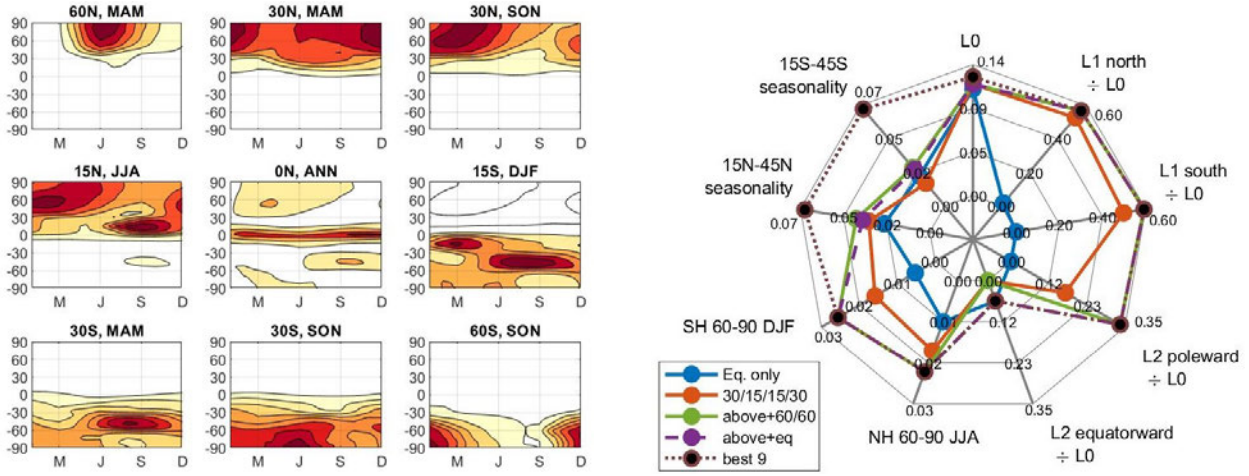

Figure 2: Left: the spatiotemporal patterns of AOD for each of the 9 injection cases included in the set described in Section 2.2. Right, the influence of different choices on different AOD metrics, where a larger radius for some particular set of injection options implies greater flexibility in choosing characteristics of the AOD that may be relevant for different climate objectives. Cases shown are (i) annually-constant injection at the equator (blue), (ii) annually-constant injection at 30°S, 15°S, 15°N, and 30°N as in [29] (orange); this adds the ability to obtain annually-averaged L1 increasing either northward or southward, and some ability to achieve a poleward-increasing projection of AOD onto L2; (iii) the same set but adding spring injection at 60°N and 60°S (green) adds the ability to significantly increase summer AOD at high latitudes; (iv) now adding back in equatorial injection (purple) provides some limited ability to achieve an equatorward-increasing projection of AOD onto L2, and finally (v) the set considered in the text (black) adds the ability to seasonally modulate the AOD over either northern- or southern-hemisphere mid-latitudes.

