https://doi.org/10.5194/egusphere-2026-6577
Preprint. Discussion started: 30 October 2026
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Resilient Stratospheric Aerosol Injection is Cooperative

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Abstract. For stratospheric aerosol injection (SAI) to reduce climate risks across the globe without producing new or exacerbating current inequalities, it must be resilient to unpredictable or even malicious disturbances (e.g., disasters, pandemics, fascists). Two significant risks which arise from mismanaged SAI are termination shock (an abrupt termination after substantial warming is being avoided) and significant changes in large-scale tropical circulation patterns, including shifts in the Intertropical Convergence Zone (ITCZ) due to unbalanced cooling. In this paper, we use a state-of-the-art climate emulator capable of simulating the global and regional climate responses of cooperative and noncooperative SAI deployment. We show that SAI without the risk of termination shock or ITCZ shift must be a cooperative and global endeavor. Given the rapidly growing interest in SAI, a widespread understanding of the frailty of unilateral deployment and a desire for cooperation would help shape current and future discussion of geoengineering into a collaboration instead of an arms race.

1 Introduction

Stratospheric aerosol injection (SAI) is a climate intervention method that injects aerosols (such as sulfate aerosols or their precursors) into the stratosphere, where they can persist for a year or more, reflecting a portion of incoming sunlight into space and cooling the planet's surface (Budyko, 1977; Crutzen, 2006). While this can counter global warming, SAI cannot simply restore the climate to a previous state. Furthermore, all SAI strategies must contend with the fact that the cooling it applies is dependent on the presence of aerosols in the stratosphere. If an actor deploying SAI is compromised (e.g., from a natural disaster, logistics issues, or a change in political appetite), the capacity to inject aerosols may be compromised as well.

Two of SAI's biggest physical risks are termination shock and changes in large-scale tropical circulation patterns, including the Intertropical Convergence Zone (ITCZ). Termination shock is the rapid increase of temperature following a sudden cessation of SAI deployment (Goes et al. (2011); Baum et al. (2013); Parker and Irvine (2018); Trisos et al. (2018); Bhowmick et al. (2021); Ritchie et al. (2023); Farley et al. (2024)), resulting in climate velocities that may outpace the ability to adapt to or migrate away from new environments (Visser (2008); Trisos et al. (2018)). Regarding tropical precipitation patterns, if the northern and southern hemispheres warm (as under climate change) or cool (as under SAI) differently, the ITCZ shifts towards the relatively warmer hemisphere (Broccoli et al. (2006); Iles and Hegerl (2014); Jacobson et al. (2020); Zuo et al. (2019);

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Haywood et al. (2013); Ridley et al. (2015); and Hwang et al. (2013)). Most simulated SAI scenarios make efforts to avoid these two (e.g., Kravitz et al. (2015); Kravitz et al. (2017); Visioni et al. (2024); Tilmes et al. (2018); MacMartin et al. (2022); Richter et al. (2022)). Nevertheless, these scenarios are often criticized for being too idealized, with arguments that non-ideal scenarios (arguably a more likely occurrence) will demonstrate a greater probability of these important risks (Diao et al., 2024).

Here we outline an SAI deployment strategy designed for resiliency to risks known and unknown – one that can, in theory, be deployed by a single global actor but better and more reliably meets the chosen objectives when deployed by a coalition of actors. This strategy's strength is its flexibility and robustness against temperature shock and tropical circulation shift. It maintains global mean temperature (T0) and North-South temperature gradient (T1) at pre-chosen targets (see methods). It uses two injection sites (one northern, one southern), with room for redundancy in each site. The northern site can be any that decreases T1, and the southern, any that increases T1. Backup sites do not have to share these same latitudes. We also outline how a coalition of actors can cancel out or reduce impacts from the actions of a rogue unilateral SAI deployer (e.g., an autocratic state), and we outline the strategy's ability to stop global warming and avoid two of SAI's largest climate risks, even when faced with politics and self-interest within coaligned deployers.

This strategy is designed to address common issues in geopolitics, where disagreements between great powers are constant, and alignment between the global community is fraught with varying levels of conflict. A question central to this strategy's development was whether it could generate deployment scenarios that existed between cooperating middle powers, that resulted in global net benefits, and that held the intrinsic ability to be resilient to control by great-power intervention.

