

Managed stratospheric aerosol injection phaseout under deep carbon removal: cross-model and aerosol-lifetime sensitivity

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Research Article

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Abstract

Stratospheric aerosol injection (SAI) has been proposed as a temporary complement to mitigation and carbon dioxide removal (CDR), but safe withdrawal depends on how rapidly greenhouse forcing falls and on the dynamics of the aerosol actuator. We execute one prespecified annual feedback controller separately in FaIR 2.2.4 and Hector 3.5.0 under matched future non-CO₂ forcing and a deliberately deep CDR stress-test pathway. In a two-layer energy-balance emulator of the SAI response, we then add a first-order aerosol-forcing reservoir with 0.67, 1.0 and 1.5 year e-folding times, spanning the approximately 8-month to 1.5-year sulfur lifetimes reported across four G6-1.5K-SAI Earth system models. Across 1,500 aerosol-lifetime-by-plant tests, median 2060 temperature is 1.200–1.206°C, no trajectory reaches the 3.5 W m⁻² command ceiling, and none of 1,192 trajectories with complete 20-year post-phaseout windows has a positive temperature trend. Phaseout emerges from the feedback law; a CO₂-indexed command ceiling never binds. FaIR and Hector temperature trajectories remain close while their long-horizon CO₂ endpoints diverge. These results show that, conditional on sustained deep CDR, no complete experiment in the tested reduced-complexity models and forcing-persistence assumptions produced a positive 20-year post-phaseout temperature trend. Regional hydrology, aerosol microphysics, ozone chemistry and governance remain outside the validated scope.

1 Introduction

Solar radiation modification (SRM) has been proposed as a temporary complement to mitigation and carbon dioxide removal (CDR), rather than as a substitute for reducing greenhouse forcing (Wigley 2006; Keith and MacMartin 2015). Feedback control of stratospheric aerosol injection (SAI) has been demonstrated in coupled climate-model experiments, including multi-objective controllers that regulate global and spatial temperature metrics (Kravitz et al. 2017; Tilmes et al. 2018a; Richter et al. 2022). A central concern is termination: if cooling is removed while greenhouse forcing remains high, rapid warming can follow (Kravitz and MacMartin 2020; Parker and Irvine 2018). This creates a control problem that is distinct from the question of whether SRM can cool the planet at all. A temporary bridge is credible only if intervention demand can decline as the underlying forcing burden declines, without creating a rebound during managed withdrawal.

Most SAI experiments hold temperature near a target under sustained or rising greenhouse forcing. The carbon-restoration case is different. If durable CDR eventually makes net radiative forcing fall, the temperature-control and atmospheric-carbon-restoration timescales can be separated: SRM can act on the faster temperature timescale while CDR acts on the slower stock of atmospheric CO₂. The resulting test is not whether SAI can permanently compensate for emissions, but whether a controller can transition from active cooling to zero intervention as CO₂ falls. Reduced-complexity climate models cannot resolve aerosol chemistry or regional circulation, but they are well suited to long-horizon carbon-cycle and feedback-control experiments and can expose whether a claimed phaseout is an artefact of a particular carbon model or actuator assumption (Kravitz and MacMartin 2020; Leach et al. 2021; Smith et al. 2024; Dorheim et al. 2024).

Here we ask three questions. First, does one prespecified annual SAI controller produce similar global-mean temperature trajectories when executed separately in FalR 2.2.4 and Hector 3.5.0 under the same emissions, CDR and non-CO₂ forcing assumptions? Second, how much of the residual temperature-target error reflects controller tuning rather than a structural climate-model limit? Third, does the phaseout result survive a more physical actuator in which aerosol forcing persists with the approximately 8-month to 1.5-year sulfur lifetimes reported across four Earth system models in the 2026 G6-1.5K-SAI GeoMIP experiment (Lee et al. 2026)? We test the third question without retuning the controller and reuse the same 500 sampled plant parameter sets as the gain-sensitivity ensemble.

The experiment is deliberately conditional on deep CDR. Deliberate removal rises to 15.2 GtCO₂ yr⁻¹ by 2043, remains at that level through 2153 and then tapers as atmospheric CO₂ approaches the preindustrial reference. These rates exceed central deployment quantities for individual CDR classes in current mitigation assessments and should be read as a stress-test pathway, not a feasibility forecast (IPCC 2021, 2022). In the no-SRM reference trajectory used by the two-layer emulator, warming peaks at 1.67°C in 2051 and falls below 1.0°C in 2229 even without SAI (Online Resource 1, Fig. S1). The experiment therefore attributes long-run cooling to CDR and tests SAI only as a temporary bridge that advances and deepens cooling while greenhouse forcing is being removed.

2 Materials and methods

2.1 Scenario architecture and carbon-removal pathway

The experiment uses the archived Planetary Restoration annual net-CO₂ trajectory from 2026 through 2183. Gross anthropogenic CO₂ declines from 42.2 GtCO₂ yr⁻¹ in 2026 to 1.5 GtCO₂ yr⁻¹ by 2051 and is then held at that residual level; permafrost and stored-carbon-reversal terms are represented separately. Deliberate CDR rises from zero in 2026 to 15.2 GtCO₂ yr⁻¹ in 2043, remains at 15.2 GtCO₂ yr⁻¹ through 2153 and then follows the inverse-FalR taper of the archived pathway. The cross-model experiment imposes 9.642612 GtCO₂ yr⁻¹ from 2184 through 2300. This is a conditional stress test and is not optimized for feasibility, cost or social acceptance. The local no-SRM screening trajectory and the executed FalR/Hector runs share the carbon assumptions but are not forced to share an identical temperature history.

