

# 1 Impacts of Potential Solar Radiation 2 Modification: Systematic Review Reveals 3 Challenges and Opportunities

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## 20 Abstract

21 Solar radiation modification (SRM) is a proposed temporary intervention to limit global  
22 warming while mitigation efforts continue. Understanding its potential consequences for  
23 human and natural systems is essential for informed deliberations. We conducted a  
24 systematic review of the peer-reviewed literature on SRM impacts published through May  
25 2024, identifying 289 studies, including 261 primary articles and 28 reviews. Studies on the  
26 potential impacts of SRM on human systems (9%) and ecosystems (25%) were infrequent.  
27 Further, primary literature is dominated (97%) by global models and thus the SRM impacts  
28 that are most reported reflect the variables available from global models, such as global  
29 mean temperature, global mean precipitation, sea ice and net or gross primary production.  
30 Those studies that did report impacts on human systems or ecosystems typically relied on  
31 chained modeling frameworks using uncertain regional-scale climate outputs. While  
32 studies relying on such frameworks are informative for identifying model sensitivities and  
33 parameterization challenges, their results remain highly uncertain. Despite this, model  
34 studies constitute an increasing majority of SRM research on human and natural systems.  
35 In contrast, empirical research using SRM-analogous events (e.g., volcanic eruptions) was  
36 rare and is declining in relative frequency. Analog studies have informed model  
37 development, revealed sensitivities rarely examined in global models, and reduced  
38 reliance on modeling's regional-scale compounding uncertainties. Our results indicate that  
39 a more integrated research strategy, one that combines climate modeling with analog  
40 studies and intermediate-scale modeling approaches, is needed to improve fidelity in  
41 assessing potential SRM impacts on human and natural systems.

42

## 43 Introduction

44 Solar radiation modification (SRM) has emerged as a potential, though controversial,  
45 climate intervention to moderate surface temperatures under anthropogenic climate  
46 change. It is not a substitute for reducing greenhouse gas (GHG) emissions. Still, SRM is  
47 gaining attention as a temporary measure to limit the impact of increased temperatures  
48 due to climate change on human and natural systems while mitigation and adaptation  
49 strategies are being adopted. At the same time, SRM would change the climate and thus  
50 human and natural systems (Honegger et al. 2021; National Academies of Sciences,  
51 Engineering, and Medicine 2021). Understanding the potential impacts of SRM on those  
52 systems, beyond the first order metrics of global mean surface temperature (GMST), as  
53 well as uncertainties associated with projected impacts, is critical to making informed  
54 decisions about SRM research and governance.

55 SRM typically refers to intentional anthropogenic climate intervention by altering how solar  
56 radiation interacts with the earth (National Academies of Sciences, Engineering, and  
57 Medicine 2021). Stratospheric aerosol injection (SAI), the most frequently studied method  
58 for SRM, was inspired by the measurable changes in sunlight and temperature that are  
59 observed following large volcanic eruptions that inject aerosol particles and other gases  
60 into the stratosphere (Cole-Dai 2010). SAI would involve intentional injection of aerosols  
61 into the stratosphere, most likely via aircraft. Unlike volcanic eruptions, however, SAI would  
62 likely take place over multiple locations globally and occur continuously over decadal  
63 timescales. Marine cloud brightening (MCB) is another methodology to enhance sunlight  
64 reflection over oceans by spraying sea salt particles into the marine boundary layer, similar  
65 to marine shipping exhaust plumes. Cirrus cloud thinning (CCT) proposes injecting ice-  
66 nucleating particles into the upper troposphere, intended to thin cirrus clouds and allow  
67 more heat, or long-wave radiation, to escape back to space. While technically not a form of  
68 SRM, CCT is included here as it has a similar intention to reduce GMST.

69 Like anthropogenic climate change, SRM would influence the processes, interactions, and  
70 feedbacks within and between natural and human systems, which can lead to complex  
71 dynamics (Liu et al. 2007). Under SRM, optimization for all possible beneficial impacts (or  
72 minimization of negative effects) may not be possible or predictable, and there is the  
73 possibility of unintended consequences (Ricke et al. 2010; Tracy et al. 2022).