2 Methods

We use the Climate Intervention Dynamical EmulatoR (CIDER) (Farley et al., 2026) configured to emulate two models. The first model emulated is the fully-coupled Community Earth System Model version 2 with the Whole Atmosphere Community Climate Model version 6 (CESM2-WACCM6) (Danabasoglu et al., 2020) with middle atmosphere chemistry (Davis et al., 2023) and a high top (∼140 km). Its meridional resolution is 0.95°, its zonal resolution is 1.25°, and it uses 79 vertical layers extending up to 10.5 hPa. For CESM2-WACCM6, pre-industrial (PI) temperature is defined as in MacMartin et al. (2022), with the 2020–2039 average global mean temperature defining 1.5 °C above PI. A second model, emulated in the supplemental material, is the U.K. Earth System Model (UKESM1) (Sellar et al., 2019), using Hadley Centre Global Environment Model version 3 with the global coupled configuration (HadGEM-GC3.1) (Kuhlbrodt et al., 2018)(as its atmosphere-land-ocean-sea ice model with the Met Office Unified Model (UM) as its atmospheric component, United Kingdom Chemistry and Aerosol (UKCA) chemistry model (Mulcahy et al. (2018); Archibald et al. (2020)) as its chemistry model with troposphere-stratosphere chemistry and coupling to a multi-species Global Model of Aerosol Processes (GLOMAP) modal aerosol scheme (Mann et al., 2010). Its meridional resolution is 1.25°, its zonal resolution is 1.875°, and it has 85 vertical layers extending up to 85 km. Pre-industrial is defined as in Henry et al. (2023), with the 2014–2033 average global mean temperature defining 1.5°C above PI.

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CIDER functions by linearly adding scaled patterns, an assumption which mostly holds (Farley et al., 2026). One exception to this is that CIDER does not model the dynamics of ocean circulation, so aspects of ocean circulation like SAI's effect on the strength of the Atlantic Meridional Overturning Circulation (AMOC) are not fully captured. For more details on how AMOC and injection location affect each other, see Lee et al. (2026). CIDER, as used here, also does not have variability, but we are controlling the mean over multi-year timescales, and variability's impact on the control's efficacy is minimal. Other forms of uncertainty are difficult to resolve at present, for example, how well CESM2-WACCM6 captures the globe's true temperature response to a given amount of SAI forcing.

In principle, any two variables can be targeted simultaneously with two degrees of freedom, so long as they are not directly conflicting with each other (e.g. global mean temperature and precipitation, see Lee et al., 2020); they behave relatively the same as described in this paper. Global mean temperature T0 and North-South temperature gradient T1 are chosen for ease of communication and for their having precedent use in the field. Like in Kravitz et al. (2016), they are calculated as follows:

$$T_0 = \frac{1}{A}\int_{-\pi/2}^{\pi/2} T(\psi)\mathrm{d}A$$

$$T_1 = \frac{1}{A}\int_{-\pi/2}^{\pi/2} T(\psi)\sin\psi\mathrm{d}A$$

Where ψ is the latitude, and A is the area-weighted latude, i.e.

$$\mathrm{d}A = \cos\psi\mathrm{d}\psi \rightarrow A = \int_{-\pi/2}^{\pi/2} \cos(\psi)\mathrm{d}\psi = 2$$

3 Managing Global Mean Temperature and North-South Temperature Gradient

We first examine how each latitude of injection affects T0 and T1 in a unique way. Figure 1 shows the seven different latitudes of SO2 injection, plotted in terms of their effects on T0 (horizontal axis) and T1 (vertical axis). We can see that all latitudes cool T0, but some (southern hemisphere injections) increase T1, and some decrease T1.

The core of this strategy is as follows: with a site that increases T1 and a site that decreases T1, there is almost always a way to reach a desired combination of T0 and T1 targets by combining the two sites. Figure 2 shows four different configurations. Figure 2a shows that given a certain T0-T1 goal, it is possible to reach it by various configurations of latitudes; hemispherically symmetric injection is unnecessary. Figure 2b shows one aspect of resilience: given the same T0, T1, and northern hemisphere deployment, but different southern hemisphere latitudes the same objective can still be met. This is useful for initial partnering of deploying actors, but also for purposes of redundancy – if one site or actor is lost, its replacement need not be at the same latitude. Also, 2a and 2b mean that if injection capacity is not a limiting factor, a deploying scheme can swap latitudes without losing its T0 or T1 goals (though there are dynamics; see Figure 3). Figures 2c and 2d show that a fixed combination of latitudes

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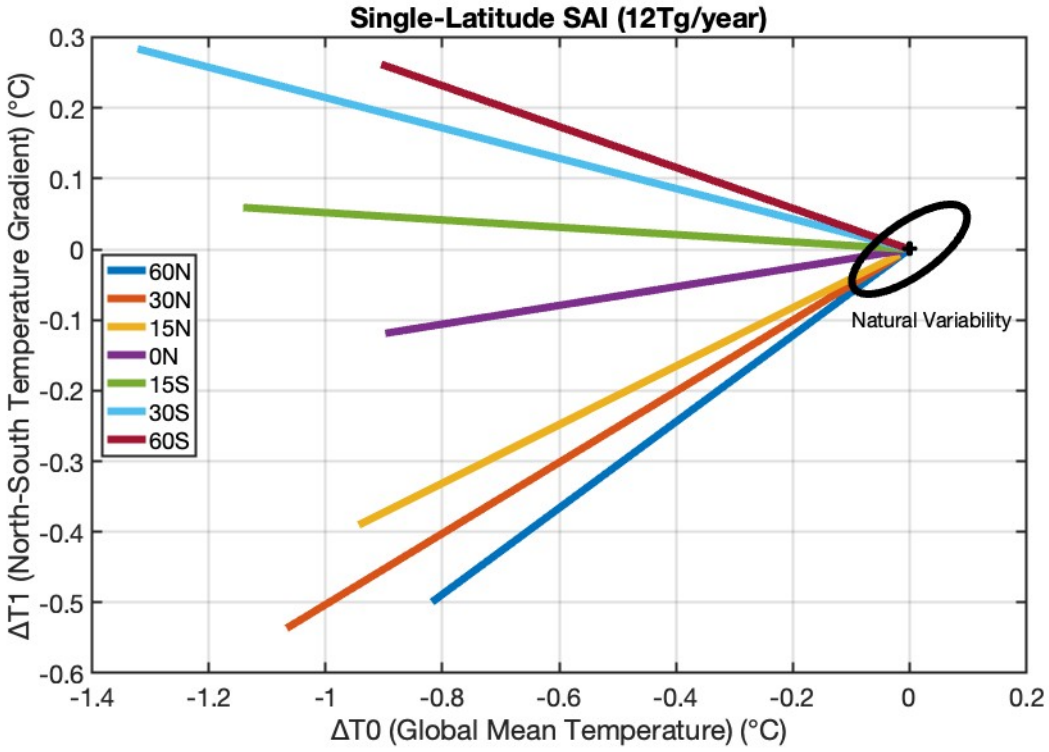

