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**No Emergency Brake:
Slow Ocean Response
to Abrupt Stratospheric Aerosol Injection**

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8 **Key Points:**

- 9
- 10 • Abrupt cooling via stratospheric aerosol injection (SAI) counteracts anthropogenic
11 climate change mostly on a surface level in Community Earth System Model 2 (CESM
12 2) simulations
 - 13 • Sub-surface ocean heat, weakened Atlantic Meridional Overturning Circulation
14 (AMOC) and collapsed North Atlantic deep convection remain after intervention
 - 15 • Decoupling of AMOC and GMST under abrupt SAI yields a climate state not seen
in purely greenhouse-gas (GHG) forced simulations

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Abstract

Given the possibility of irreversible changes to the Earth system, technological interventions such as solar radiation management (SRM) are sometimes framed as possible climate emergency brakes. However, little knowledge exists on the efficacy of such disruptive interventions. To fill in this gap, we perform Community Earth System Model 2 (CESM 2) simulations of a SSP5-8.5 scenario on which we impose either gradual early-century SRM to stabilise surface temperatures or a rapid late-century cooling, both realised via stratospheric aerosol injection (SAI). While both scenarios cool Earth's surface, we find that ocean conditions differ drastically. The rapid-cooling scenario fails to dissipate subsurface ocean heat content (OHC), ends up in a weaker AMOC state and does not restore an ailing North Atlantic deep convection. Furthermore, the weakened AMOC state mediates the climate response to rapid SAI, thus inducing an interhemispheric temperature asymmetry. Our results advise caution when considering SAI as an emergency intervention.

Plain Language Summary

Stratospheric aerosol injection (SAI) is a proposal to mask the effects of anthropogenic climate change by reflecting sunlight back into space. As such a large intervention may come along with physical and socio-political risks, SAI is sometimes framed as an 'emergency brake' to be deployed under the most dire of circumstances.

Using model simulations, we show that such an abrupt deployment fails to restore past climate conditions. While Earth's surface cools rapidly, the response is less definite in the ocean where reaction times are far longer. More specifically, rapid cooling only takes place on the ocean surface while deeper layers continue to trap excess heat. Additionally, important features of the ocean circulation and potential climate tipping elements do not quickly return to their pre-warming state. The combination of a cooled surface with an altered ocean circulation creates a novel, potentially undesirable, climate state.

Our study once again emphasizes the persistent impacts of greenhouse gas emissions. In particular, changes in inert systems, such as the ocean, act as a form of long-term debt which can not easily be redeemed. This cautions against the use of an emergency brake framing for SAI.

1 Introduction

While global heating puts increasing pressure on societies and ecosystems (IPCC, 2022a), current policies are insufficient to prevent 1.5°C or even 2°C of warming (IPCC, 2022b). To mitigate the associated risks, *Solar Radiation Management* (SRM) has been proposed as a complimentary measure to emission cuts (National Academies of Sciences, Engineering, and Medicine, 2021). Among several potential schemes, *Stratospheric Aerosol Injection* (SAI) received considerable attention due to its low perceived technical barriers (Smith, 2020) as well as its plausible physical effectiveness (Kleinschmitt et al., 2018; Plazzotta et al., 2018).

Even if global mean surface temperature (GMST) were kept constant using SRM, residual climate changes would still be present. Nevertheless, SRM would likely bring relevant climate variables closer to their pre-industrial state in many regions (Irvine et al., 2019). Besides these physical aspects, SRM has wide-reaching socio-political and ethical implications (Buck, 2019; Svoboda, 2017; Oomen, 2021) leading some to call for a ban on its research and deployment (Biermann et al., 2022) whereas others call for further scientific studies (Wieners et al., 2023).

Several scenarios of SRM governance and deployment have been suggested (Lockley et al., 2022; Barrett et al., 2014). For example, SRM might be used timely to reduce warming overshoot (“peak-shaving”) or slow down the rate of warming (Florin et al., 2020). It can also be used reactively, e.g. to prevent a climate emergency or breaching a temperature limit (Crutzen, 2006) potentially under the assumption that SRM is invoked only if more acceptable options fall short (“emergency brake”).