74 Previous studies have found that there is limited information in the peer-reviewed literature  
75 on the impacts of SRM beyond changes to GMST (which is the fundamental variable  
76 targeted by SRM scenarios) and global mean precipitation (National Academies of

77 Sciences, Engineering, and Medicine 2021). Given the complexity and diversity of human  
78 and natural systems beyond their responses to temperature, there is a need to accelerate  
79 research into other impacts of SRM with robust understanding of how well those impacts  
80 can be forecasted. Although all forecasts come with uncertainties, system-specific  
81 assessments of what is known, how it is known, and to what certainty, about the potential  
82 impacts of SRM will help decision-makers evaluate trade-offs and weigh SRM alongside  
83 other responses to climate change. This is particularly relevant for systems such as food,  
84 water, energy, human health, and ecosystems, as well as abiotic conditions that directly  
85 affect these systems.

86 Toward this goal, we conducted a systematic review of the SRM impacts literature  
87 published before June 2024 (see Methods). Below, we describe what has been studied, and  
88 what research priorities and opportunities emerge. We focus on three main groups of  
89 impacts: Abiotic Conditions (e.g., temperature, precipitation, sea level, surface UV, etc.),  
90 Human Systems (e.g., variables related to food, water supplies, etc.), and Ecosystems &  
91 Biogeochemistry (e.g., measures of effects on the cryosphere, carbon cycling, biodiversity,  
92 etc.).

## 93 Results

94 A systematic review returned 3,351 unique records, of which 289 were peer-reviewed  
95 publications that reported or discussed the potential effects of SRM on Abiotic Conditions,  
96 Human Systems, or Ecosystems & Biogeochemistry.

### 97 Climate models dominate primary SRM research

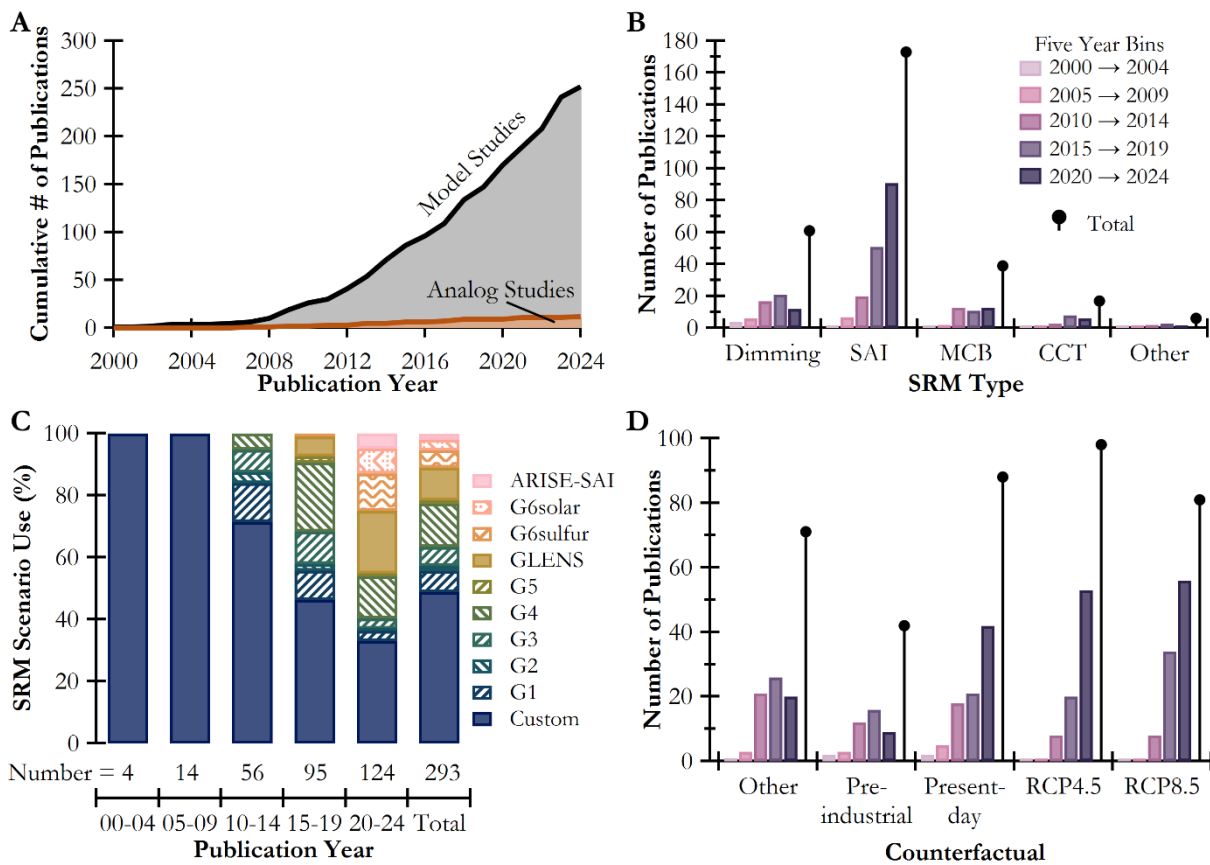
98 There were 261 primary research articles included in the review. Most (252, 96.6%)  
99 presented results from climate models, including earth system models (ESMs) and global  
100 circulation models (GCMs). Climate model studies have always dominated SRM research,  
101 and the total number of such publications has grown rapidly over the last 25 years  
102 (Figure 1A, black). In contrast, studies that use observations to study SRM by way of natural  
103 analogs were rare (12, 4.6%), and their growth rate was significantly slower (Figure 1A,  
104 orange). Analog studies focused almost exclusively on past volcanic eruptions (11 of 12,  
105 91.7%) as an analog for SAI. Only four studies combined a simulation with observations  
106 from an SAI-analogous event.