Figure 1. The sudden and sustained injection of 12 Tg/year SO2 at seven different latitudes for 35 years, emulated in CIDER. The colored lines extending from the origin use CIDER emulating CESM2-WACCM6, and the black ellipse represents 1 standard deviation of annual natural variability from CESM2-WACCM6. The horizontal axis shows the change in global mean temperature (T0) from the background that occurs because of the injection, and the vertical axis shows the change in North-South temperature gradient (T1) (see methods). Although there exists uncertainty in the precise magnitude CESM2-WACCM6's and CIDER's T0 and T1 responses to SAI, the sign is expected to be robust (i.e. all SAI cools T0, Northern hemisphere injection decreases T1, and Southern hemisphere injection increases T1).

can shift its T0 or T1 target around (cool/warm and move the ITCZ position) without needing to change the latitudes or the other target. Figure 2c shows changing T1 without changing T0, and Figure 2d shows changing T0 without changing T1. It is likely that deployers will not initially know how much their injections will shift T0 and T1 in the real world (e.g., MacMartin et al. (2014); Kravitz et al. (2016)). Figures 2c and 2d show that adjustments are possible mid-deployment.

Figure 3 shows how the addition and removal of 1 Tg of SO2 injection at various locations changes the global mean temperature and N-S temperature gradient. All deployments cool T0, and all removals of deployments warm T0, up to the maximum of zero deployments. Because the climate takes a bit of time to respond to any given change, the x's and o's mark some temporal milestones (see caption) of addition and removal, respectively. One could think of this plot as a "steering wheel" of sorts, with which a deployer can course-correct and plot a trajectory towards a particular T0-T1 target. Doing so better accounts for the system's dynamics than Figures 1 and 2. It is also useful to think of Figure 3 as a map of "shocks"

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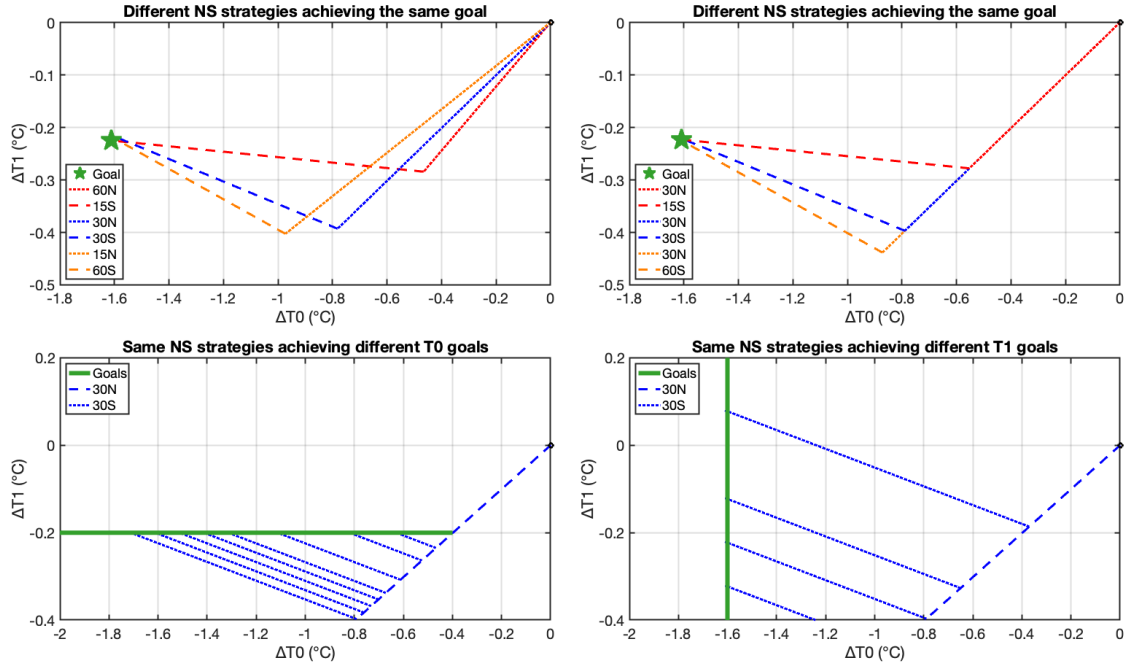

