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Scenarios for modeling solar radiation modification

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Making informed future decisions about solar radiation modification (SRM; also known as solar geoengineering)—approaches such as stratospheric aerosol injection (SAI) that would cool the climate by reflecting sunlight—requires projections of the climate response and associated human and ecosystem impacts. These projections, in turn, will rely on simulations with global climate models. As with climate-change projections, these simulations need to adequately span a range of possible futures, describing different choices, such as start date and temperature target, as well as risks, such as termination or interruptions. SRM modeling simulations to date typically consider only a single scenario, often with some unrealistic or arbitrarily chosen elements (such as starting deployment in 2020), and have often been chosen based on scientific rather than policy-relevant considerations (e.g., choosing quite substantial cooling specifically to achieve a bigger response). This limits the ability to compare risks both between SRM and non-SRM scenarios and between different SRM scenarios. To address this gap, we begin by outlining some general considerations on scenario design for SRM. We then describe a specific set of scenarios to capture a range of possible policy choices and uncertainties and present corresponding SAI simulations intended for broad community use.

solar radiation modification | solar geoengineering | climate engineering | climate intervention | scenarios

Emission reduction, even combined with large-scale carbon dioxide removal (CDR), may not be sufficient to avoid severe climate impacts. There may be inadequate ambition to reduce greenhouse gas emissions (1, 2), climate sensitivity may be high (3, 4), the impacts at a given temperature target may be worse than expected (5, 6), or some combination of all three. For these reasons, solar radiation modification (SRM) is being discussed as a potential additional element of an overall portfolio of options to address climate change (7, 8). In addition to avoiding, for example, global warming in excess of 1.5 °C above the preindustrial era, SRM is the only option that could rapidly reduce temperatures if any target were deemed insufficient.

Any assessment of SRM needs to be made in the context of climate-change impacts without SRM (7). There is substantial modeling support for understanding the range of possible impacts of climate change from, for example, simulations of the Shared Socioeconomic Pathways (SSPs) in the Climate Model Intercomparison Project (CMIP) (9, 10). Similarly, a key input to decisions surrounding SRM will be projections of the climate response and associated influence on human and ecosystem impacts. Quantitative projections under different possible futures will require simulations with Earth System Models (ESMs). As with climate-change research (11), these require choices for which scenarios are simulated, where each scenario describes a plausible future, chosen deliberately to inform decisions (12, 13). Scenarios should thus be chosen to understand the effects of different decisions that could be made about SRM—whether to deploy, when to deploy, how to deploy (14), and how much to cool—and different uncertainties that might affect decisions, including mitigation/CDR assumptions and risks such as termination or interruptions in deployment. However, a challenge that limits comparability today both across different SRM choices and between assessments of SRM and non-SRM scenarios is a degree of arbitrariness in SRM scenario choices in current modeling studies.

Recent SRM modeling scenarios that are being broadly used for impact analysis include, for example, the Geoengineering Modeling Intercomparison Project Phase 6 (GeoMIP6) scenario G6sulfur (15) and the Geoengineering Large Ensemble [GLENS (16)]. Both consider only a single SRM scenario. Both start deployment in 2020; this does not represent any plausible future. And both consider only a high-emissions scenario (SSP5-8.5 or Representative Concentration Pathway 8.5 [RCP8.5]) that is useful for generating a high "signal" relative to climate variability to better understand science, but is not consistent with current projections of mitigation efforts (17, 18) and is thus limiting for informing policy. Further scenario choices have also been explored—e.g., a decreased rate of change (19–22) or termination [e.g., GeoMIP G3 and G4 scenarios (23)]. Tilmes et al. (24) is the only example considering and comparing multiple background-emissions

Significance

The benefits and risks of solar radiation modification (SRM; also known as solar geoengineering) need to be evaluated in context with the risks of climate change and will depend on choices such as the amount of cooling. One challenge today is a degree of arbitrariness in the scenarios used in current SRM simulations, making comparisons difficult both between SRM and non-SRM cases and between different SRM scenarios. We address this gap by 1) defining a set of plausible scenarios capturing a range of choices and uncertainties, and 2) providing simulations of these scenarios that can be broadly used for comparative impact assessment. This is an essential precursor to any international assessment by, e.g., the Intergovernmental Panel on Climate Change.

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scenarios and multiple temperature targets, though they still include a 2020 start date for several cases. Few papers (25, 26) have considered a temperature target lower than that at the start date, while none explore the dependence on the assumed start date. While termination has been extensively explored, no papers include scenarios that explore the effects of a temporary interruption or other deployment inconsistencies, and only one (19) simulates a deliberate gradual phaseout to a warmer world.

Projected climate responses and inferences about SRM will depend on the scenarios simulated. For example, whether the shift in any particular variable due to climate change is compensated by SRM, overcompensated, or undercompensated will depend on how much cooling is done (20, 21, 27). Similarly, a shift in climate under SRM might be significant at high cooling, but not even detectable under more moderate cooling scenarios (28). Depletion of stratospheric polar ozone by heterogeneous chemistry will depend on remaining chlorofluorocarbon (CFC) loads and hence the presumed start date (see Fig. 3), as will irreversibilities arising from loss of permafrost carbon, melting of Greenland/Antarctic ice sheets, or ecosystem changes, for example.