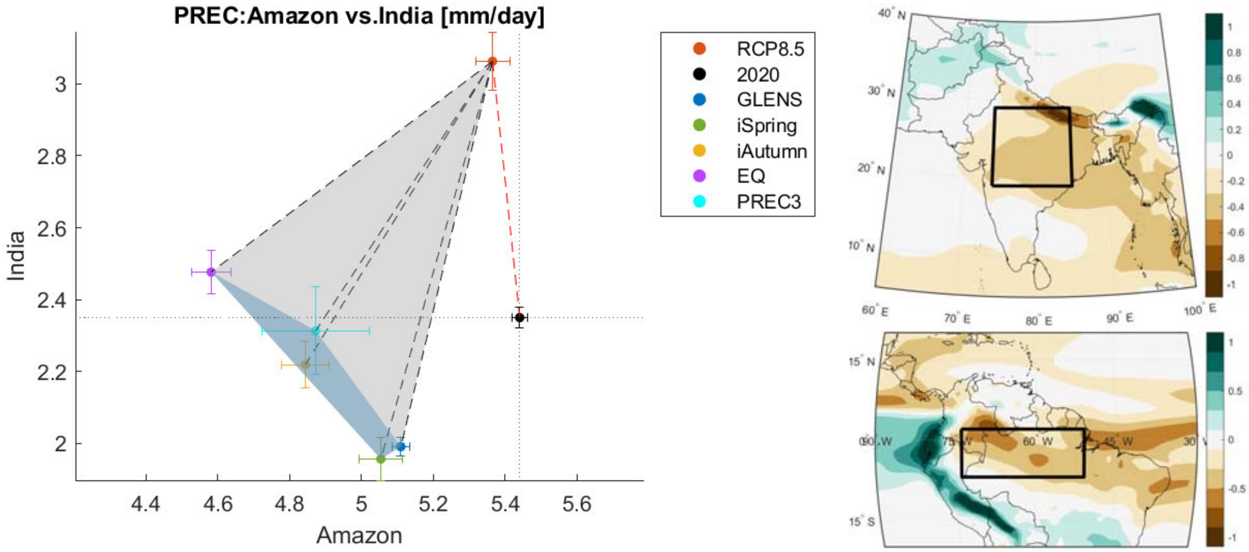

Figure 3: Left: Annual-mean precipitation over northern India (19-29°N, 74°-85° E) and Amazon (7°S-2°N, 51°-74°W) for 5 different independent simulations conducted in CESM1(WACCM), all of which maintained global mean temperature at baseline (2010-2030) levels; these regions were chosen because there was a clear decrease in precipitation in the GLENS simulations [42, 5]; right-hand panels. If the response is linear, then anywhere in the blue-shaded region (convex hull of the 5 simulations) can be achieved while maintaining global-mean temperature, and anywhere in the gray-shaded region can be achieved if higher temperatures are permitted (convex hull of the 5 simulations plus the RCP8.5 simulation). It would be premature to conclude that a trade-off between these variables exists without both a physical understanding of the mechanisms involved, and a more complete exploration of the design space, as there may be other options that achieve different outcomes. Nonetheless, this is illustrative of the questions that need to be addressed in modeling different SAI strategies.

tifying "unachievable climates" could have significant implications for developing the capacity for governance [24]; while it has certainly been postulated that different regions might have different preferences (e.g. [40]), the issue has never been settled when considering the entire design space rather than the over-simplified analogy of a single global "thermostat". Conversely, if it is possible to identify strategies that do allow multiple regions to each better satisfy regional objectives, that would also impact the needs of governance.

Pareto-optimal strategies are those in which no objective can be further improved without making some other objective worse; characterizing the set of Pareto-optimal strategies is thus a useful way of visualizing and quantifying trade-offs [33]. Initial work in exploring Pareto-optimal trade-offs in geoengineering was conducted in [25], using spatially- and seasonally-varying patterns of solar reduction in a relatively simple climate model. While this demonstrated a methodology and the idea that optimization could be used to explore trade-offs, the design space with stratospheric aerosols is constrained by stratospheric transport and aerosol lifetime, and thus the actual results obtained for solar reduction are not directly relevant.

2.4 Feedback

Feedback has been shown to be a valuable tool in past simulations to manage both uncertainty and nonlinearity. In each year of the simulation, the output from past years can be used to adjust the injection rates for the next year to meet specific objectives. Provided that the algorithm converges, this effectively "learns" the right injection rates to use for each degree of freedom (latitude/season of injection) in order to meet a particular set of objectives. This was first demonstrated for geoengineering for a single degree of freedom [28], extended to multiple degrees of freedom [23], and demonstrated for adjusting SO_2 injection rates rather than patterns of solar reduction [22]; the same process has also been used in other climate models [21, 4, 44]. A similar approach might be used if SAI were ever deployed in the real world [24].

Feedback allows us to construct and compare different simulations not on the basis of specified injection rates for different choices of latitudes/seasons (plug in a strategy and see what happens in the model), but on the basis of specified goals (tell the feedback algorithm what you want to happen and let it figure out what is needed to get there). In addition to the temperature-based metrics used in [28, 23, 22, 46, 50], we have also now demonstrated the ability to use feedback to manage goals such as global mean precipitation, ITCZ latitude, and September Arctic sea ice extent (Figure 4). The feedback algorithm in each case is based on physical understanding (in the simplest case, if it is too warm, increase injection, if it is too cool, decrease injection), allowing some confidence that the same algorithm will converge in other models (or possibly in a hypothetical real world deployment).