2.2 Controller law and plant-mismatch ensemble

The annual controller is unavailable before 2035. Its one-sided temperature objective declines linearly from the 2035 value to 1.0°C in 2060. $K_p = 5.0 \text{ W m}^{-2} \text{ K}^{-1}$ and $K_i = 0.12 \text{ W m}^{-2} \text{ K}^{-1} \text{ yr}^{-1}$. Positive cap exceedance accumulates to an integral-state ceiling of 5 K yr; below the cap the integral state bleeds at 25% of the negative error. Command magnitude is capped at 3.5 W m⁻² and annual command change at 0.20 W m⁻² yr⁻¹. The two-layer emulator's actuator uses realized cooling magnitude $\text{efficacy} \times \text{command} / (1 + \alpha \times \text{command})$, central $\alpha = 0.12 \text{ (W m}^{-2})^{-1}$, after a one-year lag. The 500-member plant ensemble samples upper-ocean heat capacity 5–12 W yr m⁻² K⁻¹, deep-ocean heat capacity 70–150 W yr m⁻² K⁻¹, feedback 0.8–1.8 W m⁻² K⁻¹, exchange coefficient 0.4–1.0 W m⁻² K⁻¹, SAI

efficacy 0.75–1.10, saturation alpha 0.04–0.24 (W m^{-2})⁻¹ and logistics lag 1–3 year. The 500 parameter sets are independent uniform draws over these ranges (the lag drawn uniformly from the integers 1, 2 and 3), generated sequentially with NumPy's default generator and seed 7001; the drawn values are supplied in D13_ctrl_uncert.csv. The noisy ensemble additionally samples AR(1) variability, with coefficient $U(0.3, 0.7)$ and innovation standard deviation $U(0.07, 0.13)$ °C (peak commands in Online Resource 1, Fig. S2); the gain sweep and aerosol-reservoir experiment are noise-free to isolate forced control behavior. The emulator is a perturbation model: each plant parameter set governs only the response to SAI forcing, which is added to a single prescribed no-SRM temperature trajectory and CO₂ pathway, so uncertainty in CO₂-driven baseline warming is not sampled by the 500-member ensemble. In all three models the command is additionally bounded by a CO₂-indexed ceiling that declines linearly from 3.5 W m^{-2} at 300 ppm to zero at 280 ppm. This ceiling never binds in the executed FaIR and Hector trajectories or in any of the 1,500 aerosol-reservoir runs, so the phaseouts reported below are produced by the feedback law itself.

2.3 Cross-model FaIR and Hector execution

FaIR uses version 2.2.4 with the official 841-member calibrated-constrained ensemble associated with fair-calibrate 1.4.1 (Leach et al. 2021; Smith et al. 2024). A common non-CO₂ effective-radiative-forcing target is derived from the official medium-extension background and matched in FaIR with a synthetic bookkeeping species; CO₂ remains emissions-driven. The matched non-CO₂ target is exported to Hector 3.5.0 so emulator differences are not generated by different prescribed non-CO₂ forcing histories (Dorheim et al. 2024). After each annual observation, the next command is calculated from the model's own temperature and CO₂ state. In FaIR the controller observes the ensemble-median temperature of the 841 configurations and applies the same command to every member; Hector is run in its default configuration. Structural checks require annual coverage, no pre-deployment command, finite state variables and compliance with command limits. Numerical equality between models is not a pass criterion.

2.4 Gain and deployment sensitivity

The same 500 sampled plant parameter sets are rerun without AR(1) noise for $K_i = 0.06, 0.12, 0.24, 0.50, 1.0$ and $2.0 \text{ W m}^{-2} \text{ K}^{-1} \text{ yr}^{-1}$, with K_p fixed at $5.0 \text{ W m}^{-2} \text{ K}^{-1}$ and deployment starts in 2030, 2035 and 2040. Recorded outcomes are 2060 and 2100 temperature, peak command, first year at or below 1.0°C and whether the annual command-rate limit binds. The sweep is a sensitivity analysis, not an optimization or deployment recommendation (Online Resource 1, Note 2).

2.5 GeoMIP-constrained aerosol-reservoir validation

The aerosol-reservoir experiment, run in the two-layer emulator rather than in FaIR or Hector, adds a first-order aerosol/forcing state A after the logistics delay. For annual time step $dt = 1$ year and lifetime τ , $A(t + 1) = \exp(-dt/\tau)A(t) + [1 - \exp(-dt/\tau)]F_{eq}(\text{command}_{in})$, where F_{eq} is the same saturated equilibrium-forcing magnitude used by the baseline actuator. Radiative forcing applied to the two-layer plant is $-A$. We test $\tau = 0.67, 1.0$ and 1.5 year, spanning the approximately 8-month to 1.5-year sulfur

lifetimes reported across four G6-1.5K-SAI models (Lee et al. 2026). τ is a forcing-persistence proxy informed by those sulfur-burden lifetimes: the lifetime of radiative forcing is not identical to sulfur residence time because aerosol size evolution and microphysics alter optical properties. No controller parameter is retuned. The three lifetimes are crossed with all 500 previously sampled plant parameter sets. Physical phaseout is defined as the first year after prior activation for which the reservoir-forcing magnitude remains below 0.01 W m^{-2} . A 20-year post-phaseout OLS trend is reported only when the full window lies within the 2026–2300 simulation; late phaseouts are unclassified rather than treated as stable. For these, a 10-year OLS trend is reported as a supplementary diagnostic. Over-cooling is measured as the mean margin by which temperature lies below the cap in post-2060 years while SAI is active.