Figure 2. Showing the addition of different combinations of injection and the implications of Figure 1. All plots are made using CIDER emulating CESM2-WACCM6. Figure 2a: Different combinations of northern hemisphere injection latitudes and southern hemisphere latitudes achieving the same change in global mean temperature (T0) and North-South temperature gradient (T1). Figure 2b: A sample northern hemisphere injection latitude combined with different southern hemisphere latitudes, achieving the same change in global mean temperature (T0) and North-South temperature gradient (T1). Figure 2c: A fixed two latitudes achieving a range of global mean temperature (T0) targets while maintaining a particular North-South temperature gradient (T1). Figure 2d: A fixed two latitudes achieving a range of North-South temperature gradient (T1) targets while maintaining a particular change in global mean temperature (T0).

and "shock absorbers". For a given shock (e.g., a new, rogue, or terminated injector), there would be a particular effect on T0 and T1 over time. By using the injection latitudes they have, a deployer can add or remove combinations of injections that compensate for or even cancel the unwanted effect.

By spreading its operation across actors with independent modes of failure from each other, a deployment can guard itself against termination shock and ITCZ shift. Figure 4 shows eight scenarios of termination. Across these eight scenarios, the difference between success and failure of deployment is whether there are two separate actors capable of injecting in the northern and southern hemispheres.

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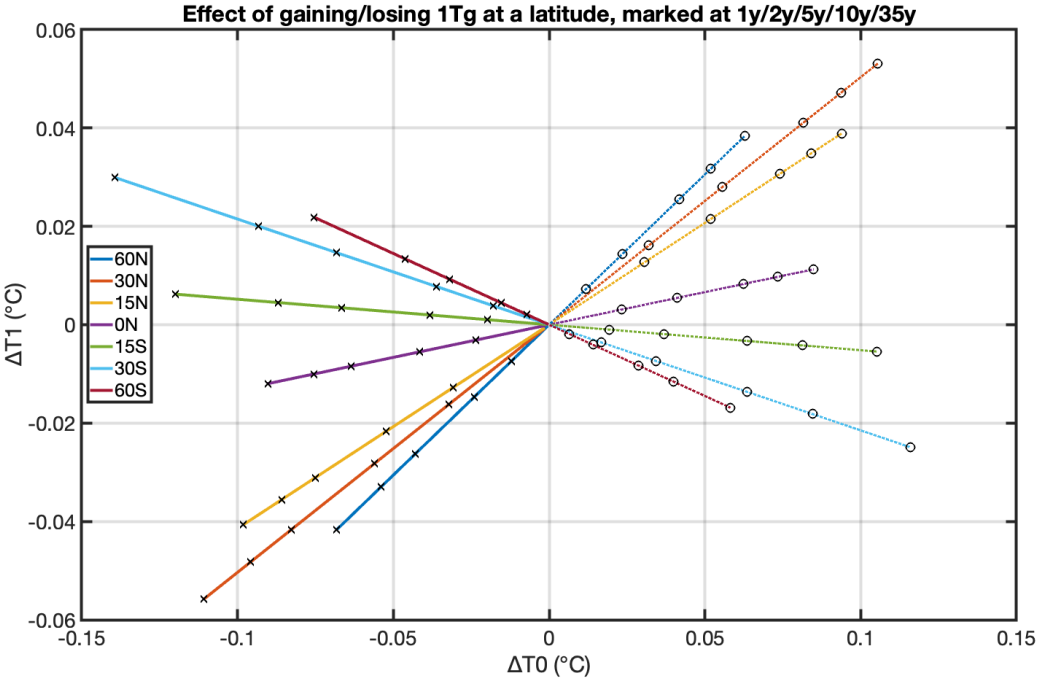

Figure 3. The effect of 1 Tg/year of SO2 as an abrupt, sustained injection at seven different latitudes for 35 years (solid line) and the effect of a sustained injection of 1 Tg/year being stopped suddenly (dotted line), with CIDER emulating CESM2-WACCM6. The horizontal axis shows the change in global mean temperature (T0) from the background that occurs because of the injection, and the vertical axis shows the change in North-South temperature gradient (T1). Starting from the origin, the marks (crosses for injection, circles for removal) show the effect after years 1, 2, 5, 10, and 35.