2.5 Gaps

While many of the building-blocks are in place to meet the Objectives in Section 1, there are a number of key gaps that need to be filled in. These are linked directly to the Statement of Work in Section 3.1.

1. Is the set of injection degrees of freedom identified in Section 2.2 robust, both across models, and for additional latitudes of aerosol injection? (Task 1 in the Statement of Work)
2. While a few different simulations have been conducted, there has never been a comprehensive evaluation of the overall space of achievable climate outcomes. (Tasks 4, 6)
3. Without this comprehensive evaluation, it is impossible to know whether some impact of SAI in some particular simulation is an inherent limitation or simply an accident of the limited set of strategies considered. (Task 7)
4. Developing the capability to explore many different strategies rather than just a few relies on approaches to do so in a computationally efficient manner, including (i) developing feedback algorithms for different climate objectives, and (ii) validating the separation between computing spatiotemporal patterns of AOD and the response to those patterns. (Tasks 3, 5)
5. Connection with policy needs – is there additional input that should be considered in defining potential goals (corresponding to the interests of different potential actors), and what are the broader implications of uncovering trade-offs? (Tasks 2 and 8)

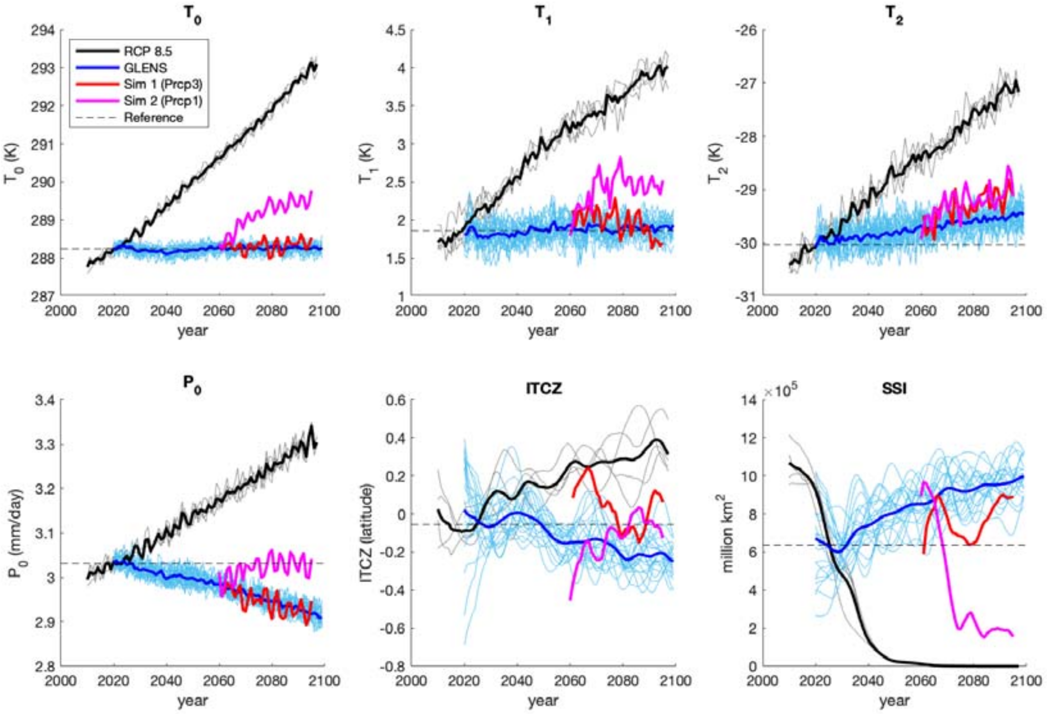

Figure 4: Illustration of the ability of feedback to manage different types of metrics and different sets. In addition to the reference RCP8.5 simulation (black), the GLENS simulations that use feedback to manage three temperature-based metrics are shown in blue [22, 46], along with two additional simulations that manage (a) global mean temperature, ITCZ, and September sea ice (red) and (b) global mean precipitation and ITCZ (purple). Note that the inability of GLENS to meet T2, and of the new simulation to meet september sea ice, are not a failure of the feedback algorithm but a limitation imposed by the combination of the set of degrees of freedom considered in these simulations and constraints imposed by stratospheric transport.