2.6 Phaseout and abrupt-withdrawal diagnostics

Planned termination is evaluated after realized physical SAI forcing has become zero (executed emulators) or fallen below 0.01 W m^{-2} (reservoir validation) following prior activation. Noise-free 10- and 20-year OLS temperature trends are used to avoid interpreting annual variability as termination shock. Abrupt-withdrawal sensitivities force command to zero in 2060 or 2100 and intentionally override the normal rate limit. These failure-mode experiments are kept distinct from state-dependent planned phaseout.

2.7 Literature-response envelope

Lee et al. report $0.11 \pm 0.01^\circ\text{C}$ global cooling per $\text{Tg SO}_2 \text{ yr}^{-1}$ across the four G6-1.5K-SAI models and a $0.11 \pm 0.04 \text{ mm day}^{-1}$ global precipitation reduction while cooling approximately 1.4°C (Lee et al. 2026). We use these values only to express the central reduced-model cooling on a contemporary coupled-model response scale. They are not used to convert the controller's W m^{-2} command to injection mass, to select injection latitude or altitude, or to predict regional precipitation.

2.8 Code, data and reproducibility

The exact code and workflow artifacts for the archived FalR/Hector trajectories are publicly available at <https://github.com/bcjohnjr/Planetary-Restoration-V70>, GitHub Actions run 35504044968, commit cf0fca1278441605dfec86ce56cc2a989aa3ef0c. The GeoMIP-constrained aerosol-reservoir validation was externally executed at <https://github.com/bcjohnjr/Planetary-Restoration-Model-V73>, GitHub Actions run 35560532219, commit 668677c2423f103ae2c324277fe1570423db8f46; the successful run produced artifact 10621583541, SHA-256

165328fef5a6294bca33f6e2347f19218a719f06c639bda8323191e1fe9adeb. The artifact outputs reproduce all reported aerosol-reservoir summary metrics to displayed precision and are included in the submission package, together with a script (C13_phaseout_diagnostics.py) that computes the ceiling-binding, over-cooling and late-phaseout diagnostics. The aerosol-reservoir experiment has no external data-download dependency. The public repositories and archived workflow identifiers provide the provenance used in this submission and are documented in Online Resource 1 (Note 5). All code, input data, model outputs and downloaded workflow artifacts used in this study are consolidated in a single

public repository, <https://github.com/bcjohnjr/climate-aerosol> (commit 03ecf05f25d946c41f5de7ad5ac0e04332a2a754). C14_make_figures.py regenerates all figures, including the abrupt-withdrawal trajectories of Fig. 4 (D37_abrupt_withdrawal_timeseries.csv).

Generative AI assistance. OpenAI ChatGPT was used under the author’s direction for literature discovery, code drafting, quantitative cross-checks, language editing, document restructuring and preparation of submission files. The author independently reviewed the source literature, model assumptions, code, numerical outputs and final manuscript and retains responsibility for all content.

3 Results

3.1 Cross-model controller transfer

SAI is unavailable before 2035. The one-sided temperature cap declines from the 2035 climate state to 1.0°C in 2060. The controller uses $K_p = 5.0 \text{ W m}^{-2} \text{ K}^{-1}$ and $K_i = 0.12 \text{ W m}^{-2} \text{ K}^{-1} \text{ yr}^{-1}$, a 3.5 W m^{-2} command ceiling, a 0.20 $\text{W m}^{-2} \text{ yr}^{-1}$ command-rate limit and a one-year actuator lag. With these prespecified gains, annual closed-loop execution produces closely aligned temperature trajectories in the two reduced-complexity emulators despite different carbon-cycle structures (Fig. 1). FaIR reaches 1.189°C in 2060 and Hector 1.178°C, a difference of 0.011°C. At 2100 the difference is 0.044°C. Peak command magnitudes are 1.326 and 1.491 W m^{-2} , respectively.

The close temperature agreement does not imply that the prespecified controller exactly tracks the target. Both models retain a positive 2060 offset. A prespecified sensitivity sweep using the same 500 sampled plant parameter sets, without annual AR(1) noise, shows that the offset is strongly gain-dependent (Fig. 2). For a 2035 start, median 2060 temperature declines from 1.190°C at $K_i = 0.12$ to 1.158°C at $K_i = 0.24$, 1.117°C at $K_i = 0.50$, 1.070°C at $K_i = 1.0$ and 1.035°C at $K_i = 2.0 \text{ W m}^{-2} \text{ K}^{-1} \text{ yr}^{-1}$. Stronger integral action comes at a control-cost: the fraction of members touching the annual command-rate limit rises from 0.76 at $K_i = 0.12$ to 1.00 at $K_i \geq 0.50$. Even the earliest and strongest swept case, deployment in 2030 with $K_i = 2.0$, leaves a median 2060 temperature of 1.021°C. We therefore interpret the prespecified-gain offset as a tunable controller result, not a demonstrated physical lower bound on SAI performance.

3.2 Aerosol-persistence sensitivity

The baseline actuator makes a delayed command available as effective forcing after one year. To test whether this simplification drives the result, we inserted a first-order aerosol/forcing reservoir after the logistics delay in the two-layer emulator. The reservoir e-folding time was set to 0.67, 1.0 or 1.5 year, spanning the approximately 8-month to 1.5-year sulfur lifetimes reported for UKESM, CESM, E3SM and MIROC in G6-1.5K-SAI (Lee et al. 2026). Controller gains and limits were left unchanged. The central 2060 temperature is 1.164, 1.164 and 1.166°C across the three lifetimes, while peak commands are

1.147, 1.150 and 1.164 W m⁻² (Fig. 3). The small spread indicates that the controller compensates for persistence over this published lifetime range without approaching its command ceiling.