4 Internal Politics, Rogue Actors, and Novel Deployers

While the pursuit of global well-being is admirable and hopefully a widely held goal, it is certain that nation-states participating in a coalition will have additional priorities beyond T0 and T1. There are at least two additional (limited) degrees of freedom resulting from the choice of injection latitude, intentionally left unconstrained for flexibility and resiliency (Lee et al. (2020); Zhang et al. (2022)). However, while latitude doesn't matter for keeping a T0-T1 target, the choice of latitude creates different climate distributions, which might favour some nations or regions over others even without changing T0 or T1. Figure 5 shows this - 5a, 5b, and 5c have identical T0s and T1s, and, as such, are "successful" for the purposes of the controller's goals – avoiding termination shock and significant changes in tropical circulation pattern. A deployer's ability to compensate for the actions of a rogue deployer by adjusting their strategy has its limits, as shown in Figure 6. Based on a linear addition of available latitudes, there is a space of achievable targets (after MacMartin et al. (2013)). As long as T0 and T1 are within this cone, any actor or coalition of actors can inject using some combination of latitudes to fulfil its goals. If a rogue actor's

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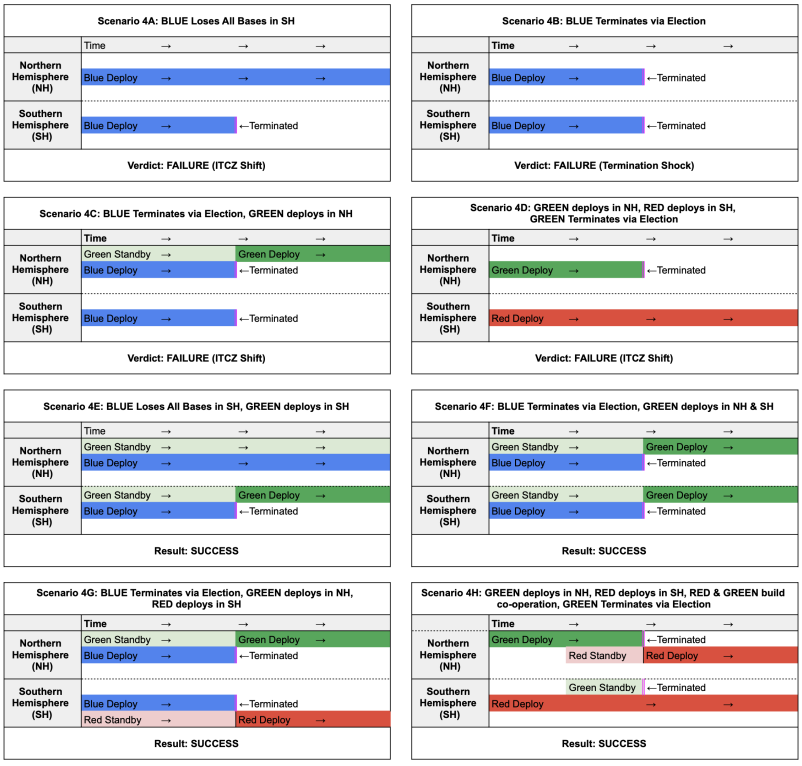

Figure 4. Four failures and four successes of SAI deployment. Figure 4a: Blue deploys in both hemispheres initially, then terminates in the southern hemisphere (SH). This shifts tropical circulation patterns and the ITCZ. Figure 4b: Blue deploys in both hemispheres initially, then terminates in both. This causes a rapid increase in global mean temperature. Figure 4c: Blue deploys in both hemispheres initially, then terminates in both. Green begins deployment at this point, but only in the northern hemisphere (NH). This shifts tropical circulation patterns and the ITCZ. Figure 4d: Green deploys in the NH, while Red deploys in the SH. Green then terminates all its injections, which shifts tropical circulation patterns and the ITCZ. Figure 4e: Blue deploys in both hemispheres initially, then terminates in the southern. Green, on standby, deploys in the SH, thus avoiding the ITCZ shift. Figure 4f: Blue deploys in both hemispheres, then terminates in both. Green, on standby, deploys in both hemispheres, thus avoiding termination shock. Figure 4g: Blue deploys in both hemispheres initially, then terminates in both. Green, on standby, deploys in the NH, and Red, also on standby, deploys in the SH. Since both deploy, neither ITCZ shift nor termination shock occurs. Figure 4h: Green deploys in the NH, while Red deploys in the SH. Green and Red help each other establish the capability to inject into the opposite hemisphere, which goes on standby. Green then terminates all its injection, and Red deploys in the NH and avoids the ITCZ shift.

maximum capacity to inject lies within this cone, the coalition strategy will always be able to account for the rogue and meet the T0-T1 objective. The rogue actor may still achieve their specific goals – if they deploy at a new latitude, a new degree of freedom appears, so a new target could be simultaneously fulfilled, as long as it is not T0 or T1. The ability to add additional degrees of freedom is limited, depending on the level of cooling (Zhang et al., 2022).