This paper aims to advance understanding and development of decision-relevant scenarios for SRM. The next sections describe broad considerations that inform scenario design, motivated by framing the question around decisions and the role of ESMs. Drawing on that, Section 3 describes the specific illustrative scenarios that we have chosen, and Section 4 presents corresponding climate model simulations (with SAI, though the scenarios are more generally applicable to other methods, such as marine cloud brightening [MCB]). We focus here solely on scenario design for ESM simulations. While these will be essential for informing decisions surrounding SRM, not all important policy-relevant questions about SRM depend on—or can be usefully informed by—ESM simulations, and different scenarios will therefore be important for understanding different questions, such as governance challenges surrounding a possible decision to deploy, for example.

Scenarios play an important role in informing and influencing policy debates (29–34). Consequently, a broad, inclusive, international, and interdisciplinary process to scenario design will be essential (7, 31)—perhaps similar to the process that led to the RCP/SSP scenarios (35, 36). Starting such a process, however, requires early scenario-based exploration of potentially relevant dimensions—e.g., amount of cooling, choice of start date, intermittency or inconsistency in goals, etc.—to begin to assess their relative importance. We view the scenarios and simulations presented here as an initial contribution to this process.

1. Considerations for Scenario Design

Scenario design has a long history in a diverse set of fields, from industrial planning to climate change. Before considering scenario design specific to SRM, we first briefly note some general guidelines and criteria for effective development and use of scenarios that are also applicable here:

- Scenarios come in groups, to represent alternative possible choices or key uncertainties, because it is often the comparison among these that is most informative. The differences between individual scenarios should be large enough to be meaningful.
- Each scenario must meet some threshold of plausibility, in that the broad conditions represented must be sufficiently likely, given the stakes, to be worth considering in planning.
- Scenarios usually prioritize informing near-term decisions, even when they portray more distant conditions to explore longer-term consequences of early choices. Later decisions may be enabled or constrained by earlier decisions, but will be made in the context of different knowledge and capabilities, making current scenarios less relevant.
- Representing conditions in a scenario does not imply approval. Rather, scenarios are judged only on their plausibility and their relevance to decisions. Scenarios portraying failures or undesirable conditions are often especially informative.

Relevance and plausibility of a scenario are, of course, subjective and contestable. Scenarios that have been developed for climate change and those we consider here for SRM are of interest to a diverse audience with widely varying knowledge, interests, and responsibilities, making it difficult to reach consensus on plausibility and relevance. In response, scenario developers for climate change have endeavored to span a wide range of possible trajectories and to be explicit about the reasoning and assumptions underlying each scenario (13). The RCP/SSP scenarios aim to represent the most important uncertainties to inform near-term decisions about mitigation, adaptation, and other forms of climate response. They are presented in groups to illustrate the dependence on these factors, with meaningful separation between them and careful attention to conveying underlying assumptions and reasoning. They are all presented as plausible pathways and include some that clearly portray undesirable futures, notably, the high-emissions scenarios that illustrate the danger of unchecked climate change. These general principles similarly apply in developing scenarios to inform decisions related to SRM. Note that these do not preclude other modeling exercises, such as abrupt $4\times CO_2$ simulations for climate change or GeoMIP G1 [offsetting $4\times CO_2$ with a solar reduction (23)], but those are clearly not intended to directly inform impact assessment and should not be used as such.

Our focus here is specifically on scenario development for use in ESMs. The purpose of an ESM is to project the global and regional climate response to a nontrivial forcing applied over a nontrivial duration. As such, an ESM is not the right tool to address all questions, and this affects scenario design—by focusing scenarios on the subset of questions for which ESMs are the appropriate tool to address. For example, there are high-stakes uncertainties and associated decisions about the geopolitics of SRM, such as risks of unilateral or unauthorized deployment under various climate conditions and states of international governance capacity (37, 38). Such crises would move fast, playing out over months or a year or so, rather than decades. Over such a short period, the deployment would not have scaled up to detectable cooling, so its geopolitical importance would greatly exceed its geophysical importance. A scenario exercise to explore options and risks in such a chain of events would mainly concern political events, structures, and capabilities, not climatic consequences of the deployment (37); as such, ESM simulations of the deployment would not be relevant tools to help inform these challenges.

Similarly, some long-term consequences of SRM deployment are unlikely to be usefully informed by ESM simulations, for several reasons. First, questions such as the implied duration of commitment under an overshoot scenario [a common framing for SRM (24, 39–41)] are clearly policy-relevant, but the answer depends almost entirely on the cumulative CO_2 emissions and assumptions about CO_2-removal potential (42), and not on the SRM deployment itself; ESM simulations are thus of limited value in addressing this question. Second, simulations to date suggest that, for the most part, the regional climate response to a deployment converges to reach a pattern of response that approximately scales with the amount of cooling (28) and would not continue to evolve significantly if deployment were sustained for a long time (43); long-term responses can thus be estimated if desired by using simpler modeling tools (44). Third, the long-term response is likely dominated by technological change: While the physics of CO_2 don't change with time, technology associated with SRM likely would, as might the goals for a deployment, and thus long-term projections of the climate response to SRM are speculative in a way that is not true for CO_2. Finally, in developing scenarios today, we are primarily concerned with informing near-term decisions; while CO_2 has a long lifetime in the atmosphere, aerosols added for SAI or MCB do not, and, thus, deployment choices can be adapted later when more information is available—making long-term projections less important today. Given finite computational resources, scenarios for ESM simulations should thus prioritize nearer-term (multidecadal) rather than long-term (century-scale or longer) projections.