3 Technical Approach:

The background work described above enables an approach to quantifying the design space of SAI, specifically in determining the space of achievable climates. In this section, we describe our technical approach toward meeting this proposal's objectives (see also Figure 5 below).

3.1 Statement of Work

1. Use new model version CESM2(WACCM6), and repeat 5-year SO_2-injection simulations at multiple latitudes and seasons to evaluate the robustness of spatiotemporal AOD patterns. Compare with results from CESM1(WACCM), and with other models where output is available.
2. Engage policy/governance experts regarding span of climate goals to consider.

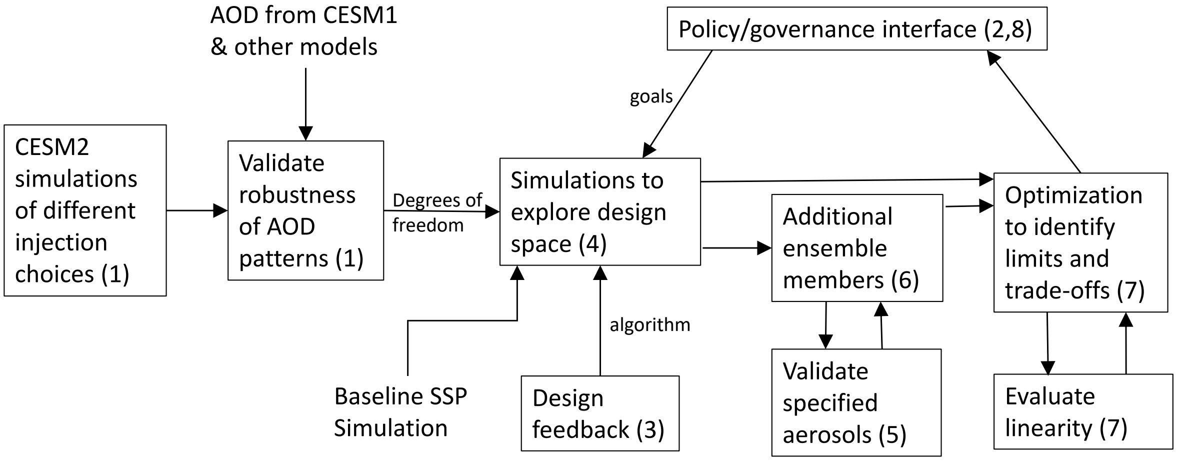

Figure 5: Flowchart illustrating relationship among the various tasks described in the SOW (numbers in brackets refer to the numbering in the SOW).

3. Design feedback laws needed to simultaneously adjust multiple degrees of freedom to meet heretofore novel goals in SAI, including objectives focused on temperature, hydrological cycle, or sea ice, both on global and regional scales (e.g., precipitation over India).
4. Generate independent simulations out to 2100, with each adjusting injection rates for different sets of latitudes/seasons to manage different combinations of climate goals.
5. Validate that simulations with specified aerosols in (low-top) CESM2(CAM6) result in similar tropospheric climate response to the full CESM2(WACCM6).
6. Generate additional ensemble members for each of the simulation options in step 5, using specified aerosols in CESM2(CAM6) and assess ensemble-averaged climate response across a broad set of climate objectives for each of the 21st century simulations.
7. Conduct optimization to evaluate different Pareto-Optimal solutions and identify fundamental trade-offs.
8. Engage policy/governance experts regarding governance implications of trade-offs.

Tasks 1-3 will be completed in year 1, 4-6 in year 2, and 7-8 in year 3, with results documented in publications along the way.

3.2 Climate Model

This research will rely on CESM2(WACCM6), the more recent version of the model used in the work described above, at the same ∼1 degree resolution used previously. The newer version has already been used in one study on SAI [44], validating the ability to use the feedback algorithms developed previously in the new model version. The first step in our research will compare results in CESM2(WACCM6) with those previously obtained with CESM1(WACCM); we already know from [44] that there are indeed some differences in climate response between the model versions.