Climate model simulations typically assume SRM to be used immediately (Tilmes et al., 2018, 2019) or in the near future (MacMartin et al., 2017). Less attention has been paid to the question what would happen if SRM were deployed only after several decades of GHG-induced heating. This question is far from trivial. Even for identical greenhouse gas trajectories, it may be impossible to return from a world where SRM has started “late” to the state that would have been achieved if SRM had started earlier. Such a lack of reversibility might be temporary (early and late SRM eventually converge) or absolute (they never converge). Even a temporary lack of reversibility might have socio-economic and political repercussions and limit SRM’s potential to act as an emergency brake.

Ocean processes involving long timescales could potentially bring about a temporary lack of reversibility. Such processes include changes in the ocean heat content (OHC) (Fasullo et al., 2018) and changes in the North Atlantic circulation such as a weakening of the Atlantic Meridional Overturning Circulation (AMOC) (Hassan et al., 2021; Schwinger et al., 2022) or the shutdown of deep convection (Sgubin et al., 2017; Swingedouw et al., 2021).

In this study, we ask how effective SAI would be as emergency brake, i.e. to what extent abruptly lowering GMST with aerosol-induced shading would reverse climate change, and how this implementation compares to a gradual, earlier deployment. Aforementioned ocean features are our main focus as we suspect long response timescales to give different outcomes depending on the SAI strategy.

2 Methods

We use the CMIP6 model CESM2 (Danabasoglu et al., 2020) with atmospheric component CAM6. While the configuration CESM2-WACCM is more comprehensive, it is also more computationally expensive. As CESM2-CAM6 lacks interactive stratospheric sulphate chemistry, we prescribe aerosol fields based on prior CESM2-WACCM simulations (Tilmes et al., 2019).

While our WACCM-derived aerosol fields have a fixed spatial and seasonal pattern, we can scale the overall amplitude of the forcing every year. This (single) degree of freedom is used to stabilise GMST at its target value of 1.5°C above pre-industrial conditions under a SSP5-8.5 scenario. More specifically, a feedforward-feedback controller (Kravitz et al., 2016, 2017) dynamically adjusts the aerosol burden in the stratosphere to target a specified GMST. Technical details are outlined in the supplementary material.

We simulate three scenarios based on SSP5-8.5 background emissions:

- Control (2015-2100): historical spin-up continued by SSP5-8.5
- SAI2020 (gradual SAI): branch off from Control in 2020, stabilise GMST at a target value of 1.5° above pre-industrial conditions
- SAI2080 (emergency brake): branch off from Control in 2080, deploy SAI to restore GMST to the same target as SAI2020.

As our scenarios involve very high levels of GHG and aerosol forcing, they are intended as physical edge cases rather than realistic or desirable real-world scenarios. In that sense, SAI2080 serves only as an upper boundary for the response to SRM-induced cooling.

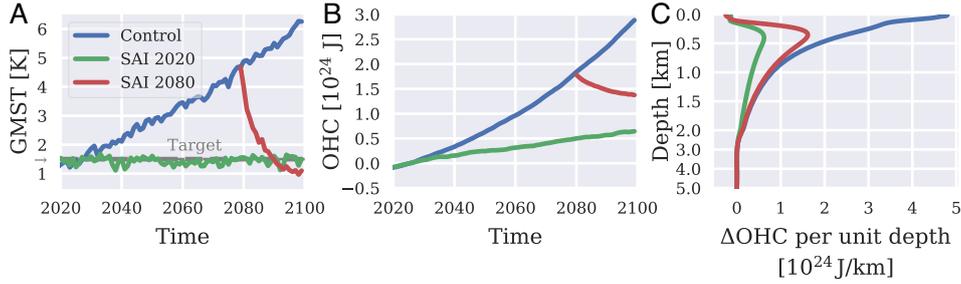


Figure 1. **A:** Annual mean GMST above pre-industrial reference temperature **B:** Change in annual mean total depth OHC relative to 2020-2030 conditions in Control. **C:** Difference in vertical OHC between end-of-simulation (2090-2100) conditions and present-day conditions in Control.

3 Results

3.1 Temperature Response

In Fig. 1A, we see that the gradual SAI strategy (SAI2020) indeed stabilises GMST at target level. By contrast, SAI2080 experiences rapid cooling. The latter can be reduced by tuning the feedback procedure (see Fig. S1).