107 Most of the 252 climate model studies presented results on SAI (173, 68.6%) or an SRM  
108 model-proxy termed “solar dimming” (61, 24.2%, of which 14 also studied SAI), in which  
109 the model’s solar constant is reduced (Figure 1B). The MCB (39, 15.5%) and CCT (17, 6.7%)  
110 methods were infrequently modeled. Most studies of CCT were published in the past

111 decade, while simulations using solar dimming as a proxy for SRM decreased sharply in  
112 2020 – 2024. There were also 28 literature reviews (9.7% of the 289 total publications) and  
113 one study that used expert elicitation to explore possible impacts.

114 **Figure 1. Overview of publication types and methods used to research SRM impacts.** **A:** Cumulative  
 115 number of publications using a climate model (black) and/or empirical analog (orange) by publication year. **B:**  
 116 Number of publications that modeled the shown form of SRM in five-year bins indicated by color. “Other”  
 117 forms include uniform increases in ocean or land surface albedo as proxies for SRM. Circle-and-stick  
 118 indicates total for each. **C:** Percent use of an SRM model scenario (relative to the total in that five-year bin and  
 119 total). Many publications modeled more than one SRM scenario. **D:** Number of publications that used the  
 120 shown counterfactual in five-year increments indicated by color as in **B**. RCP4.5 and RCP8.5 include SSP2-  
 121 4.5 and SSP5-8.5, respectively. Present-day and pre-industrial baselines include CO<sub>2</sub> levels of 350-440 ppm  
 122 and < 285 ppm, respectively. Counts in panels B, C, and D sum to more than the number of model studies as  
 123 some studies use multiple SRM scenarios and/or counterfactuals.

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127 **The number and diversity of standardized SRM climate scenarios are**  
128 **growing**

129 Of the 252 model studies, 143 (56.7%) used at least one custom (non-standardized) SRM  
130 deployment scenario (Figure 1C). Standardized SRM scenarios define an SRM deployment  
131 scenario and a counterfactual. As an example, the G4 scenario injects 5 Tg SO<sub>2</sub> from one  
132 point on the Equator into the lower stratosphere every year from 2020 until the end of the  
133 simulation against a background of RCP4.5 (see SI for brief descriptions of other  
134 standardized scenarios). These standardized scenarios allow for comparisons across  
135 models and studies, essentially acting as research methodologies. The first set of  
136 standardized SRM scenarios was proposed in 2011 (B. Kravitz et al. 2011). Such scenarios  
137 grew in number and diversity over the last ten years (Figure 1C). In this review, the most  
138 frequently used scenarios were G4 (41, 16.3%), GLENS (31, 12.3%), and G3 (18, 7.1%).