As the goal is to inform decisions, designing scenarios needs to start by clarifying what those decisions are. The most consequential decision is whether to deploy SRM, but this is not a simple binary choice. Any decision to deploy or not to deploy would take place at a specific time, under specific climate conditions and trends. Moreover, any decision to deploy entails choices including both how much cooling and how to achieve that [e.g., aerosol injection latitude and season (14, 45–47) or material (48)]. These choices will affect the distribution of benefits and harms, creating trade-offs and influencing assessments and incentives. (We do not distinguish scenarios by who is taking the specified actions, nor even presume that deployment is under the control of any single actor, although these issues may have to be reconsidered in later scenario-based analyses.) Any decision to deploy will also be affected by assessments of future risks, such as termination or interruption in deployment. ESM projections of the climatic consequences for all of these dimensions will be valuable for informing these decisions.

Scenarios therefore need to describe the following five dimensions of SRM deployment and its context; these are also illustrated in Fig. 1. We propose and explain our specific choices for initial scenarios in the next section.

1. The background climate-change scenario: Choosing this from existing climate-change scenarios will allow more straightforward comparison between SRM and non-SRM scenarios.
2. The desired target or amount of cooling: It is not essential to describe SRM scenarios in terms of global mean temperature (22, 49); however, temperature targets are how the United Nations Framework Convention on Climate Change has operationalized climate-change goals in the Paris Agreement and are thus a reasonable starting point. In making this choice, it is important to recognize that, while for more conventional climate policy, temperature is a proxy for a broad set of climate-change impacts, SRM does not simply undo the climate changes, but can increase some risks while decreasing others, and, thus, it will ultimately be important to consider targets described through other variables. Risks of sea-level rise, for example, will be minimized by reducing to a lower temperature, whereas effects such as ozone depletion or acid-rain deposition will be minimized with a smaller amount of cooling, but the trade-offs are still unclear.
3. The start date of a deployment: Research is most urgently needed for the closest decisions on SRM development and deployment and is less urgent for further-out ones; scenario choices should reflect this, but should also inform the impact of delaying a decision.
4. How the cooling is achieved: Even for a given global mean temperature, outcomes will still depend on factors such as (for SAI) the latitude and season of injection or the aerosol material. Furthermore, the same level of forcing could be achieved through a single, globally coordinated effort or through the combined effects of several smaller efforts. Note that our scenarios in the next section leave the deployment strategy open for exploration, rather than prescribing it.
5. What else might happen that could affect decisions? For example, if SRM were started, some future actor might terminate or deliberately phase out a deployment, there could be an interruption for a year or two or other inconsistencies in deployment (that could arise due to multiple actors with conflicting goals, for example) or a large explosive volcanic eruption (50).

Clearly, the combinatorial aspect prevents anyone from simulating every possibility. Emulators (28, 44) may be useful for expanding the range of scenarios considered, provided the response is sufficiently linear (which needs to be more thoroughly evaluated). However, many of these dimensions can initially be explored independently to better understand which factors most affect conclusions. Given the current status of modeling, where few studies consider more than a single scenario, even a limited exploration provides the opportunity to compare across scenarios

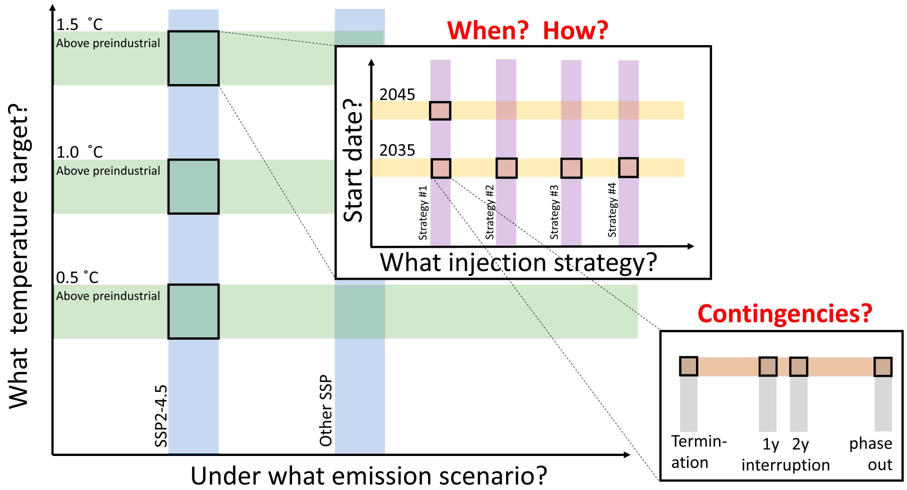

Fig. 1. There are multiple dimensions to future scenarios for SRM: the emission scenario, temperature target, start date, deployment strategy (for SAI, the injection latitudes, seasons, altitude, and material), and other events that might occur, providing a combinatorial challenge. The proposed scenarios are illustrated here and graphically in Fig. 2.