3.3 Simulations and Analysis

(a) Robustness of AOD patterns:
The first step is to understand the set of injection options and number of degrees of freedom in the newer model CESM2(WACCM6), and to evaluate these conclusions across models to understand model differences, both through comparison with simulations previously conducted in CESM1(WACCM) and through comparison with additional models. To do this, we will conduct a set of 5-year simulations in CESM2(WACCM6) to evaluate the spatiotemporal patterns of AOD due to different choices of latitude and season. Previous research has shown that 5 years is sufficient to reach steady-state AOD values [51]; see Figure 1. We do not propose to directly fund other modeling centers to deliver similar results with their models, however we will work with other modeling groups to obtain and compare output where possible. We have colleagues who have expressed interest in producing simulation results at several different latitudes from GISS Model E [15], ECHAM, and possibly GEOS-5; some comparisons can also be made with models participating in GeoMIP6 that conducted the G6 scenario [18].

(b) Baseline scenario:
The baseline case that we will use for subsequent geoengineering simulations is the SSP2-4.5 scenario; this has already been conducted with both CESM2(CAM6), and with the high-top version CESM2(WACCM6) so there is no need to repeat these simulations. The GLENS studies [46] used RCP8.5 as a baseline; while that provides a high signal-to-noise ratio for improved detectability, and re-scaling to project outcomes for a different emissions pathway is in principle possible [31], we prefer to sacrifice some signal-to-noise ratio in order to better emphasize that geoengineering should only be considered in addition to mitigation and not in place of it. In the PI's experience, conducting simulations where the background scenario involves no mitigation complicates essential conversations with policy experts and the broader public, limiting the impact of this research. Furthermore, evaluating differences in an extreme scenario can potentially over-emphasize small changes that may not be detectable in a more moderate scenario [31] and put undue attention on nonlinearities. To make a stronger tie to policy-relevance, we will start geoengineering simulations in 2030, a plausible estimate for when 1.5°C of climate warming will be achieved [13]; the 1.5°C target is already reached by 2020 in CESM2(WACCM6), which clearly isn't valid in the real world.

(c) Climate response to SAI strategies:
To evaluate the climate response to different injection choices with high enough signal-to-noise ratio to distinguish the SAI-response from natural variability, we need multi-decadal simulations, each with multiple ensemble members. There are three broad considerations that influence our design of these simulations.

i) We need to establish a *basis* that spans the space of achievable objectives. In the past, this was done by conducting single simulations at each latitude/season of interest and then forming combinations of those simulations to understand how chosen objectives could be met [25]. However, this mathematical approach cannot account for nonlinearities (like non-additivity between two different injections), and the results of the simulations themselves are not directly policy-relevant. Instead, we will design a series of simulations, each of which meets a different set of objectives as described below. These simulations implicitly form a basis and are more directly relevant for subsequent analysis of tradeoffs or downstream applications like impact analysis.

ii) Climate outcomes will be maintained using feedback as in prior simulations [22, 46, 44, 50]. This compensates for uncertainty and nonlinearity, and enables simulations that maintain particular sets of objectives without a time-consuming trial-and-error approach for learning the necessary injection rates.

iii) The first simulation for each set of objectives will be conducted with the "high-top" model version CESM2(WACCM6) that includes a full representation of stratospheric dynamics, chemistry, and aerosol microphysics. To obtain additional ensemble members, the aerosol fields from this simulation will be applied in specified-aerosol configuration in CESM2(CAM6), which is a factor of 3 less computationally expensive. We will validate whether the two model versions yield similar climate outcomes (which we expect will be a valuable paper by itself!). We expect small differences due to climate sensitivity (5.3 with CAM6 vs 4.8 with WACCM, [7]) and climate-aerosol interactions. This step is novel and enables separating how injection choices affect AOD (requiring an accurate stratosphere that relatively fewer climate models capture, but not requiring fully dynamic ocean for example) from intercomparisons to evaluate how those patterns of AOD affect surface climate (requiring longer simulations, but not requiring stratospheric modeling capability that many models do not have).