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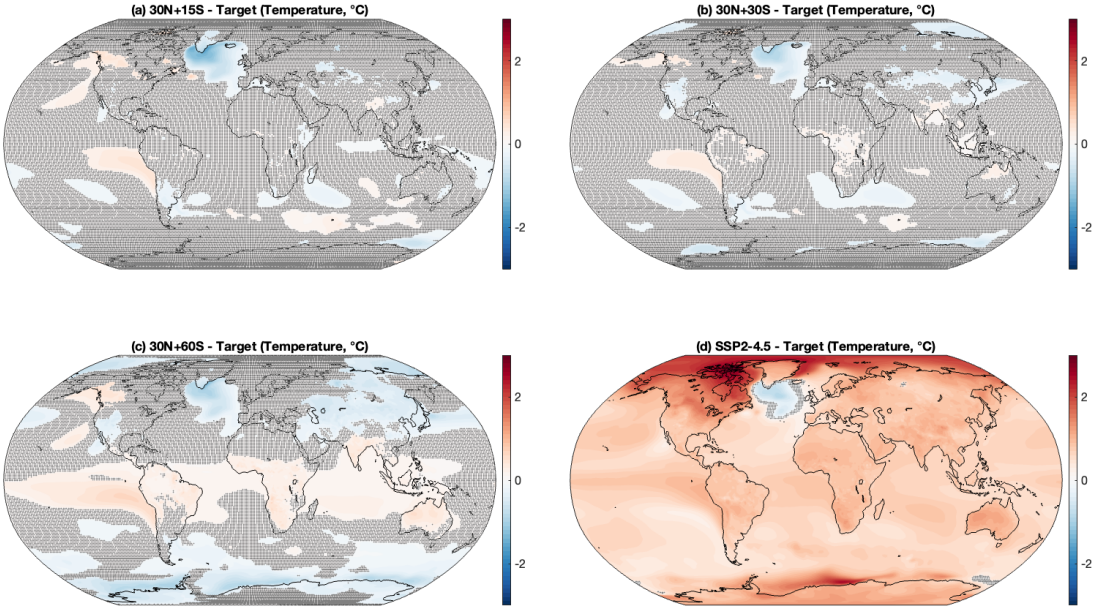

Figure 5. 20-year averages (from 2050-2069) temperature difference in °C between a scenario and its reference (2035) when attempting to fully offset the change in global mean temperature (T0) and North-South temperature gradient (T1) from SSP2-4.5, beginning in 2035. Grey stippling marks where the change in temperature is smaller than two standard errors. Figure 5a: A strategy using 30°N and 15°S to maintain T0 and T1. Figure 5b: A strategy using 30°N and 30°S to maintain T0 and T1. Figure 5c: A strategy using 30°N and 60°S to maintain T0 and T1. Figure 5d: SSP2-4.5, with no SAI.

Actors will have varying degrees of ability to engage in deployment. 'Low-capacity' actors will be constrained by factors such as financial capacity, research potential, and aerospace technology. Meanwhile, 'high-capacity' actors will have the means to deploy at sufficient scale to exert influence potentially beyond the means of other powers to respond (see Figure 6). For instance, a high-capacity actor such as the United States likely could utilize its military industrial complex to develop and deploy launch systems rapidly and at scale; a middle power such as the United Kingdom or Germany (or perhaps a private actor such as SpaceX) could certainly engage in deployment, however with limitations on both speed and scale; finally, a low-capacity actor such as Stardust Solutions (an Israeli-US startup developing SAI technologies) could likely not engage in deployment on their own. A myriad of additional variations arise when considering alliances of middle powers, or low-capacity actors sponsored by great-powers, enabling them to engage in deployment beyond their individual capacity. A rogue actor with high-capacity to inject, as illustrated in Figure 6 by points outside the cone, is far harder for this strategy to accommodate than a rogue actor with low-capacity. While the ability for a high-capacity rogue actor to dictate global outcomes is concerning, it is reflected in contemporary geopolitics, where great-powers often dictate global economic, social, and environmental priorities;

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the ability for coalitions to form to combat great-powers, both in contemporary geopolitics and in this model, demonstrates the ability for coalitions of smaller powers to align to combat these effects. Additionally, Figure 6 shows that the climate effects from even high-capacity actors take time to develop, only breaching the cone after a number of years, depending on latitude and magnitude. In other words, a rogue actor's ability to cause a disruption is also tempered by the inertia of the climate system.