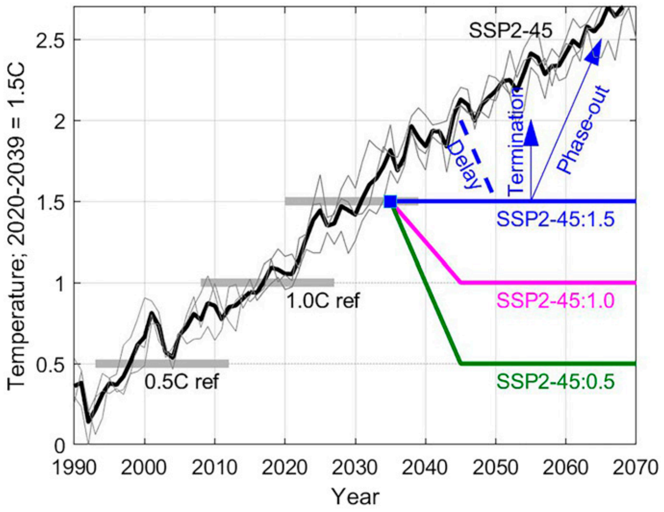

Fig. 2. Graphical illustration of scenarios described in Section 3. Simulation results for historical (through 2014) and SSP2-45 (2015 on) are from the CESM2(WACCM6) model, as described in Section 4 (three ensemble members; mean shown in thicker lines); simulation data for the SRM scenarios here are shown in Figs. 3 and 4.

and can thus help inform which aspects to focus on in designing a broader, more inclusive approach for scenario design.

2. Our Specific Scenario Choices

Providing quantitative information from scenarios requires actual simulations, which, in turn, require specific, concrete choices. We have chosen a set of simulation parameters, which we present here, along with our reasoning. We do not intend for these to capture every case that decision makers might be interested in, and, as noted earlier, some broader inclusive process would be valuable (7, 31). Nonetheless, analyzing initial simulations is an essential step to informing which dimensions are most critical to focus on in any eventual, more inclusive process.

Following from the preceding sections, defining scenarios requires defining 1) background emissions scenarios, 2) targets, 3) start dates, 4) strategies for reaching targets, and 5) additional risks or inconsistencies. Herein, we do not prescribe the deployment strategy as part of our scenario definition, leaving this as a free variable to be explored within a particular scenario (though some consistent choices would need to be made if these scenarios were used for model intercomparison).

The choice for the emissions scenario is influenced by our conclusions on required simulation length; based on the preceding discussion, we choose 35 y as long enough to converge for analysis of the regional climate response, but not so long as to be simply guessing on long-term technology trends.

To integrate with impact assessment of non-SRM scenarios, it is essential to branch simulations from an existing widely used scenario. We choose to only simulate SSP2-45; this is roughly consistent with the Paris Agreement's Nationally Determined Contributions without increased ambition (17, 18) and is also a tier-1 case in ScenarioMIP (11). A higher forcing scenario could also be simulated to explore the risks of overreliance on SRM, while presumably in a low-forcing, high-mitigation scenario, SRM would be less likely to be considered. However, given our choice for simulation length, the choice of SSP makes less difference to future projections (9), and given limited computational resources, we opt to focus on other dimensions of the simulations that have, to date, been relatively unexplored. The risks created by any "moral hazard" effect of SRM (8) could be explored by comparing simulations of SSP2-45 with SRM to simulations of a more aggressive emissions-reduction scenario without SRM.

An obvious first choice for a temperature target is to use the 1.5 °C aspirational goal of the Paris Agreement [which will be exceeded at least a decade or more before the 2 °C goal (9), making it a more urgent target of research]. After anchoring their global mean temperature to recent observations, the median estimate across CMIP6 models for when the climate might reach 1.5 °C is 2028, but with considerable range across models (9). To ensure a straightforward intercomparison between different models, we choose the average over the 20-y period 2020 to 2039 as representative of when the climate might reach 1.5 °C.

To explore a range of target temperatures, we also consider targets 0.5 °C and 1 °C below the 1.5 °C target, roughly representative of 1.0 °C or 0.5 °C above preindustrial; this enables some exploration of trade-offs with amount of cooling. Even lower targets may have value (26). We do not consider here a scenario that only halves the rate of warming (20, 21) or limits the rate of warming (19), as those scenarios are likely the easiest to estimate by using emulators.

A rapid cooling toward a lower-temperature target would also have consequences arising from climate dynamics (e.g., differential rates of warming between oceans and land can affect monsoon circulation), and ecosystems that have already partially adapted to a higher temperature might not be able to keep up, while slower-adapting ecosystems may benefit from more rapid cooling. While this is yet another independent variable to be explored, for initial simulations, we arbitrarily choose to fix the transition period at 10 y. For a 0.5 °C lower target, this results in roughly double the current rate of temperature change, and for a 1 °C lower target, it is four times larger. This transition will thus likely be fast enough to introduce detectable impacts; these simulations might thus answer questions both about the lower target temperature and the speed of changing the temperature.

Choosing the starting year for deployment in scenarios will affect the evaluation of impacts because of potential irreversibilities in climate, ecological, or human systems and because delaying the start date would mean additional years of climate change and climate impacts. Choosing too early of a starting date may be unrealistic, given the slow pace of research, the current state of governance, and that the deployment technology itself does not yet exist (51). Modeling certain years as the start date also risks an implicit anchoring bias. In light of these considerations, and given the focus on limiting warming below 1.5 °C, we choose 2035 as the start date in most scenarios. To evaluate the impact of this choice, we choose a second scenario with a start date 10 y later. Earlier deployment may be possible, but it is our view that it is not sufficiently likely to focus limited computational resources on.