Even though GMST is stabilised, total depth OHC accumulates continuously in SAI 2020 (Fig.1B) in agreement with a past study (Fasullo et al., 2018). The warming takes place below the surface and is likely a consequence of deep ocean response timescales (Cheng et al., 2022) in combination with the feedback controller. As sub-surface layers have not yet adapted to increased surface temperatures, they act as a heat sink for the ocean surface. The induced downward heat flux is then compensated by the feedback controller that allows for some top-of-atmosphere radiative imbalance in order to stabilize GMST.

SAI2080 accumulates more total depth OHC than SAI2020. The sub-surface vertical OHC distribution of SAI2080 (Fig.1C) matches that of Control. On the surface, however, both SAI scenarios have comparable OHC anomalies. This suggests that while abrupt SAI readily cools the ocean surface, heat anomalies trapped in deeper layers are more persistent.

Surface temperature responses to SAI are spatially inhomogeneous (Fig. 2). Most strikingly, the subpolar North Atlantic is significantly overcooled in both SAI scenarios. This pattern resembles an intensified *North Atlantic Warming Hole* known from purely GHG-forced simulations (Drijfhout et al., 2012; Menary & Wood, 2018), which to some extent is also visible in Control. While the strong overcooling is limited to the warming hole in SAI2020, SAI2080 shows a large-scale overcooling covering most of the Northern Hemisphere, while the Southern Hemisphere remains warmer than in SAI2020.

Multi-objective feedback procedures (Kravitz et al., 2017; MacMartin et al., 2017) allow for a more elaborate control of the global temperature pattern including the interhemispheric temperature gradient. Therefore, the asymmetric response of SAI2080 (Fig. 2E) may be mitigated in a refined control scheme. In our study, however, both SAI scenarios use spatially identical aerosol patterns with a single degree of freedom which rules out a control of the asymmetry.

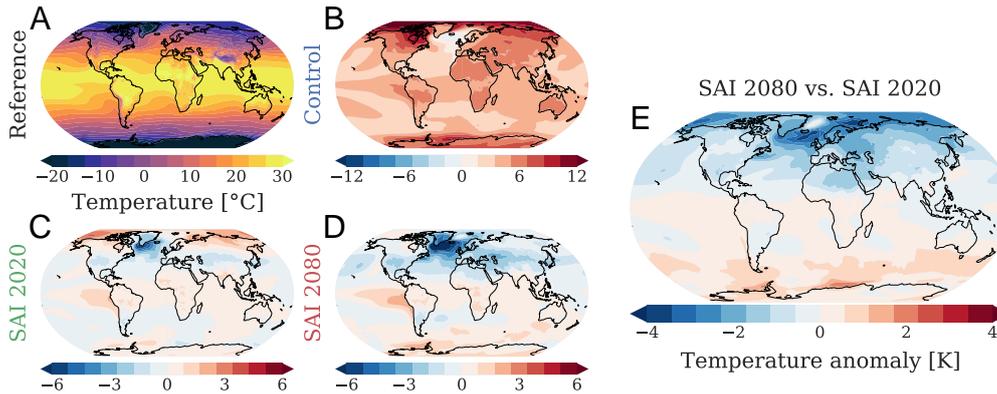


Figure 2. **A:** Reference (2020-2030) annual mean near-surface air temperatures in Control **B-D:** Late-century (2090-2100) temperature changes with respect to the reference for Control, SAI 2020 and SAI 2080 respectively. **E:** Difference between SAI scenarios (**D** minus **C**)

141 3.2 AMOC Response

142 The AMOC index and meridional heat transport (MHT) roughly halve in Control
 143 (Fig. 3A-B). Even the CMIP6 low-emission SSP1-2.6 scenario is projected to lead to sim-
 144 ilar AMOC index changes. SAI 2020 drastically mitigates but does not halt the AMOC
 145 and MHT decline. SAI 2080 stabilizes the AMOC index but only has an inconclusive im-
 146 pact on the MHT.

147 Interestingly, SAI effectively decouples the GMST and the AMOC index (Fig. 3C).
 148 This could explain the interhemispheric temperature contrast featured in SAI 2080: a
 149 weak AMOC impedes northward heat transport leading to a see-saw temperature pat-
 150 tern (Stocker, 1998; Liu et al., 2020) that is not masked by heat otherwise present in Con-
 151 trol.