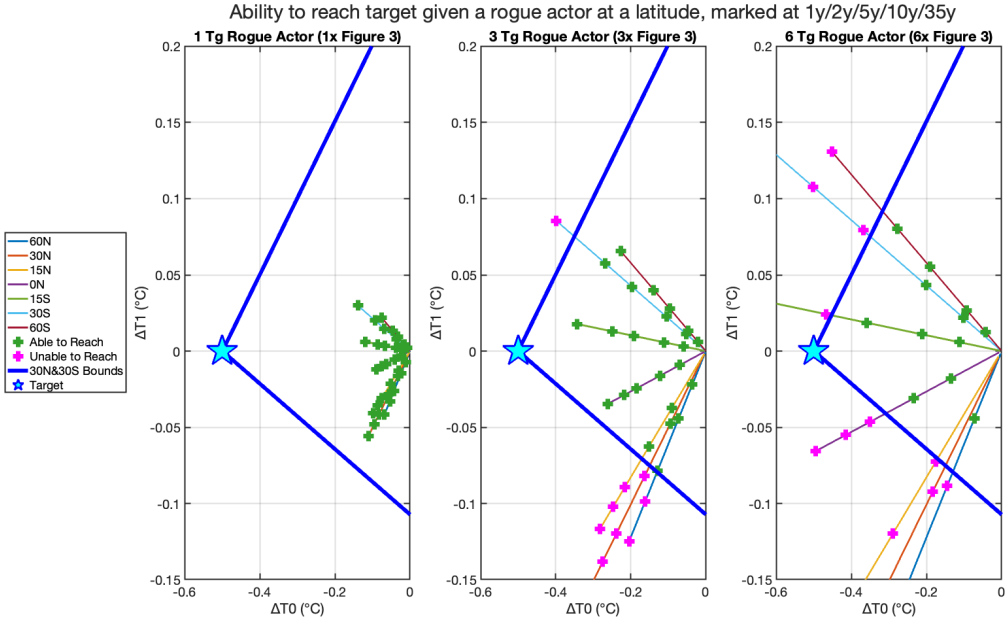

Figure 6. One example of the ability for a deployed actor to meet their target, even with a rogue actor (and the limits of that ability). The example actor is shown as the rightwards-facing blue cone, using 30°N and 30°S as the injection latitudes, and their goal (the star) is 0.5°C of cooling with no change in North-South temperature gradient. The rogue actor is shown with the leftwards-facing lines, using the same convention as in Figure 3. Starting from the origin, the crosses represent the effect of the injection at 1 year, 2 years, 5 years, 10 years, and 35 years. A green cross represents that the example blue actor is able to use 30°N and/or 30°S to reach their goal, and a magenta cross represents that there is no way for the blue actor to use 30°N or 30°S to achieve its goal. From left to right, the figures show a 1 Tg SO2/year rogue actor, a 3 Tg SO2/year rogue actor, and a 6 Tg SO2/year rogue actor.

5 Discussion

This paper assumes the existence of actors who have motivations and priorities that include possessing the ability to harm others (and using it, even at a direct cost to themselves), as well as goals which may seem inscrutable due to complex geopolitics and strategic interests. This strategy is designed with the intention of making these 'attacks' more difficult. In a world where SAI is deployed, bad actors must be taken as seriously as a global threat as climate change itself; after all, they can try to cause it. If geoengineering is deployed, we believe the ones who should get to control the climate are those with an interest in

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global well-being. We wanted to encourage cooperation, coalition, and democratic decision-making, rather than control by a hegemonic superpower. In fact, we wanted a strategy that would be difficult for a single actor to shut down (whether from fear of chemtrail conspiracies or fear of something being outside its control).

Additionally, we hope that this strategy is particularly user-friendly and encourages intention with self-imposed constraints and goals, with an understanding that each degree of freedom allows about one target to be pursued. The reason the 30°N+30°S symmetric deployment, as in G6-SAI-1.5K, controls only global mean temperature is that it has only one degree of freedom. 30°N+30°S, non-symmetric, can control for up to two targets, but no more. X°N+Y°S, non-symmetric, can control for four targets. We chose T1 as our second, and to leave the third and fourth unfilled. We hope that charting a course for T0 and T1 without a transformation of basis makes communicating SAI to policymakers and non-experts simpler.

We wish to avoid global risks once this meets the real world and potentially selfish actors, so we left two degrees of freedom unconstrained to act as pressure release valves. This does not mean we like the notion of power grabs with the climate and that those with influence may try to drive it towards distributions that particularly favour themselves or an ally. Although this control algorithm itself provides no guard against this, its implementation and internal governance potentially could (and we believe should). Putting the distribution strategy in the hands of the whole coalition, not just those with the actual capability to deploy, would ameliorate this jockeying to some extent. Ideally, being able to vote on all parts of the process, including who is deploying and where, would give non-deploying members more agency over the climate they live in than they would have otherwise (more than both the world where only the deployers have a say and the world where there is no deployment whatsoever). How that vote and governance is to be carried out (e.g., how many votes each member state can cast and how one becomes a member) is beyond the scope of our expertise and should be developed further. Another area of needed research is the actual capacities of potential actors – who has access to what technology within the coalition may end up a limiting factor to a democratic process. Regardless, a diversification of assets like launch vehicles, such that no one actor can have a chokehold on the entire operation, is advised.

This N-S strategy is one that is potentially implementable in integrated assessment models, and different coalitions with different priorities may yield different results. In particular, examination of technology readiness within potential actor states and the emergence of a peer-to-coalition rogue actor should be explored. The full implications of the T0-T1 vector framework, reachability, and the ability to be reached with respect to game theory are another area of great interest. Additionally, more specific control of the ITCZ location is worth exploring.

In an increasingly multi-polar world regularly defined by conflict more than cooperation, this scenario demonstrates that collaboration between a group of aligned middle powers can produce an SAI deployment providing global net-benefits, while being resilient to disruption, and responding effectively to rogue action. The findings suggest that shocks (such as termination shock), while still of concern, are more manageable than previously understood, that cooperative action on SAI can be effective and resilient when deployed by actors beyond contemporary great powers, and that these great powers do not have complete control over any potential future SAI deployment scenarios.