139 Nearly half of the model studies (116, 46.0%) used more than one counterfactual. The  
140 most common counterfactual (across all model studies, regardless of the number of  
141 counterfactuals used) was the intermediate emissions scenario RCP4.5 (for simplicity,  
142 SSP2-4.5 is included for a total of 98 studies, 38.9%) as seen in Figure 1D. The  
143 counterfactuals of present-day conditions (88, 34.9%), RCP8.5 (81, 32.1%, including SSP5-  
144 8.5), and pre-industrial conditions (42, 16.7%) were also common. It is important to note,  
145 however, that the definitions of pre-industrial and present-day conditions varied by study  
146 and by model. Less common counterfactuals included but were not limited to doubled  
147 (530-800 ppm) or quadrupled (> 1100 ppm) CO<sub>2</sub> levels (17, 6.7%, each) and the SRES A1B  
148 scenario (10, 4.0%), which are classified as “other” in Figure 1D.

149

150 **Impact studies focused on mean temperature and precipitation**

151 The most studied impacts were in the Abiotic Conditions category (Figure 2, orange). Mean  
152 temperature (189 of 261 primary research studies, 72.4%) and mean precipitation (156,  
153 59.8%) were the most reported overall. Note that some papers reported multiple impacts,  
154 thus the percentages will not add to 100%. Temperature and precipitation extremes were  
155 counted separately for this review and were less frequently reported. Statistically extreme  
156 (i.e., historically anomalous) temperature and precipitation were reported in ~11% of  
157 studies (29 and 28 studies, respectively). Studies reporting results on dangerous extremes  
158 (i.e., explicitly tied to harmful effects on human health or ecosystems or likely to be  
159 considered dangerous or extreme by the lay public) were rare: 9 (3.4%) and 2 (0.8%) for  
160 dangerously extreme temperature and precipitation, respectively. Lastly, sea level, ozone  
161 (at any altitude), light quality (i.e., diffuse, direct), and cyclone-related impacts were

162 infrequently reported (between 10-20 studies each) while changes in monsoons, surface  
163 UV, and air quality were reported in fewer than 10 studies each.

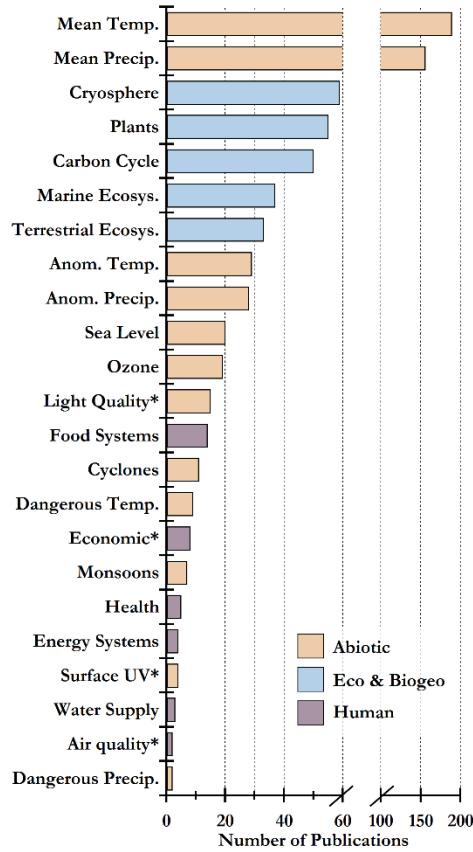
164 The second most common impact category was Ecosystems & Biogeochemistry (Figure 2,  
165 blue). These impacts were studied less often than mean temperature or mean precipitation  
166 but more frequently than the other Abiotic Conditions (Figure 2). Within this category,  
167 studies of cryosphere- and plant-related impacts were the most common and were  
168 primarily reporting results on sea ice and net or gross primary production (NPP or GPP),  
169 respectively. Studies of marine and terrestrial ecosystems were the least frequent within  
170 the Ecosystems & Biogeochemistry category.