(d) Climate objectives and SAI strategies:
Previous and ongoing studies have chosen impacts-relevant objectives like global-scale temperature [22, 46] or precipitation, P-E, and sea-ice extent (Figure 4). However, moving beyond purely proof-of-concept natural science/engineering studies requires a broader investigation of objectives. We will engage with policy and governance experts to better design more societally-relevant simulations. From a policy perspective, relevant scenarios for assessing the range of SAI options include not only "global" strategies that balance possibly competing goals, but also regionally-focused strategies. Additional objectives could include regional changes (e.g., precipitation over India), polar-only objectives (e.g. sea ice or permafrost area), and potentially single-hemisphere approaches (which will have negative impacts on ITCZ [12]; including options like this captures possible poor choices for deployment and thus increases the span of possible outcomes). Each simulation would manage multiple goals simultaneously using multiple different input degrees of freedom, as in other recent studies [22, 50].

Finding injection strategies to meet these objectives requires some physical understanding of the relationship between injection strategy and outcomes. For example, feedback will not be effective if the response is an order of magnitude different than we thought, or if we get the sign wrong. Prior studies have been successful by separating how injection rates affect patterns of AOD and how those AOD patterns affect climate objectives [29]. For example, using feedback to manage ITCZ latitude requires knowing that the ITCZ position depends primarily on the interhemispheric gradient of AOD (L1), which in turn depends on injection rates at different latitudes, but the magnitude of the relationship does not need to be known exactly.

Expanding on this general idea, an example objective could be maintaining Indian monsoon precipitation under climate change. This requires three observations:

1. Indian monsoon precipitation is strongly influenced by summer temperature contrast between the Tibetan plateau and the Indian ocean [52, 39].
2. Ocean temperature does not react strongly to seasonal variations in AOD, but the Tibetan plateau temperature does [50].
3. Changing the season of injection at 30°N results in the mid-latitude AOD varying with season [50], see also Figure 2).

This information is sufficient to design a feedback algorithm that can adjust injection rates in an effort to maintain precipitation rates over India, provided that objective is achievable (aerosol lifetime and stratospheric circulation will limit how much seasonal variation in AOD is possible) and compatible with other objectives. In another example, Arctic sea ice will respond to high-latitude summer AOD (in addition to heat transport from lower latitudes; [45]): all else being equal, then increased spring injection at 60°N will increase sea ice. This will also shift the ITCZ southward, which could be counter-balanced by a corresponding injection in the southern hemisphere, similarly to the solar-reduction study by Kravitz et al [23].

(e) Pareto-optimality:

The simulations will be analyzed both individually, evaluating the climate response for each simulation, and collectively as an overall set that describes the achievable space of climate responses in order to identify underlying trade-offs. The latter can be characterized in terms of Pareto-Optimal surfaces – for any given set of objectives, what set of strategies are optimal for some relative weighting between them, and which strategies are never optimal (that is, some other strategy yields better outcomes for at least one metric, and no worse outcome for any). As an example, in Figure 3, depending on the relative weighting on precipitation over India vs the Amazon, the "best" choice (for these two metrics) is some linear combination of the equatorial, the new simulation labeled "PREC", or GLENS, and neither the seasonal injection simulations (labeled iSPRING or iAUTUMN) is ever better; for different choices of metrics the result will be different.

Given some set of N climate objectives, the outcome of the i^{th} simulation can be described as a vector a_i of length N. With M different strategies simulated, the space of achievable outcomes can be described by $z = Au$, where the $N \times M$ matrix A is composed of the columns a_i, the elements of the vector $u \in \mathbb{R}^M$ describe how much of each strategy to use, and the vector z describes the predicted outcome of a combination of strategies. For any objective function involving z, the optimal choice of u can be estimated [25]. With $N \gg M$, it will not be possible to simultaneously achieve all climate objectives with any combination of the simulated strategies; we seek to understand what outcomes are or are not achievable.

An important assumption in this process is that predicted outcomes can be obtained from linear combinations of the specified forcing simulations. While imperfect, this is a reasonable approximation (e.g. [25, 29, 31]). Nonetheless, it is useful to evaluate whether there are particular objectives for which the linearity approximation is poorer than for others; we thus include in our computational requirements a final evaluation simulation. This involves choosing a particular optimization criterion, finding the predicted optimal vector u, which can then be related into a particular set of injection rates at each latitude and each season, simulating this case, and comparing the simulated outcomes with the predicted ones.