We then crossed the three aerosol lifetimes with the 500 plant parameter sets, yielding 1,500 noise-free actuator-physics tests (summarized by lifetime in Online Resource 1, Table S1). Median 2060 temperature is 1.200°C for $\tau = 0.67$ year and 1.206°C for $\tau = 1.0$ and 1.5 year. The corresponding 5–95% ranges are 1.149–1.248, 1.151–1.255 and 1.155–1.255°C. Median peak command rises only from 1.415 to 1.433 W m⁻² across the lifetime range; no trajectory reaches the 3.5 W m⁻² ceiling. Median maximum cap exceedance remains 0.207–0.208°C. Thus the long-horizon bridge is not dependent on an assumption that aerosol forcing disappears immediately after each annual command.

The complete aerosol-reservoir experiment was executed in a clean GitHub Actions environment without code or parameter changes (public run 35560532219 in bcjohnjr/Planetary-Restoration-Model-V73, commit 668677c2423f103ae2c324277fe1570423db8f46, artifact 10621583541, SHA-256 165328fef5a6294bca33f6e2347f19218a719f06c639bda8323191e1fe9adeb). The external run reproduced every reported summary metric to the displayed precision; the largest numeric difference from a local execution was approximately 1×10^{-16} , attributable to last-bit floating-point evaluation.

As an external scale check rather than a mass-forcing conversion, we divide the central reduced-model cooling by the G6-1.5K-SAI multi-model response of $0.11 \pm 0.01^\circ\text{C}$ per Tg SO₂ yr⁻¹ (Lee et al. 2026). The maximum cooling corresponds to about 4.6 Tg SO₂ yr⁻¹ on that published response scale, below the 10–20 Tg SO₂ yr⁻¹ range in which earlier modelling often finds declining injection efficiency (Niemeier and Timmreck 2015; Lee et al. 2026). This comparison does not specify an injection strategy and does not validate aerosol optical depth, microphysics or chemistry; it only tests whether the magnitude of the modeled global cooling is grossly outside a contemporary coupled-model response envelope.

3.3 Managed phaseout and abrupt withdrawal

In the executed FaIR and Hector trajectories, SAI demand declines as CO₂ falls and realized forcing reaches zero from 2267 and 2269, respectively. The decline is produced by the feedback law; the CO₂-indexed ceiling never binds. Their subsequent 20-year ordinary-least-squares temperature trends are -0.00335 and $-0.00289^\circ\text{C yr}^{-1}$. In the aerosol-reservoir validation, central physical forcing falls below 0.01 W m⁻² after prior activation in 2263 for all three lifetime cases, with 20-year trends of -0.00321 to $-0.00315^\circ\text{C yr}^{-1}$. Across the 1,500 plant-by-lifetime tests, 1,192 have enough simulation time after physical forcing falls below 0.01 W m⁻² to calculate the prespecified 20-year diagnostic; none of these complete-window cases has a positive trend. The remaining 308 cases phase out too near the 2300 horizon for classification and are not counted as stable. These late-phaseout cases are not a random subset: their mean SAI-response feedback parameter is 1.62 versus 1.23 W m⁻² K⁻¹ for classified cases, and their mean efficacy 0.86 versus 0.93. Of the 305 with a complete 10-year window, 303 have negative 10-year trends; the other two are positive by at most $4 \times 10^{-5}^\circ\text{C yr}^{-1}$ (0.0004°C per decade; Online Resource 1, Note 6).

The one-sided controller also over-cools. Because the integral state bleeds at only 25% of the negative error, SAI remains active long after temperature first falls below the cap (2137 in FaIR, 2127 in Hector). While SAI is active after 2060, temperature lies on average 0.156°C (FaIR) and 0.142°C (Hector) below the 1.0°C cap; the median across the 1,500 reservoir runs is 0.153°C. This is intervention beyond what the cap requires and is a tunable property of the integral-bleed rule rather than a physical requirement.

These planned-phaseout results should not be conflated with termination shock. Separate failure-mode experiments force the command to zero in 2060 or 2100 while substantial greenhouse forcing remains, overriding the normal rate limit. Those abrupt stops produce transient warming (Fig. 4), consistent with the established termination literature (Parker and Irvine 2018). The difference is state-dependent: managed withdrawal occurs only after the CDR pathway has reduced the warming burden, whereas abrupt withdrawal removes cooling while that burden remains high.

Carbon-cycle uncertainty is more consequential for the endpoint than for temperature-control transfer. Under the common post-2183 removal schedule, FaIR reaches 279.3 ppm CO₂ in 2300 whereas Hector remains at 285.7 ppm. FaIR crosses 280 ppm in 2297; Hector does not reach 280 ppm within the simulation horizon. The same open-loop removal schedule is therefore insufficient to guarantee a model-robust preindustrial CO₂ endpoint even though the SAI controller can be phased out in both models.

4 Discussion

The experiments separate two quantities that are often conflated in debates about temporary solar geoengineering: the time needed to suppress a temperature excursion and the time needed to remove the atmospheric carbon stock that caused it. In this conditional pathway, feedback-controlled SAI operates on the first timescale while CDR works on the second. The central result is not that SAI solves climate change, but that once greenhouse forcing has fallen sufficiently, managed phaseout produced no positive 20-year post-phaseout temperature trend in any complete experiment. That result transfers between two independently developed reduced-complexity carbon-climate models and remains stable when the emulator's actuator is given aerosol persistence spanning the four-model G6-1.5K-SAI sulfur-lifetime range.