152 To study the spatial pattern of the AMOC, we plot meridional streamfunction changes
 153 under all scenarios from 2070-2080 to 2090-2100 (Fig. 4). This choice of time intervals
 154 helps to reveal the immediate AMOC response to SAI 2080. Additionally, we subtract
 155 the changes in Control from the ones in the SAI scenarios in an attempt to disentangle
 156 GHG from SAI-related impacts.

157 Fig. 4D reveals a potential feedback in the AMOC stabilization under SAI 2080. Fol-
 158 lowing the deployment, the pattern of relative AMOC strengthening closely mirrors the
 159 pre-deployment streamfunction, albeit mostly near the surface and in the northern hemi-
 160 sphere. This suggests that the AMOC response to abrupt SAI is dependent on the AMOC
 161 state itself. While a similar observation can be made for SAI 2020 (Fig. 4C), disentan-
 162 gling the forced response from internal feedback is not obvious during the gradual change
 163 in aerosol forcing. SAI 2080 gives a much better indication that it is indeed the state of
 164 the AMOC which steers its response to SAI.

165 This result again highlights the lack of immediate climate reversibility under SAI.
 166 A weakened AMOC state likely presents an obstacle to a SAI-based stabilization or re-
 167 covery.

168 3.3 North Atlantic Deep Convection

169 We now focus on deep convection processes in the North Atlantic. Using mixed layer
 170 depth as a proxy for deep convection, we identify two regions, *East* and *West*, where the

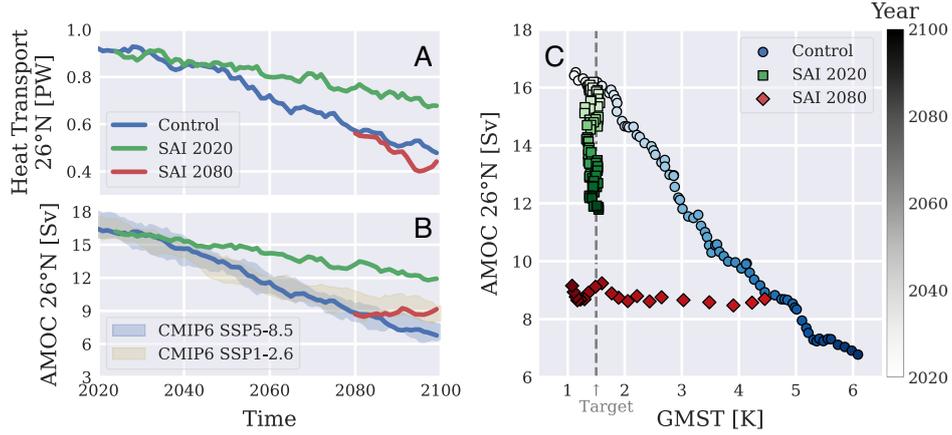


Figure 3. **A:** Annual mean Atlantic northwards heat transport at 26°N where we apply a rolling average over five year periods with backward window **B:** AMOC index defined as the maximum of the annual mean meridional overturning streamfunction at 26°N below 200 m - Partially transparent uncertainty bands depict three CESM2 CMIP6 ensemble members (Danabasoglu, 2019a, 2019b) per GHG concentration pathway. The uncertainty is the ensemble standard deviation. Again, we apply rolling averages over five year periods. **C:** Annual mean GMST vs. AMOC index - The marker saturation denotes the year: light (2020) to dark (2100).