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Appendix A: Emulating Multiple Earth System Models

Because CIDER can emulate any Earth System Model on which it is trained, it is relatively trivial to output figures that contain multiple emulated models. In this way, Figure A1 is a replicated Figure 1, but containing emulations of both CESM2-WACCM6 and UKESM1. Since (as mentioned in Figure 1's caption) the signs of the T0-T1 responses are robust, the results from this paper hold regardless of the underlying model. The methods shown in Figure 2 can correct for incorrect assumptions made in one's model (e.g., using CESM2-WACCM6 to predict and control a "real climate" of UKESM1) through using either feedback control or model repair.

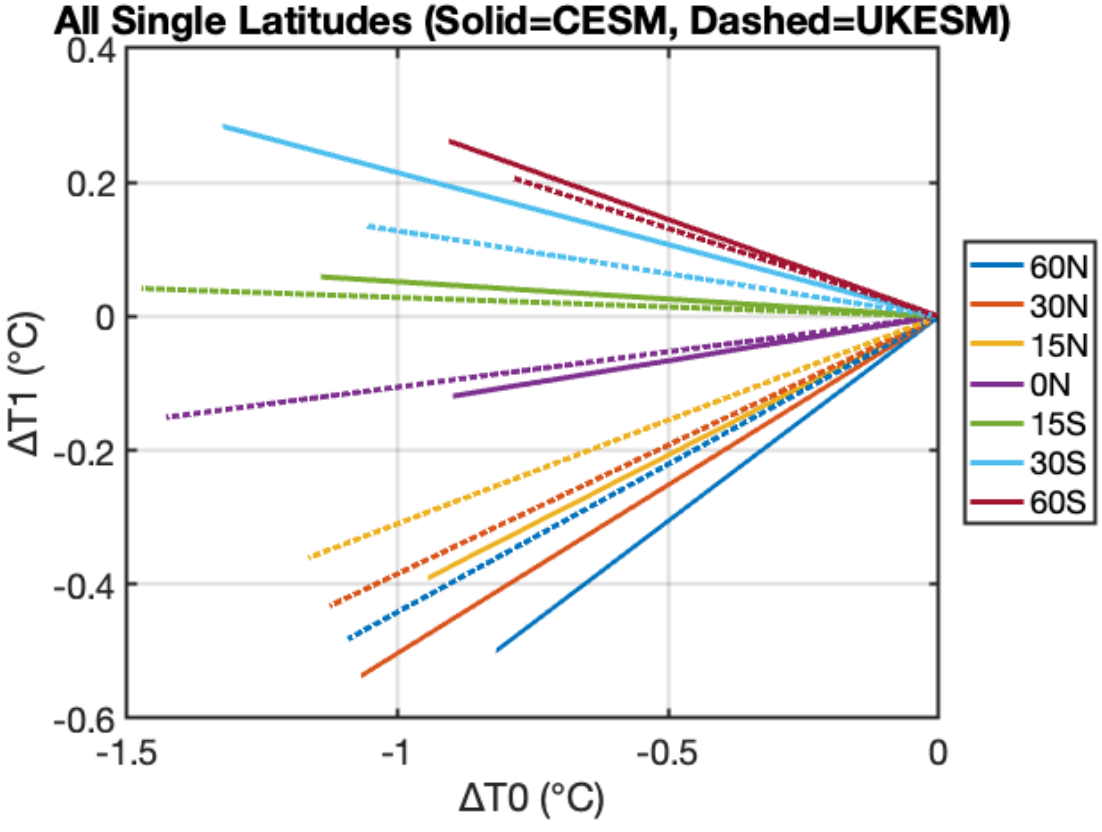

Figure A1. The sudden and sustained injection of 12 Tg/year SO2 at seven different latitudes for 35 years, emulated in CIDER. The solid lines extending from the origin use CIDER emulating CESM2-WACCM6, The solid lines extending from the origin use CIDER emulating UKESM1. The horizontal axis shows the change in global mean temperature (T0) from the background that occurs because of the injection, and the vertical axis shows the change in North-South temperature gradient (T1) (see methods).

Author contributions. JF prepared the manuscript with assistance from all co-authors.

https://doi.org/10.5194/egusphere-2026-6577
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Competing interests. BK is a member of the editorial board of ESD.

Acknowledgements. This work was partially supported by a grant from the Quadrature Charitable Foundation. Support for JF was also provided by the Cornell Atkinson Center for Sustainability. Support for BK was provided in part by NOAA's Climate Program Office, Earth's Radiation Budget (ERB) (grant no. NA22OAR4310479), and the Indiana University Environmental Resilience Institute. Support for BLP was provided by the Cadieux-Léger Fellowship with Global Affairs Canada, the Sciences and Humanities Research Council of Canada (SSHRC) Canada Graduate Scholarships – Doctoral program, the Ontario Graduate Scholarship, the Department of National Defence MINDS Scholarship Initiative, the Climate Security Association of Canada Research Fellowship, the Balsillie Doctoral Fellowship, and the University of Waterloo's President's Graduate Scholarship.

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