The validation also narrows what is and is not robust. Temperature-control trajectories transfer more closely than atmospheric CO₂ endpoints: FaIR and Hector differ by only 0.011°C in 2060 under the prespecified controller yet differ by 6.4 ppm CO₂ in 2300. The 500-member emulator ensemble shares one prescribed no-SRM temperature trajectory, so its post-phaseout trends test the decay of the SAI perturbation against that trajectory; uncertainty in CO₂-driven warming enters only through the FaIR and Hector runs. Deep-restoration claims therefore require adaptive CDR rules or cross-model endpoint constraints rather than a removal schedule calibrated to one carbon cycle. Conversely, the aerosol-reservoir test suggests that the phaseout result is not an artefact of assuming an instantaneous radiative actuator. The controller tolerates 0.67–1.5 year forcing persistence without saturation of the

command ceiling, although stronger coupled-model tests are needed before this can be interpreted as engineering feasibility.

Global-mean temperature control is not climate restoration. G6-1.5K-SAI shows that SAI cools land more than ocean and that models disagree on residual Arctic amplification and tropical precipitation; the same experiment reports a mean global precipitation reduction of 0.11 ± 0.04 mm day⁻¹ while cooling about 1.4°C (Lee et al. 2026). Applying that result only as a response-scale diagnostic, the approximately 0.51°C maximum central cooling in our reservoir test corresponds to roughly -0.04 mm day⁻¹ globally. This is not a regional forecast. West African precipitation, monsoons, ozone chemistry, stratospheric heating and circulation can respond materially to injection strategy and remain unresolved here (Tilmes et al. 2018b; Visioni et al. 2020; Bednarz et al. 2023, 2026; Lee et al. 2026; Da-Allada et al. 2020; Alamous et al. 2022). SRM also does not reverse ocean acidification, so the CO₂ trajectory remains independently important.

The imposed CDR pathway is itself the largest conditional assumption. Sustained removals of 15.2 GtCO₂ yr⁻¹ would require a portfolio much larger than current deployment and would raise land, energy, water, permanence and governance constraints (IPCC 2021, 2022). The present study does not evaluate the feasibility or optimal composition of that CDR portfolio; it treats the pathway as a stress-test boundary condition for the phaseout-control question.

The next decisive validation is a coupled Earth-system experiment that applies the same state-dependent phaseout logic while resolving aerosol microphysics, ozone, precipitation and regional temperature gradients. Multi-model GeoMIP protocols provide a natural benchmark for this step. Governance should be co-developed rather than treated as a later implementation issue, especially because regional risks and benefits can be distributed unevenly and scholarship has repeatedly called for substantive Global South participation in solar-geoengineering research (National Academies of Sciences, Engineering, and Medicine 2021; Winickoff et al. 2015; Quagrainie et al. 2025). Until such tests are complete, the result should be read as a falsifiable control insight: under a sufficiently deep and sustained decline in greenhouse forcing, temporary global cooling can be tapered as a state-dependent bridge rather than terminated against a fixed high-forcing background.

5 Conclusions

In reduced-complexity climate models, a feedback-controlled SAI intervention can be tapered to zero with no positive 20-year post-phaseout temperature trend in any complete experiment when deep CDR has already reduced the underlying greenhouse forcing; this diagnostic does not imply that every individual year cools. The result transfers between FalR and Hector at the level of global-mean temperature and, in a two-layer emulator, shows the same outcome across a 0.67–1.5 year forcing-persistence range without controller retuning or command-ceiling saturation. It does not establish regional safety or deployment feasibility. The next decisive test is a coupled Earth-system

implementation that resolves aerosol microphysics, ozone, circulation, precipitation and regional temperature gradients while applying the same state-dependent phaseout logic.

Declarations

Author information and declarations

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Authorship

Jonathan Karl Bily is the sole author of this submission.

Competing interests

The author declares no relevant financial or non-financial interests to disclose.

Generative AI disclosure

OpenAI ChatGPT was used under the author's direction for literature discovery, code drafting, quantitative cross-checks, language editing, document restructuring and preparation of submission files. The author independently reviewed the final manuscript and retains responsibility for all claims, assumptions, code, data and references.

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Author contributions. Jonathan Karl Bily conceived the study, defined the SAI control and carbon-removal stress-test questions, directed the modelling and validation, interpreted the results, and prepared the manuscript.

Data and code availability. All code and data supporting this study, including the FalR and Hector trajectories, the aerosol-reservoir experiment, the phaseout diagnostics and the figure scripts, are available at <https://github.com/bcjohnjr/climate-aerosol> (commit 03ecf05f25d946c41f5de7ad5ac0e04332a2a754). The original workflow executions are also public: the FalR/Hector trajectories at <https://github.com/bcjohnjr/Planetary-Restoration-V70> (GitHub Actions run 35504044968; commit cf0fca1278441605dfec86ce56cc2a989aa3ef0c) and the aerosol-reservoir experiment at <https://github.com/bcjohnjr/Planetary-Restoration-Model-V73> (GitHub Actions run 35560532219; commit 668677c2423f103ae2c324277fe1570423db8f46; artifact 10621583541). Running C12_geomip_reservoir_validation.py, C13_phaseout_diagnostics.py and C14_make_figures.py from the climate-aerosol repository reproduces all aerosol-reservoir and phaseout-diagnostic values and all figures reported here.