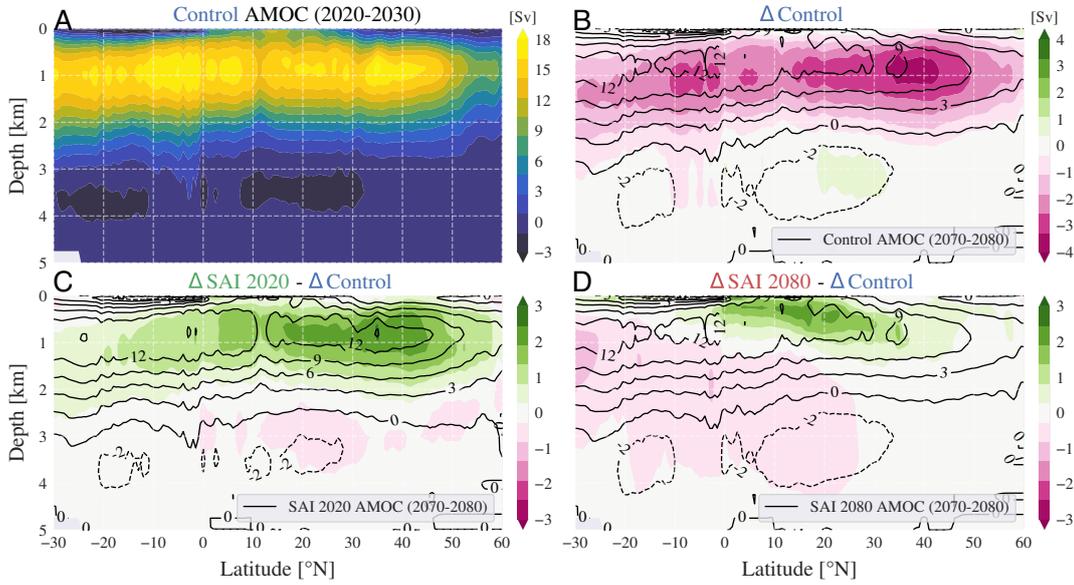


Figure 4. **A:** AMOC streamfunction in Control averaged over 2020-2030. In **B-D**, for any simulation X , ΔX is the mean over 2090-2100 minus the mean over 2070-2080. **B:** Change in AMOC streamfunction under Control - Black contour lines show the mean streamfunction over 2070-2080 for Control while the shading indicates Δ Control. **C:** Change in AMOC streamfunction in SAI2020 relative to Control - Black contour lines show the mean streamfunction over 2070-2080 for SAI2020 while the shading indicates Δ SAI 2020 - Δ Control. **D:** Analogous to **C** but for SAI2080.

171 mixed layer depth in April (the month with the deepest mixed layer) exceeds 550 m (Fig. 5A).
172 This threshold depth was chosen as it is sufficiently large to distinguish deep convection
173 from regular mixed-layer conditions and small enough to provide a good signal-to-noise
174 ratio. The regions are separated longitudinally by the southern tip of Greenland.

175 In Control, deep convection in *West* ceases around 2050, followed by a shutdown
176 in *East* around 2060. SAI2020 prevents the shutdown in *East*, but only postpones the
177 shutdown in *West* by about a decade. The *West* shutdown is not as definite as in the
178 case of Control and isolated years with deep convection still occur. For SAI2080, deep
179 convection remains absent in both regions with the exception of a single outlier year for
180 *East*.

181 Why does cooling in SAI2080 not revive deep convection? We address this ques-
182 tion by studying the ocean stratification over both deep convection regions. Deep con-
183 vection in April is inhibited if the surface density in the previous September has been
184 too low, i.e. the water column is too stratified (Fig. S3). Thus, surface density serves as
185 a proxy for favorable convection conditions.

186 The sea surface density is determined by temperature and salinity, also seen in Fig. 5.
187 In all scenarios, final salinities are well below reference conditions. SAI2020 roughly halves
188 the decline with respect to Control. This difference becomes very noticeable mid-century
189 simultaneously with the *East* and *West* shutdown in Control. SAI2080 does not fun-
190 damentally alter the trajectory of Control apart from a transient increase in salinity that
191 correlates with an isolated year of deep convection. Therefore, freshening contributes to
192 density loss in all scenarios.

193 Temperature trends are rather complex in the case of Control (Fig. 5D-F.). An ini-
194 tial phase of slight cooling is interspersed with rapid, intense variability mid-century and
195 finally succeeded by warming. Multiple factors like GHG-induced heating, cooling from
196 a declining AMOC as well as convection related surfaces fluxes and currents overlap and
197 are causing this behaviour.

198 SAI2020 shows an overall cooling trend dominated by a quick decline at time of
199 *West* shutdown. In SAI2080, prior deep convection shutdown combined with SAI leads
200 to drastic cooling even falling below SAI2020 levels (Fig. 5D). These temperature drops
201 have a positive effect on density and thereby convection. Still, the dramatic cooling in
202 SAI2080 does not elevate densities to SAI2020 levels (Fig. 5F). Therefore, the salinity
203 deficit of SAI2080 with respect to SAI2020 (Fig. 5E) presents a clear obstacle for restart-
204 ing deep convection.