Finally, we consider a few cases to explore contingencies that decision makers would want to consider before beginning any deployment: an abrupt termination, a deliberate gradual phase-out, and interruptions of 1 or 2 y, all starting in 2055 (providing the largest signal and thus describing the largest risk within our simulation window, while still having 15 y of simulation time to explore the effects). While these cases clearly do not span the full space of all possible inconsistencies in deployment that might arise, we expect that they will capture key features.

Not included here is the role of deployment "strategy"—i.e., for SAI, what latitude(s) are used for injection, aerosol material, etc. By independently adjusting injection rates at multiple latitudes and/or seasons, additional goals could be met in addition to the global mean temperature that we specify in our scenarios. While research indicates that different strategies will have different distributions of benefits and harms, the scope of what is possible

Table 1. List of simulations

Simulation name	Description	Goal	Start/end years
SSP2-45-1.5 ("baseline")	Maintain temperatures representative of 1.5 °C (2020 to 2039 average)	Reference case	2035 to 2069
SSP2-45-1.0	Decrease temperature over 10 y to 1.0 °C (0.5 °C lower than baseline)	Effect of target	2035 to 2069
SSP2-45-0.5	Decrease temperature over 10 y to 0.5 °C (1.0 °C lower than baseline)	Effect of target	2035 to 2069
SSP2-45-1.5-D	Delayed start by 10 y; decrease temperature back to 1.5 °C over 5 y	Effect of start date	2045 to 2069
SSP2-45-1.5-T	From baseline, abrupt termination in 2055	Risk evaluation	2055 to 2069
SSP2-45-1.5-P	From baseline, gradual phaseout over 10 y from 2055 to 2064	Risk evaluation	2055 to 2069
SSP2-45-1.5-I1	From baseline, a 1-y interruption in 2055, resuming in 2056	Risk evaluation	2055 to 2065
SSP2-45-1.5-I2	From baseline, a 2-y interruption in 2055 to 2056, resuming in 2057	Risk evaluation	2055 to 2066

is currently an open research question (14, 47). Pragmatically, then, it is reasonable today to separate the strategy question—that is, pick a single strategy and explore multiple choices for other aspects of the scenario and then hold the other aspects constant and explore the effect of different strategies. Emulators may then be useful to incorporate the combined results to better understand regionally specific preferences and incentives and how those might affect both deployment of SRM and mitigation (26, 52–54). The word strategy implies deliberate choices; we recognize that strategies would be more complex and could have less predictable effects if there were multiple simultaneous uncoordinated and potentially inconsistent efforts. Future explorations of this dimension should thus also explore such cases.

The different scenarios described here are shown in Figs. 1 and 2 and in Table 1 with the question that each can address.

3. Simulations

Based on the recommendations developed above, we conduct simulations of SAI, as listed in Table 1. These are intended to provide a basis for considerable further exploration by anyone interested in impact assessment of SAI; as such, herein, we only present the simulations and some high-level characteristics of the response sufficient to illustrate the importance of spanning a range of scenarios in drawing conclusions about the effects of SAI.

The climate model used here is the fully coupled Community Earth System Model, version 2, with the Whole Atmosphere Community Climate Model version 6 as the atmospheric component, CESM2(WACCM6) (55). The version we use only has middle-atmosphere (stratospheric) chemistry, similar to the configuration of the earlier version CESM1(WACCM) described by ref. 56 and used by refs. 16 and 57 and numerous subsequent papers. The horizontal resolution is 0.95° in latitude by 1.25° in longitude, with 70 vertical layers up to $\sim$140 km; such a "high-top" model with adequate representation of stratospheric chemistry is essential for capturing stratospheric processes involved in the sulfate aerosol life cycle. Model output is saved monthly and daily for all CMIP6 variables with Priority 1 in each realm (ocean, land, atmosphere, ice, chemistry, and aerosols); daily output is available for temperature (mean, maximum, and minimum) and precipitation (mean and maximum) to allow subsequent evaluation of extremes, as well as sea ice and all surface and top-of-atmosphere radiative fluxes.

The SAI injection strategy we choose is the same as in refs. 16, 24, and 57, in which SO_2 is injected at 30 °N, 15 °N, 15 °S, and 30 °S, with the injection rates adjusted each year using a feedback algorithm to maintain not just the global mean temperature, but the interhemispheric and equator-to-pole temperature gradients. SO_2 is injected continuously (at every 20-min time step of the model) into the gridbox centered at 21.5 km (the grid resolution in WACCM6 at this altitude is about 1.2 km), as this appears to be plausibly achievable with existing aircraft engines (but new aircraft designs) (51); to achieve higher altitude would require radically different lofting platforms that are more speculative (58).

The global mean temperature in these simulations is shown in Figs. 3 and 4, along with the required SO_2 injection rates and several other important metrics of change in the Earth system. These results illustrate the importance of scenario choices in evaluating impacts.