171 Impacts in the Human Systems category were studied far less frequently (32, 12.3%, Figure  
172 2, purple) than those in the Abiotic Conditions or Ecosystems & Biogeochemistry  
173 categories. The most frequently studied human system was the food system (14, 5.4%),  
174 with results overwhelmingly derived from models; only one study used observations of  
175 crop yield after a large volcanic eruption to investigate potential impacts of SRM. Only five  
176 studies (1.9%) reported human health impacts, which included effects of SRM on  
177 dangerously extreme temperature, air quality, UV exposure, and/or malaria. Four (1.5%)  
178 studies reported impacts on solar power generation. Finally, only three (1.1%) studies  
179 reported impacts on water supply. The review also identified eight studies comparing  
180 economic damage from climate change with and without SRM; however, because no  
181 economics-related search terms were used in the initial search, this result is not  
182 necessarily as representative of the literature as the other Human Systems impacts  
183 discussed here.

184

185 **Figure 2. The number of primary research publications reporting results relevant to selected impact**  
 186 **categories in total.** Orange, blue, and purple indicate Abiotic Conditions, Ecosystems & Biogeochemistry,  
 187 and Human Systems, respectively. Many publications reported results relevant to more than one impact  
 188 category. Impact categories marked with an asterisk emerged during the review and were not related to  
 189 search terms.

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## 193 Regional studies are increasing

194 Of the 261 primary research articles, most studies (153, 58.6%) discussed results for one  
195 or more specific region(s). One third (85, 32.6%) reported results at a regional scale only,  
196 and 108 (41.3%) reported results only on a hemispheric, zonal, or global scale. Publications  
197 were only classified as “regional” if authors discussed results for at least one impact in a  
198 specific region. The number of such papers has increased sharply since 2015. Overall,  
199 21.8% of regional studies reported results for Asia, 20.7% for a polar region, 18.4% for the  
200 Americas, and 15.3% for sub-Saharan Africa, with other regions receiving less attention.

## 201 Most authors were affiliated with the U.S., U.K. or China

202 Nearly one-third of authors were affiliated with U.S. institutions (183 of 606 affiliations,  
203 30.2%). The U.K. was the second most common (81, 13.3 %) and China was third (72, 11.9  
204 %). Western and northern European countries also accounted for a significant fraction of  
205 affiliations (160, 26.4 %). Asia and eastern Europe were also represented (57, 9.4 %,  
206 excluding China). Australia represented the only affiliation in Oceania (15, 2.5 %).  
207 Affiliations in Africa (11, 1.8 %) and South America (5, 0.8 %) were rare.

## 208 Discussion

### 209 SRM impacts research is dominated and defined by modeling

210 SRM impact studies were primarily focused on SAI or solar dimming (Figure 1B) and were  
211 conducted using climate models (Figure 1A) by global north-affiliated authors. Modeling  
212 offers clear benefits, such as exploring various aspects of SRM without physical risk (Ben  
213 Kravitz and MacMartin 2020). Models can also utilize standardized SRM scenarios,  
214 essentially research methodologies, that are readily accessible (See SI).

215 Since the stated goal of SRM is to reduce GMST, it is not surprising that mean temperature  
216 is the most reported SRM impact. Temperature is historically used in climate change  
217 research and is a benchmark for current climate policy. The focus on temperature may also  
218 stem from the dominant use of climate models to study SRM. While earlier SRM climate  
219 model scenarios (e.g. G3, G4) use radiative forcing as the model’s benchmark, more recent  
220 scenarios (e.g. G6, GLENS, ARISE) explicitly use temperature as the benchmark.

221 Precipitation is the second most reported impact, and it responds differently than surface  
222 temperature under SRM due to the combined influence of multiple factors. SRM would  
223 fundamentally introduce a novel climate state because it would cool surface temperature,  
224 thus altering surface evaporation, while CO<sub>2</sub> would continue to influence atmospheric  
225 temperature, and thus precipitation. This means that the historically observed

226 relationships between temperature and precipitation cannot be assumed (Niemeier et al.  
227 2013; Bala et al. 2008).