The overall summary of proposed simulations is given in Table 1, along with the computational requirements (which are roughly commensurate with our previous allocation on Cheyenne); if more limited resources were available then additional prioritization will be made (e.g., reducing the length of simulations to evaluate AOD, or conducting these without dynamic ocean).

3.4 Policy integration

While it is straightforward to come up with a list of relevant climate goals involving temperature, global and regional precipitation changes, sea ice, and so forth, one of the first steps in this research will be to engage policy and governance experts, including those internationally (e.g., through the

Purpose	Model	# of years	# of sims	Simulation-years	Core-hours
AOD, different latitudes & seasons	CESM2(WACCM6)	5	24	120	1.2M
Performance-evaluation	CESM2(WACCM6)	70/30*	9	310	3.1M
Performance with specified-aerosols	CESM2(CAM6)	70/30*	18	620	2.1M
Linearity assessment	CESM2(WACCM6)	30	1	30	0.3M
Total				460 + 620	6.7M

Table 1: Simulations required and estimated computation time. To reduce total computational requirements, simulations marked with * will involve a single simulation 2030-2100, with alternate performance objectives branched from this run in 2070 and only simulating the final 30 years, allowing 10 years to re-converge for different objectives, and 20 years for analysis. This approach has already been demonstrated [50]. CESM2(CAM6) uses 3431 core-hours/year (https://csegweb.cgd.ucar.edu/timing/cgi-bin/timings.cgi). CESM2(WACCM6) uses ∼8000 core-hours/year with only middle-atmosphere chemistry, but no dynamic ocean, based on PI experience and NCAR WACCM liaison; we estimate 10,000 with dynamic ocean, and we budget above to use the full ocean through the project, although it is not necessary for the first set of simulations.

DECIMALS program and C2G), to ensure that we have captured many of the most critical concerns regarding physical impacts of SAI. We have included in our budget travel allocation to participate in two SRMGI workshops that will enable direct conversations regarding these issues with scientists and policy-makers in the developing world.

In addition, to strengthen the pathway to impact, we will hold a focused workshop near the end of the proposed research that will bring both physical scientists and policy/governance experts together (including from SRMGI, C2G, and academics) to discuss the implications of identified trade-offs and limitations, how these might shape governance concerns, and explore steps for further research to support the development of policy and governance.

3.5 Team and Management:

Douglas MacMartin will be the overall project PI, responsible for overall project direction and supervision of the graduate student and any undergraduate researchers working on this project. He has extensive experience in geoengineering research, including design of feedback algorithms and optimization. Ben Kravitz, Indiana University, will serve as co-PI, contributing expertise throughout the project but in particular on coding of specified-aerosol simulations and coordinating simulations with other models. Assistance from Jadwiga (Yaga) Richter and others at NCAR is available if needed in setting up simulations with WACCM.

Broader Impacts

While geoengineering should never be considered as a substitute for mitigation, it might be the only pathway to limit some climate change impacts. This poses a crucial need to understand geoengineering risks, especially potential tradeoffs in geoengineering, which are directly related to the policy-relevant questions of a design-space (what climates can geoengineering achieve?) and geopolitics/ethics (will there be winners and losers?). Moreover, despite the outcomes of geoengineering depending upon design, most climate model simulations of SAI have employed ad hoc strategies, and even those that have considered deliberate design (including significant work by the PI and collaborators) have still made some arbitrary choices out of computational necessity with an aim of demonstrating potential rather than rigorously assessing the design space. GLENS [46], for example, is being used internationally for impacts research (e.g., [38]), yet it represents only a single strategy among many possibilities, conducted with a single model. The research herein will both provide a more comprehensive set of simulations covering different options that meet different sets of climate objectives, and will assess the extent to which different objectives can or cannot be simultaneously met – that is, what are the fundamental limits or trade-offs. By engaging governance communities both early in the research (to discuss specific climate objectives to consider in simulations), and through a workshop towards the end of the project that will disseminate the results, we will enable a reflexive process whereby the identified trade-offs will influence governance concerns, and define further research needs. The PI has long-standing connections with the geoengineering governance community; indeed, the proposed research is in part born out of those conversations and the need to provide better information for policy-makers.