The frequently-used "napkin" diagram (39, 40) implies the use of SRM to avoid global mean temperature rise above some particular threshold, such as 1.5 °C. However, in contrast to emission reductions, SRM could be used to achieve lower targets still, introducing a range of trade-offs (and associated governance challenges). A lower-temperature target leads to greater recovery of Arctic sea ice, greater recovery of the Atlantic Meridional Overturning Circulation (AMOC) that continues to collapse in the 1.5 °C case, and decreased upper ocean heat content and associated thermosteric sea level rise. However, a lower-temperature target overcompensates (relative to changes in temperature) global changes in precipitation minus evaporation (P-E), increases polar stratospheric ozone loss, and increases acid-rain deposition (proportional to injection rate). These examples illustrate that, even without considering choices such as locations of aerosol injection, it is incorrect to describe SAI as having some particular quantitative effect, as the effects will depend on how much cooling is desired.

The choice of different temperature targets also allows us to explore how linear the relationship is between the SO_2 injection rate, the resulting global optical depth, and the desired global cooling. In these simulations, 1 °C of cooling (roughly what is needed to maintain the 1.5 °C target in 2070) requires an annual injection rate of 10 Tg of SO_2. But an additional 0.5 °C cooling requires close to an additional 10 Tg/y, due to microphysical sublinearities in the aerosol growth (59). The relationship between global optical depth and achieved cooling is roughly linear.

Even for the same temperature target, the effects depend on when deployment is started. A 10-y delay results in more significant overshoot and associated climate impacts. While the same ultimate climate state is reached for the metrics shown here, the delay in recovery of global mean temperature or ocean heat content, for example, is considerably longer than 10 y because the climate system cannot be instantly cooled. While the 2035 start date modeled here results in a decrease in polar stratospheric ozone, that decrease is largely avoided with the 2045 start date because of the projected reduction in stratospheric ozone-depleting substances (primarily CFCs). In addition to highlighting trade-offs associated with the choice of start date, this case further illustrates why it is problematic to assess impacts based on simulations conducted with scenarios that have arbitrarily chosen aspects, such as the 2020 start in GLENS or GeoMIP G6: A drop in polar