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Figures

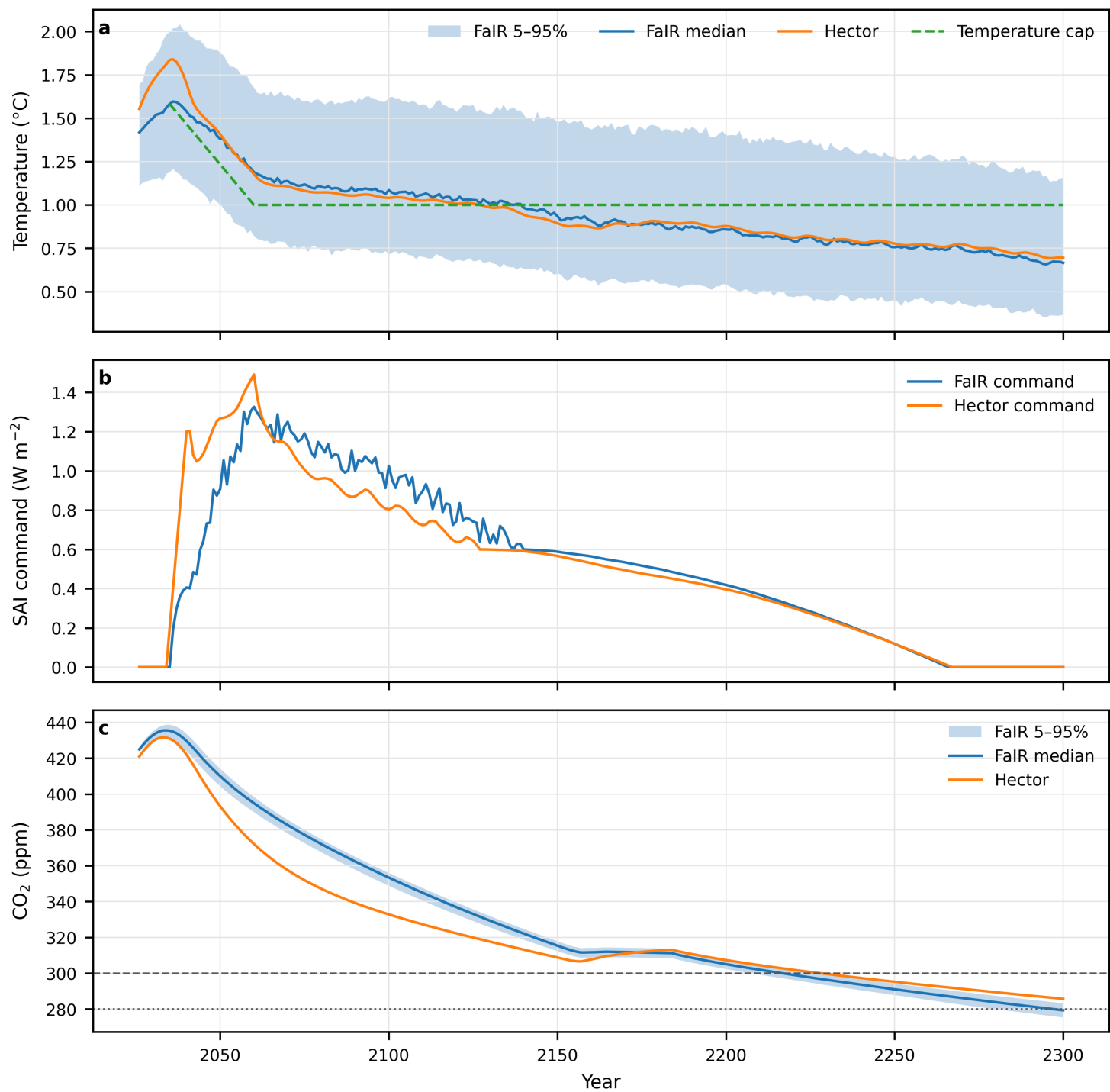


Figure 1

Cross-emulator annual closed-loop execution. Top: global-mean temperature in FaIR 2.2.4 and Hector 3.5.0 under the same controller and matched future non-CO₂ forcing; shading is the FaIR 5–95% calibrated-constrained ensemble. Middle: accepted SAI command magnitude. Bottom: atmospheric CO₂; horizontal lines at 300 and 280 ppm mark where the CO₂-indexed command ceiling begins to decline and reaches zero (it never binds). The controller transfers closely in temperature while carbon-cycle endpoints diverge