205 Our results can be explained in terms of multiple physical drivers. Firstly, all sce-
206 narios see an increase in surface freshwater forcing (Fig. S2) which contributes to a grad-
207 ual salinity loss. This weakens convection and consequently the AMOC. Subsequently,
208 weak AMOC and convection conditions lead to less salt transport into the subpolar gyre,
209 hence reinforcing the salinity decline (Kuhlbrodt et al., 2007). This is particularly true
210 for the late years of Control and SAI2080. Finally, increasing the surface density via cool-
211 ing has ‘diminishing returns’: density gains are less than proportional to temperature
212 decreases owing to the nonlinear properties of sea water density. As shown in the sup-
213plementary material (Fig. S4), this further reduces the efficacy of SAI2080.

214 To summarise, SAI2020 partially stabilizes deep convection. In contrast, the salin-
215 ity deficit accumulated up to deployment time in SAI2080 becomes an obstacle for strength-
216 ening convection. There, the absence of positive convective feedback combined with a
217 weak AMOC offers little hope of a decisive recovery but internal variability may still lead
218 to isolated events of deep convection. It is not implausible that multiple such events could
219 compound and eventually restore deep convection in the longer term.

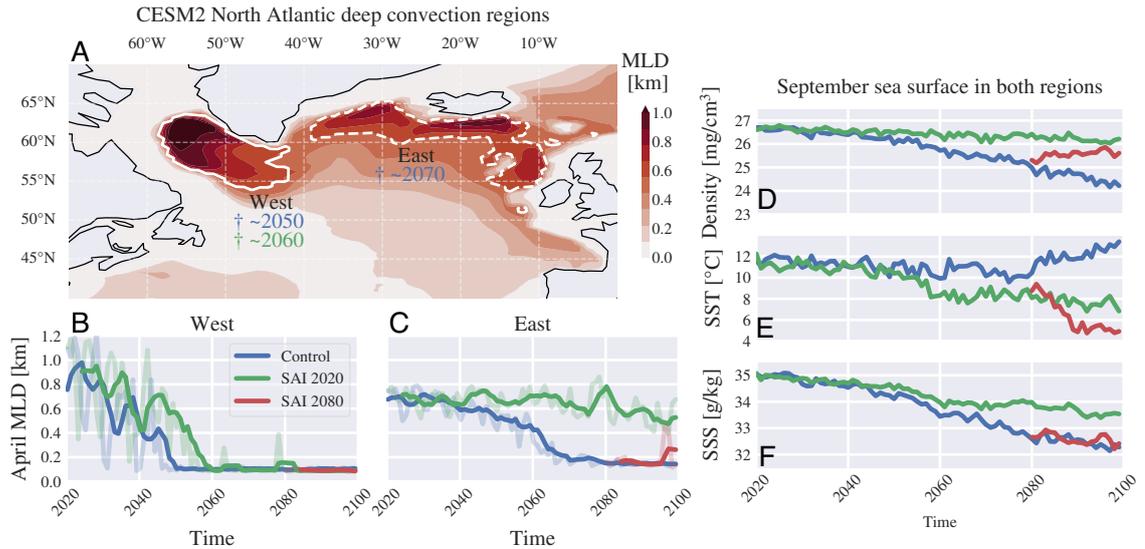


Figure 5. **A:** North Atlantic April mixed layer depths in CESM2 (2020-2030) - *East* and *West* are enclosed by solid and dashed lines respectively. Shutdown dates are denoted with a cross and colored according to scenario (blue: Control, green: SAI 2020). **B-C:** April mixed layer depths in *West* and *East* respectively - Solid lines are five year rolling means (with backward window) applied to the data shown by transparent lines. **D-F:** September mean sea surface density, temperature and salinity over the total *East* and *West* region

4 Discussion

In our simulations, the quick drop in GMST due to abrupt SAI is contrasted by a slow ocean response. Gradual SAI, on the other hand, retains an ocean state much closer to the present-day reference. Elevated OHC, weak AMOC and absent deep convection coupled with a lower GMST presents a (transient) climate state unknown from purely GHG-forced scenarios.

Note that our scenarios are extreme cases with a high signal-to-noise ratio, rather than desirable or plausible futures. More cautious protocols typically deploy SAI in tandem with emission mitigation to limit a temporary temperature overshoot (National Academies of Sciences, Engineering, and Medicine, 2021). If a cooling scenario were actually considered, a ramp-up of SAI would be more sensible than the sudden deployment in SAI2080. Such a gradual approach would enable a fine-tuning of the injection scheme based on observations.