228 Overall, the majority of SRM impacts research reflected the variables that were most  
229 available from climate models. Both temperature and precipitation are standard climate  
230 model outputs (Richter, Glanville, et al. 2022). Cryosphere impacts were the third most  
231 reported impact (59 studies, Figure 2), and most of these were results related to sea ice  
232 (42) or permafrost (10). Sea ice metrics are embedded in common ESMs, and permafrost  
233 can be determined from embedded land models. However, ice sheets (five studies) and  
234 glaciers (one study) require additional offline models (Applegate and Keller 2015; Zhao et  
235 al. 2017). Similarly, plant-related impacts (fourth most reported), were mainly on NPP and  
236 GPP. Both can be estimated using embedded land surface models (Dagon and Schrag  
237 2019; Duan et al. 2020).

238 The study of most other impacts required chained modeling, that is using climate model  
239 outputs as inputs to offline specialized models. This added layer of complexity likely  
240 contributed to the far smaller number of studies for the Ecosystems & Biogeochemistry  
241 category. Similarly, the infrequently studied Human Systems category always required  
242 chained modeling.

243 Chained modeling approaches relied mostly on temperature and precipitation as primary  
244 inputs for the offline models. In limited cases, other model outputs were important for  
245 chained studies. These included solar radiation (for agriculture (Parkes et al. 2015), energy  
246 (Smith et al. 2017), or human health (Moch et al. 2023)), humidity (agriculture (Fan et al.  
247 2021)), CO<sub>2</sub> (agriculture (Lili Xia et al. 2014a)), sea level rise (economy (Y. Chen et al. 2020)),  
248 or surface ozone and PM<sub>2.5</sub> (human health (Moch et al. 2023)). Any chained modeling will  
249 include the foundational uncertainty that stems from the parent model's output. Therefore,  
250 evaluating the robustness in the climate model outputs for chained modeling is critical.

## 251 Results from chained models rely on an uncertain foundation

252 On a global scale, climate model outputs of surface temperature and precipitation are  
253 generally consistent. Climate models agree that SAI scenarios will reduce GMST relative to  
254 climate change projections (Vioni et al. 2021). Modern SAI scenarios agree it is possible  
255 to maintain GMST near present day levels when compared to unmitigated climate change  
256 (Richter, Vioni, et al. 2022; Tilmes et al. 2018). Climate models also agree that SAI would  
257 likely decrease global mean precipitation (Vioni et al. 2021).

258 However, determining impacts on a scale practical for human and natural systems, which  
259 often uses chained modeling, requires regional results. While most studies presented  
260 some or all their results at a regional scale, most reported a resolution greater than 1 °

261 (>100 km). Even though some studies downscaled the initial output to finer resolution, the  
262 choice of downscaling method can cause large differences in the regional result (e.g.,  
263 precipitation and agriculture (Lili Xia et al. 2014b)). The relatively coarse resolution from  
264 climate models may be insufficient for understanding surface level impacts (Vioni et al.  
265 2021) that affect human and natural systems.

266 Furthermore, there exists notable disagreement at the regional level across models for  
267 basic abiotic variables such as temperature and precipitation, which are critical for the  
268 chained model approach. For example, the G6Sulfur model intercomparison found that  
269 half of the models (3 of 6) disagreed on the sign of temperature or precipitation change  
270 depending on the region (Vioni et al. 2021). Although there are some regions for which the  
271 sign of change is consistent, the magnitude and even sign are highly scenario dependent.  
272 For example, comparisons across the GLENS and ARISE scenarios also showed regional  
273 temperature and precipitation differences, especially related to the Atlantic meridional  
274 overturning circulation and Indian summer monsoon (Richter, Vioni, et al. 2022; Duffey et  
275 al. 2023; Fasullo and Richter 2023).

276 Even when there are multiple regional-scale findings on the same impact, interpretation  
277 can be complicated by differences in the choice of study region, SRM scenario, model,  
278 and/or counterfactual. For example, some studies suggest dangerous or extreme  
279 temperatures would be reduced under SAI, but none studied the same region, and each  
280 used a different model and scenario (Jones et al. 2018; Wang et al. 2022; Kuswanto et al.  
281 2022).