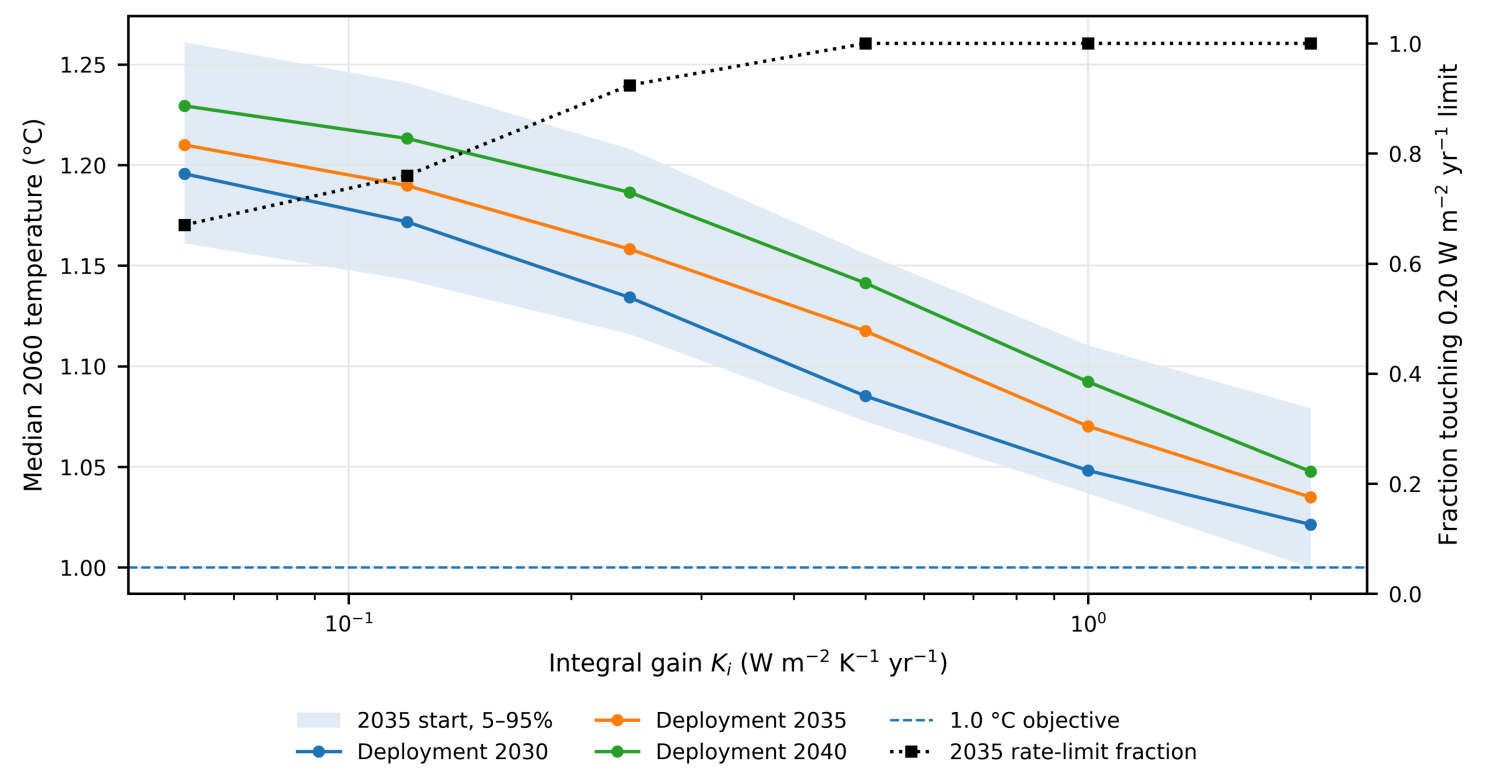


Figure 2

Controller tuning and deployment-date sensitivity. Median 2060 temperature across integral gain and deployment date using the same 500 sampled plant parameter sets without AR(1) noise; shading is the 2035-start 5–95% interval. The secondary axis shows the fraction of 2035-start members that touch the $0.20 \text{ W m}^{-2} \text{yr}^{-1}$ command-rate limit