Furthermore, the simulations conducted herein will be made available to the wider international community, including developing world researchers funded through DECIMALS, enabling a more holistic perspective on impact assessment rather than assessing one particular deployment strategy. The PI and Co-I are advisors to the DECIMALS program, providing a pathway toward more broad use of these simulations. Furthermore, we budgeted travel support for the PI to attend SRMGI workshops, allowing a first-hand discussion with a broader cross-section of participants in developing-world countries (scientists and policy-makers) regarding what climate objectives are of particular importance.

In addition to supporting a graduate student that will conduct the bulk of the research, this project will also provide an opportunity for undergraduate research involvement. Undergraduate engineering students at Cornell can fulfill design requirements for their degree through additional for-credit design-related activity connected with coursework. The project PI teaches the undergraduate/graduate feedback design class, in which undergraduates have been successfully involved in this research area. Specifically, potential senior design projects associated with this research include (i) constructing low-order dynamic models from system identification simulations, (ii) design of feedback algorithms based on dynamic models, and (iii) optimization of climate impacts, given simulated climate response functions.

Finally, this research integrates an engineering perspective into climate science research. One of the outputs, therefore, is not simply the research knowledge itself, but the ideas and engineering tools, that have the potential to impact not only how the scientific community thinks about geoengineering, but could potentially impact climate science more broadly. Training a truly interdisciplinary graduate student, integrated into a network of expert collaborators, is thus a valuable output of this work in itself.

Results from prior NSF Support

a) NSF award CBET-1818759, $299,529, April 1, 2018 – March 31, 2021: "EAGER: Introducing a design element into stratospheric aerosol geoengineering" (PI Douglas MacMartin).

Intellectual Merit: Solar geoengineering is not just a scientific endeavor, but also an engineering one. Much of the research conducted under this award has been described in the background above as it is an enabler for the research proposed herein. Key results include (i) demonstrating for the first time that not only does the latitude of aerosol injection affect the climate response, but so does the season of injection, including the potential to alter critical outcomes such as Indian monsoonal precipitation, (ii) demonstrating the ability to design feedback algorithms to manage metrics other than temperature-based ones, including precipitation, ITCZ, or sea ice (see Figure 4 above), and (iii) preliminary assessment of the "size" of the SAI design space, including latitudes, seasons, and in particular including single-season injection at high-latitude that greatly enhances efficiency relative to annually-constant high-latitude injection, and thus opens up a new range of as-yet-unexplored possible SAI strategies.

Broader Impacts: It is plausible that temporary and limited geoengineering deployment could be used to reduce climate risks, but making such an assessment requires understanding projected impacts and particularly the undesired side-effects. This research has taken a major step forwards towards that objective, illustrating the potential to reduce side-effects through seasonal injection strategies. Furthermore, the multidisciplinary perspective gained by applying engineering optimization, dynamic systems, and feedback design to climate science provides an opportunity to broaden both communities with the potential to spark additional insights and research.

Publications to date: References [26, 20, 51, 50], with two additional papers in preparation; one on managing different objectives (Figure 4), and one looking at the number of relevant degrees of freedom (roughly Section 2.2).

Research products and availability: Initial climate model output is available through the PI's website at Cornell; further climate model simulations are still being analyzed, and will then be archived either at NCAR or Cornell, with links provided in papers and through the PI's website.

b) NSF Award CBET-1931641, $299,994, 7/1/2019 – 6/30/2021: "EAGER: Marine Sky Brightening: Prospects and Consequences" (PI: Ben Kravitz).

Intellectual Merit: The aim of the project is to use models on a variety of scales to understand the effectiveness, feasibility, and efficiency of Marine Sky Brightening, which focuses on geoengineering via direct scattering of sea salt aerosols in the marine boundary layer. This idea will, for the first time, be systematically compared to Marine Cloud Brightening, a long studied geoengineering idea. The team has begun preliminary simulations using CESM to understand the sensitivity of the global climate to various strengths of solar reduction (a proxy for aerosol cooling) over the Gulf of Mexico and has identified and begun setting up regional and radiative transfer models to look at different scales of impact.

Broader Impacts: Marine Sky Brightening is applicable to regions where there are not clouds that can be reliably brightened. Does it work? Is it effective? What are the side effects and trade-offs? Understanding these questions will allow decision makers to better evaluate geoengineering options in the future.

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