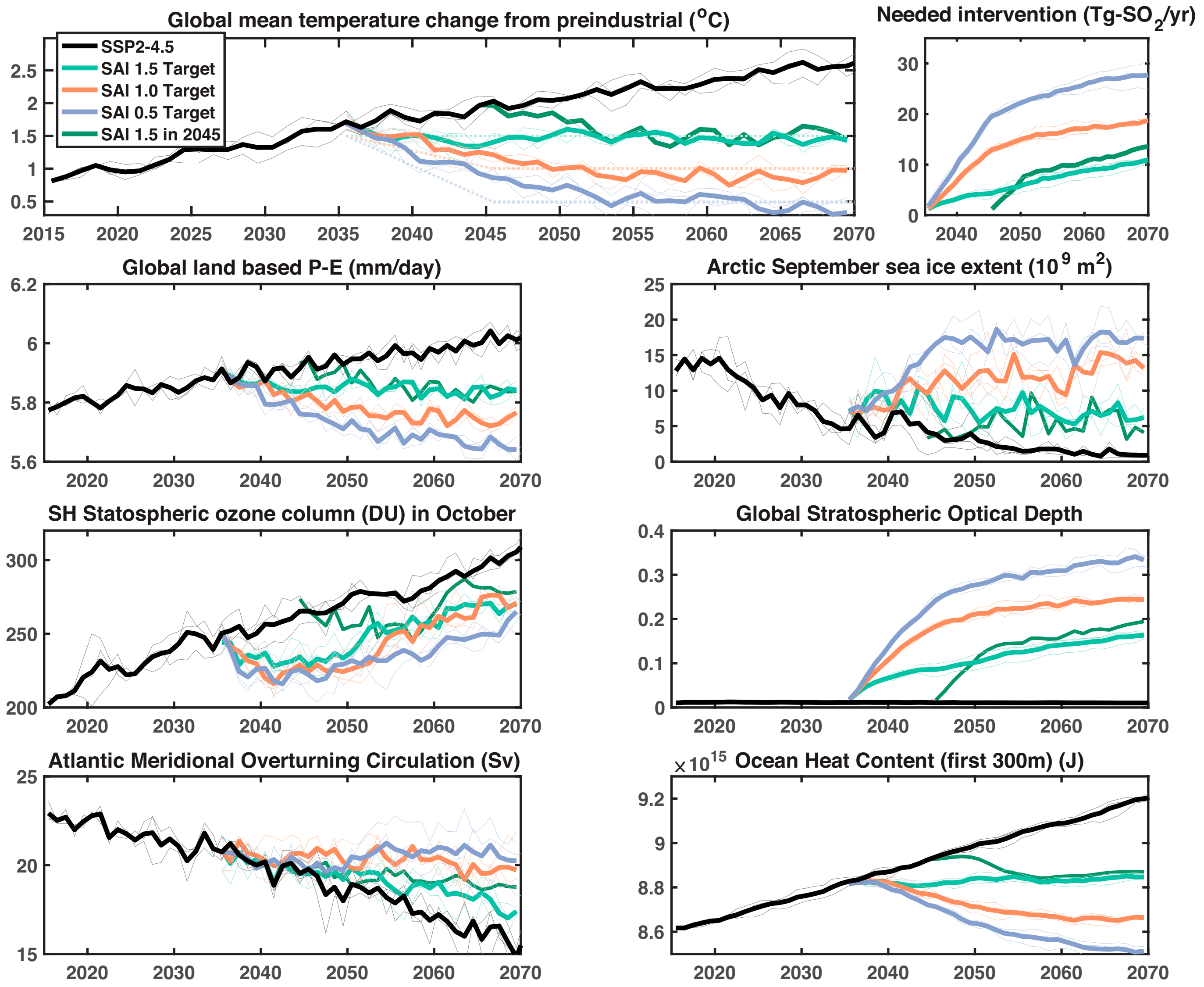

Fig. 3. High-level results from simulations involving different temperature targets: global mean temperature; SO_2 injection rates; land average precipitation minus evaporation P-E; Arctic September sea-ice extent; total column ozone in southern hemisphere (SH), 60 to 90 °S in October (in Dobson Units, DU); Global Stratospheric Optical Depth; AMOC; and upper ocean heat content (indicative of thermosteric sea-level rise).

stratospheric ozone has long been listed as a negative consequence of SAI (60), yet depends strongly on the start date.

There have been many papers exploring the effects of a sudden termination, and our results do not directly add to that; the aerosol layer takes a few years to decay, and the global mean temperature gradually returns to the values without SAI over the next 15 y (the difference in these time scales indicates that it is the climate-system inertia that dominates). However, there are other less severe inconsistencies in deployment that are important to consider in assessing overall risks. First, depending on the reason for termination, deployment might be restarted after a relatively brief interruption. While the stratospheric optical depth responds fairly quickly to interruption, the combination of climate-system inertia and natural variability means that changes in many other metrics due to a 1- or 2-y interruption may not even be detectable. Second, understanding the effects of a deliberate gradual phaseout of a deployment (19, 61) would illuminate the extent to which deploying SRM might present even later decision makers with difficult trade-offs if, for example, undesired impacts developed. For most of the metrics shown here, a gradual phaseout over 10 y is not too dissimilar from an abrupt termination; this has serious implications for the possibility of an "exit strategy" for SRM, as it suggests that a much slower phaseout would be needed.

Different injection strategies, and different climate models, will lead to different quantitative conclusions that will need careful evaluation.

4. Discussion

Analysis of a set of simulations that consider a range of plausible future options is essential to move toward a comparative assessment of impacts between different SRM scenarios and between scenarios that do include SRM with those that do not, recognizing, of course, that the physical impacts are only one piece of the information needed to support decisions and, further, that any choice of a finite set of scenarios has some implicit anchoring bias—particularly choices (as here) that are not made through a broad international and interdisciplinary deliberative process. Despite this last caution, we believe it is essential to start with some concrete choices and begin to understand the impacts of different scenarios; indeed, better understanding of which dimensions are most critical is an essential precursor to such a broad process.