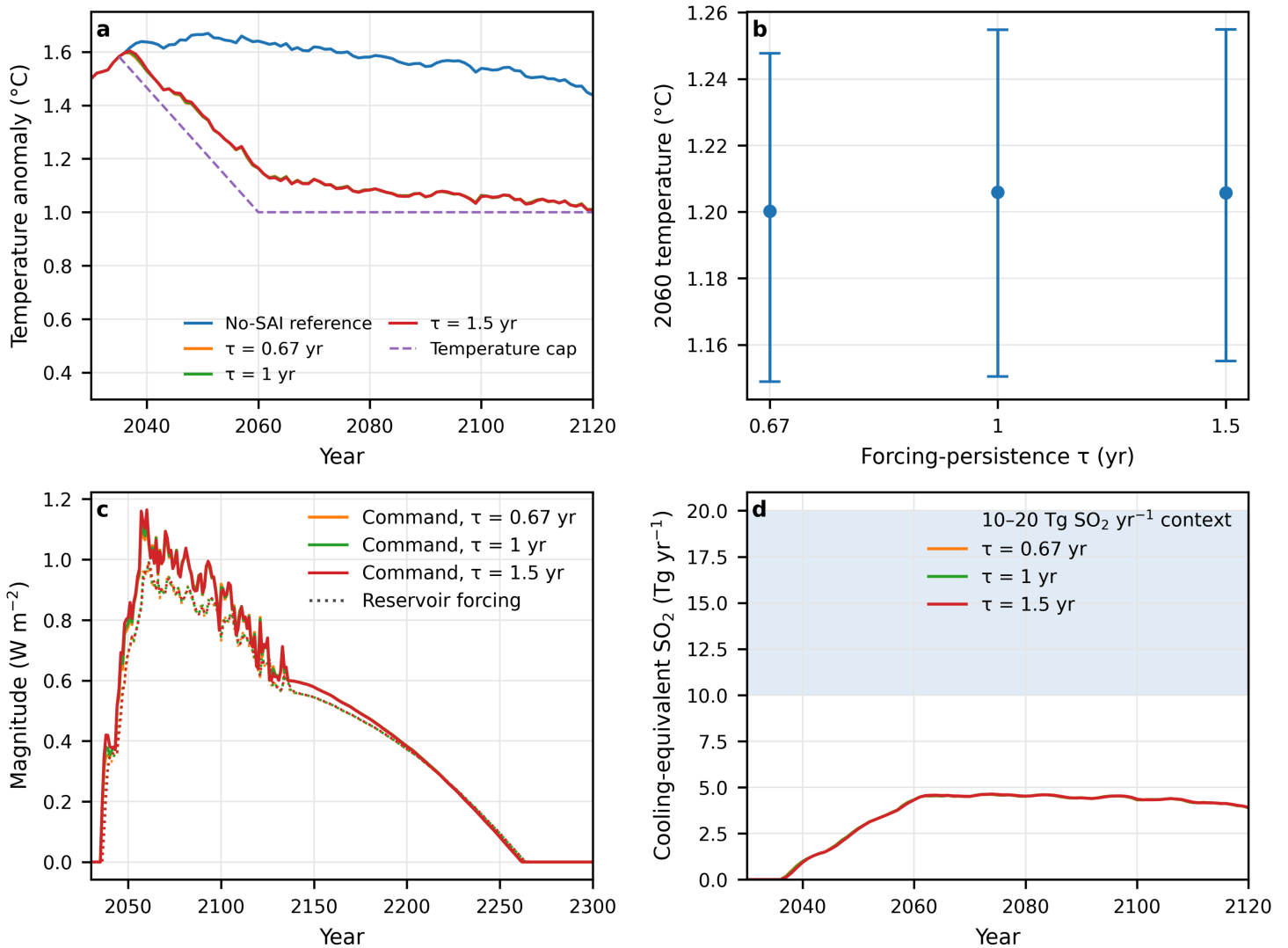


Figure 3

GeoMIP-constrained aerosol-reservoir experiment in the two-layer emulator. (a) Central controlled temperature for forcing-persistence times $\tau = 0.67, 1.0$ and 1.5 yr. (b) 2060 temperature across the unchanged 500-member plant ensemble. (c) Command and persistent aerosol-reservoir magnitude. (d) Literature-response-envelope diagnostic using the G6-1.5K-SAI cooling-per-injection relationship; the shaded 10–20 $\text{Tg SO}_2 \text{ yr}^{-1}$ band is contextual rather than an operational threshold

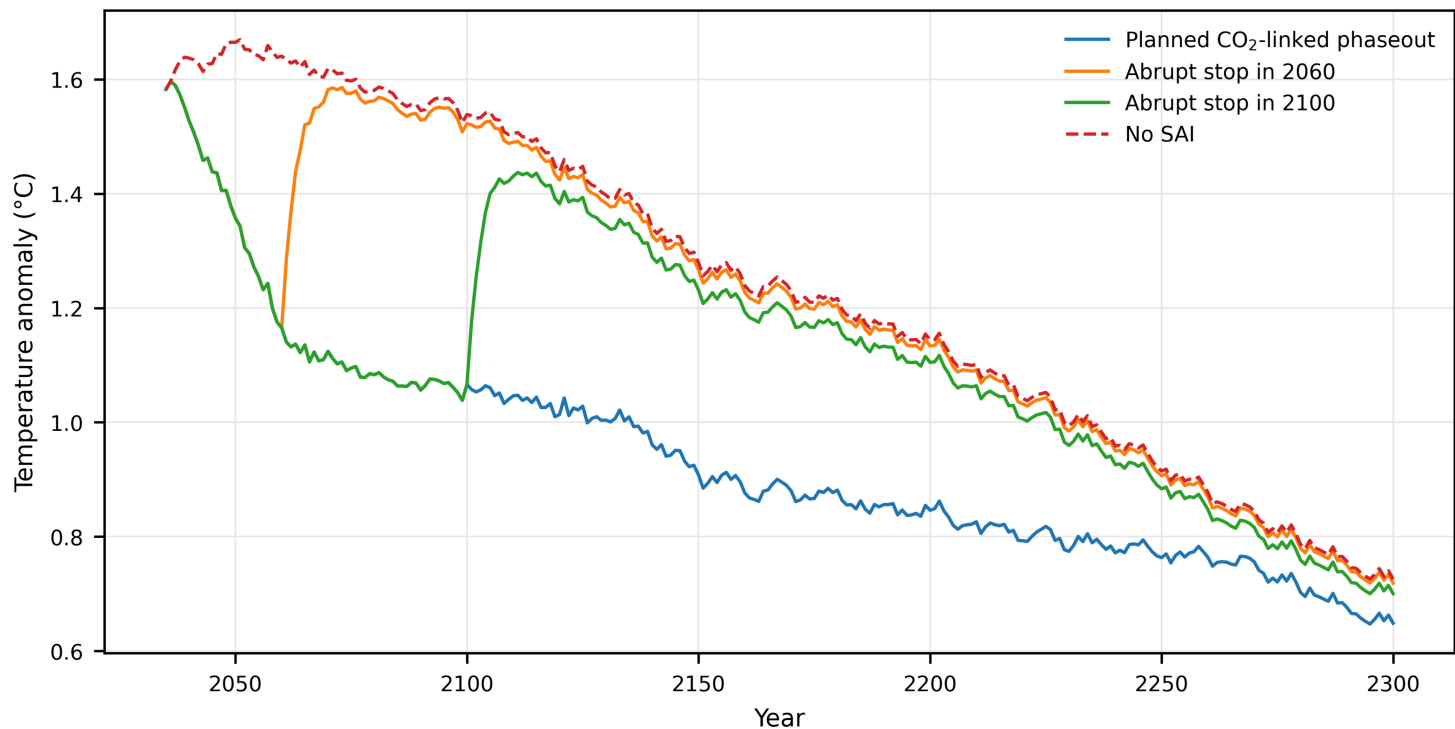


Figure 4

Planned phaseout versus abrupt withdrawal. The planned CO₂-linked phaseout is compared with failure-mode sensitivities that force command to zero in 2060 or 2100. Abrupt cases intentionally override the normal annual rate limit; they are not the planned operating policy