Besides the high forcings, our scenarios also involve a limited SAI scheme. As our implementation relies on a single degree of freedom, we can only meet a GMST target but not control other aspects of the temperature pattern. More control parameters, on the other hand, may be beneficial to prevent a interhemispheric temperature asymmetry which risks a displacement of the ITCZ (Broccoli et al., 2006; Bischoff & Schneider, 2016). Still, restoring the meridional temperature pattern in SAI2080 would come with problems of its own: less cooling over the North Atlantic further endangers deep convection.

As for our results, a mitigating effect of SAI on AMOC decline was already known in multiple models (Tilmes et al., 2018, 2019; Xie et al., 2022) but not in the case of late-

243 century abrupt deployment. Similarly, the impaired effectiveness of abrupt SAI on re-
244 ducing OHC is a new result. To our knowledge, no studies have been performed on the
245 effect of SAI on deep convection shutdown either. Regarding this aspect, model depen-
246 dencies are certain as deep convection shutdown is not a universal phenomenon in CMIP6
247 (Swingedouw et al., 2021).

248 It is worth pointing out similarities between our abrupt SAI case and rapid neg-
249 ative emission scenarios (Schwinger et al., 2022). Removal of GHG after prolonged heat-
250 ing can lead to an interhemispheric temperature asymmetry if the timescale of extrac-
251 tion is shorter than that of the AMOC recovery. Therefore, the possibility of SAI to man-
252 age the interhemispheric temperature gradient is an advantage compared to GHG re-
253 moval.

254 A major questions remains open: do the climates of both SAI scenarios eventually
255 converge? This question cannot be answered without extending the simulations, which
256 is outside the scope of this study. When extrapolating our results, the OHC difference
257 is expected to lessen due to residual ocean warming in SAI2020. Whether the gap fully
258 closes may also depend on the AMOC and deep convection because of their impact on
259 ocean heat uptake (Marshall & Zanna, 2014). As for deep convection, the aforementioned
260 salinity deficit in SAI2080 inhibits convergence of the SAI scenarios. Nevertheless, should
261 some years of deep convection arise in SAI2080 (e.g. as a result of natural variability),
262 salt import would be strengthened, thereby improving long-term prospects for deep con-
263 vection.

264 5 Summary

265 In this study, we presented model results of a late-century “emergency brake” SAI
266 deployment that aims to restore surface temperatures under simultaneous GHG forcing.
267 By comparing our findings with a gradual early-century SAI scenario, we show that abrupt
268 late-century SAI is less effective at mitigating changes in OHC, the AMOC and North
269 Atlantic deep convection.

270 Firstly, abrupt SAI failed to release heat trapped in deeper ocean layers. Even an
271 early onset of SAI only mitigates but does not halt OHC accumulation. Both results are
272 linked to slow ocean equilibration times.

273 Secondly, abrupt SAI partially stabilized a weakened AMOC, albeit not halting the
274 decline of northward heat transport. Under earlier SAI, the AMOC decline is mitigated
275 in both, volume and heat transport. As a result, the scenarios achieved drastically dif-
276 ferent AMOC states despite comparable GMST. A weaker AMOC may contribute to the
277 observed overcooling of the northern hemisphere in the emergency brake scenario. This,
278 in turn, may be relevant for the choice of injection pattern.

279 Thirdly, a shutdown of North Atlantic deep convection could not be reversed with
280 rapid, SAI-induced cooling. We suspect that a weakened AMOC, absence of convective
281 feedback, fresher surface conditions as well as non-linear properties of water density pose
282 an obstacle for restarting deep convection. An early intervention, on the other hand, re-
283 tains more salt in the North Atlantic, hence the partial stabilization of deep convection.

284 All these findings suggest that SAI is not an effective emergency brake. Ocean changes
285 induced by anthropogenic climate change can persist despite a rapid lowering of GMST.
286 That is why, if SAI were ever considered, its efficacy would be limited by the ocean changes
287 already locked-in. To avoid facing the choice of whether and how to deploy SAI all to-
288 gether, further climate change must be mitigated by curbing GHG emissions.

6 Open Research

The code for our SAI protocol will be shared upon reasonable request.

The CMIP6 data used for comparison in Fig. 3 is publicly available (Danabasoglu, 2019a, 2019b).

Acknowledgments

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