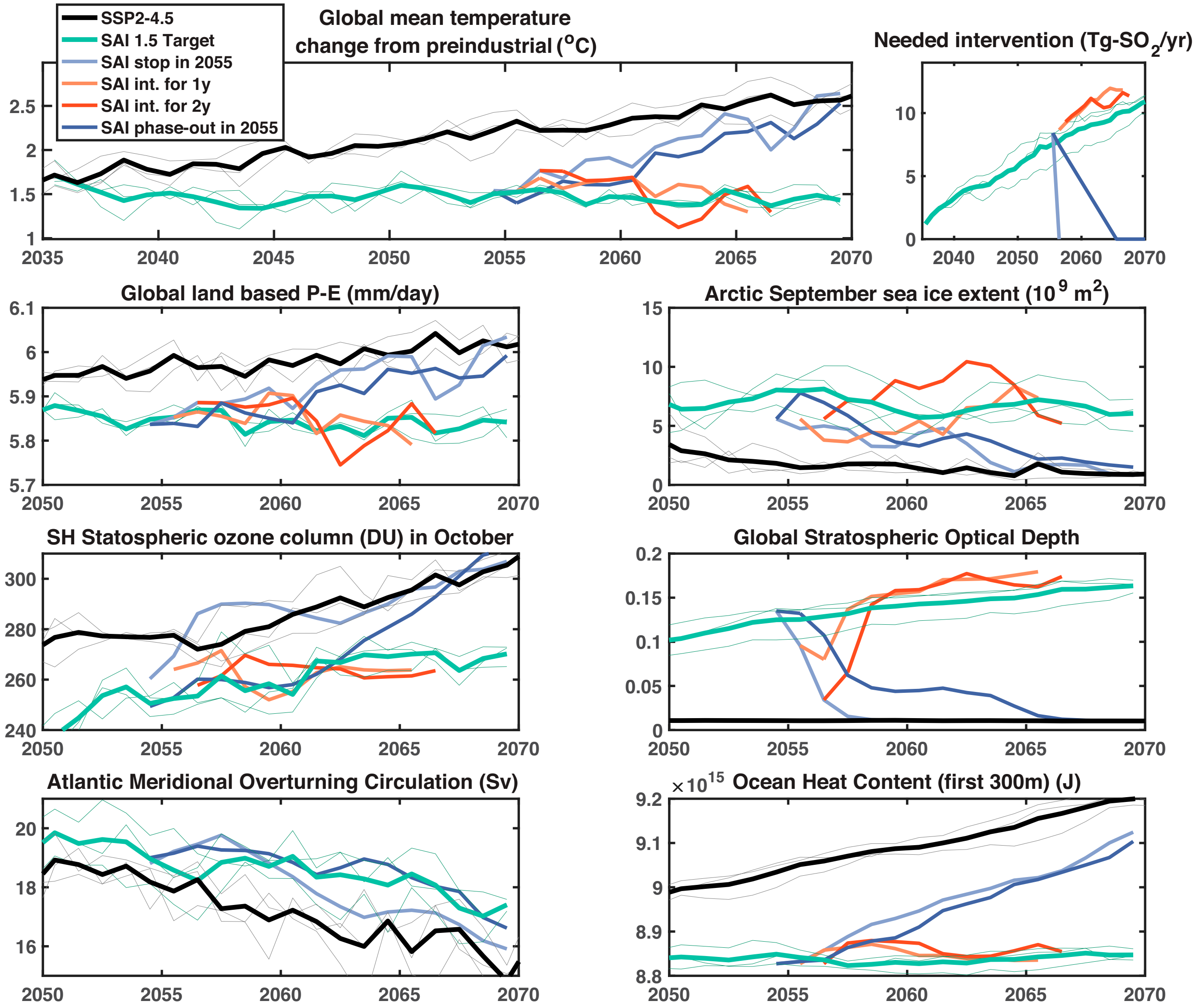

Fig. 4. High-level results from simulations of different events—termination, interruptions, or a deliberate gradual phaseout. As in Fig. 3.

As noted earlier, some scenarios or aspects of scenarios are currently missing; this is, of course, an inevitable consequence of finite computational and human time. These include, for example, a broader range of possible inconsistencies in deployment, although the characteristics of these may be adequately captured by what we have included. Perhaps more critical is to articulate a set of scenarios to explore different deployment strategies—a deployment focused on the Arctic (49) will look different from one focused more globally or hemispherically or an "uncoordinated" case with multiple actors targeting different goals. MCB or other approaches (62) might enable even more regionally targeted approaches that are not even readily amenable to the specification here in terms of global mean temperature.

The simulations presented and analyzed herein demonstrate the importance of the choice of scenario in reaching conclusions about the effects of SRM—and, hence, the importance of carefully choosing the set of scenarios. The change in any climate metric depends on how much cooling is done; for some variables, such as Arctic sea-ice extent, there may be value in cooling below current temperatures—an entirely plausible scenario not typically represented in the literature. The effect on stratospheric polar ozone depends strongly on the presumed start date; conclusions drawn from past simulations that begin deployment in 2020 should be interpreted cautiously. Moderately short interruptions in deployment might not have significant detectable impacts, providing some basis for assessing the risk associated with inconsistencies in deployment less serious than a termination. However, a gradual phaseout over 10 y may not appreciably reduce risk relative to a termination, with implications for the potential of an exit strategy or off-ramp decades after deployment has started.

Nonetheless, while we illustrate some important trends and trade-offs, there is considerable room for further analyses. Our hope is that these simulations are useful for better understanding trade-offs between different climate impacts beyond those illustrated in Figs. 3 and 4. These include, for example, areas of key concern, such as risks of Antarctic melting contribution to sea-level rise, Arctic sea-ice loss, or permafrost thaw, along with issues where SRM might exacerbate or overcompensate climate changes (21) or create novel ones, such as increased acid-rain deposition (63) or ozone loss from sulfate SAI (64); ref. 24 already illustrates some trade-offs with different temperature targets. Regionally specific information on trade-offs will be crucial in understanding regional preferences and game-theoretic outcomes (52–54), global inequality (26), and governance challenges (65, 66). What variables simply scale with the amount of forcing (enabling projection of any other scenario with emulators), and what variables exhibit significant nonlinearity, memory, or time-dependence? If someone wanted to reduce temperatures, what are the trade-offs with how rapidly that reduction is phased in? Does a delayed start recover a similar climate state? What are the consequences from irreversibilities, such as ice-sheet melt or permafrost thaw? Is a gradual phaseout almost as problematic as a termination [e.g., for climate velocity for ecosystems (67)], as suggested here, or a plausible response option available for future people? Interruptions are arguably more likely than a permanent termination (61) and may be a useful proxy for less severe inconsistencies, and, thus, risk assessment might be more strongly influenced by the impacts of a short interruption than the impacts of a termination. Does the sudden change in forcing have unacceptable impacts on monsoon circulation, for example, where the differing time scales of land vs. ocean response matter? How robust are all of these conclusions? Conducting similar simulations in multiple climate models will be essential as an element of better characterizing uncertainty, while exploring a range of different deployment strategies, both intentionally "designed" and more ad hoc, could illuminate the importance of that dimension. Research to address all of these questions will be invaluable both to increase our understanding of the benefits and risks of SRM and as input into the important aspects on which to focus in future scenario exercises.

Data Availability. Key simulation variables, including all data used in the figures presented in this manuscript, are available through the Cornell eCommons platform (https://hdl.handle.net/1813/111357) (68). All climate-model simulation output is available at Globus https://app.globus.org/file-manager?origin_id=dc637352-3cfc-11ec-8908-417713cb3dee&origin_path=%2F; authorization is needed to access the dataset; please contact D.V. Data include both monthly mean and limited higher-frequency fields (see text, Section 3).

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