282 Indeed, additional comparisons outside of focused model intercomparison projects (MIPs)  
283 are difficult due to the limited number of studies using the same SRM deployment strategy  
284 (the location, frequency, amount, and duration of aerosol injection, Figure 1C),  
285 counterfactual (Figure 1D), and parent model. Although about half of studies used multiple  
286 counterfactuals, which could enable better comparison across studies, the different ways  
287 of setting up modeling experiments and consequent variety in results can make  
288 understanding and deliberation about the potential impacts and risks of SRM more difficult  
289 (Vioni et al. 2023; Müller et al. 2024b; Lee et al. 2024; Müller et al. 2024a).

290 The increasing number of standardized SRM scenarios such as those defined by the  
291 geoengineering model intercomparison project (GeoMIP, G1–G6), GLENS, and ARISE-SAI  
292 (Figure 1C) may alleviate this challenge as these specify an underlying GHG emissions  
293 scenario and an SRM scenario (see SI). Still, these prescribed scenarios are not always  
294 intended to suggest—and thus study—realistic SRM deployment. For example, GeoMIP  
295 has focused on SRM scenarios for model comparisons and SRM deployment in GLENS  
296 (Tilmes et al. 2018) begins in the past (year 2020).

297 Overall, the current state of SRM impacts science casts doubt on the robustness of the  
298 chained model approach for understanding impacts on Ecosystems & Biogeochemistry  
299 and Human Systems. The coarse climate model resolution, model-to-model differences in  
300 regional temperature and precipitation, and wide diversity of SRM scenarios and  
301 counterfactuals present notable barriers. Thus, care must be taken when interpreting  
302 projections of SRM impacts on human and natural systems based on analyses from  
303 climate models.

304

## 305 Despite uncertainty, model results suggest where to improve

306 While the conclusions regarding downstream SRM impacts from climate models may be  
307 uncertain, the research can offer insight into knowledge gaps and sensitivities that should  
308 be improved to better study SRM impacts. For example, while high emission scenarios  
309 (e.g., RCP8.5) are now considered unlikely (Sarofim et al. 2024), they can be a valuable  
310 counterfactual to separate the “signal from the noise” (i.e. effect of SRM on the  
311 background, (Yue et al. 2023)). Similarly, idealized scenarios such as solar dimming are  
312 unrealistic but offer a type of counterfactual for the implementation of aerosols in models.  
313 For example, model intercomparisons found better agreement for solar dimming  
314 comparisons than models that simulated more complex aerosol injection, suggesting  
315 some model disagreement was due to aerosol treatment (Visioni et al. 2021). Indeed,  
316 research gaps in stratospheric processes related to aerosol were noted as the most likely  
317 to reduce uncertainties for the Earth system response to SAI (Eastham et al. 2025).

318 In the case of Ecosystems & Biogeochemistry impacts, some tractable knowledge gaps  
319 were apparent. For example, many current models are based on parameterizations that  
320 rely on established relationships between temperature and precipitation, which would be  
321 decoupled with SRM. Several studies noted that a lack of explicit nitrogen cycling in current  
322 land surface models degrades the models’ ability to correctly predict NPP under high CO<sub>2</sub>  
323 concentrations (Glienke et al. 2015; Cao 2018). The models also assumed consistent  
324 sunlight reaching the ground, but SAI would change light quantity and quality (e.g., the ratio  
325 of diffuse and direct light), thus potentially changing processes like photosynthesis. This  
326 change in shortwave radiation is not incorporated into some models, such as those  
327 studying glacial melt rates (Moore et al. 2019). Some crop models included diffuse  
328 radiation (Fan et al. 2021), while others did not (Lili Xia et al. 2014a; Pongratz et al. 2012).  
329 Changes in light affect numerous biological processes and systems including seed  
330 germination, plant photosynthesis, plant water use efficiency, forest dynamics, and  
331 herbivory (F. Chen et al. 2024; Neimane-Šroma et al. 2024; Gu et al. 2002; Roberts and Paul

332 2006; L. Xia et al. 2016). Such changes to light may or may not be critical to understanding  
333 SRM impacts, but without its consideration it remains an open question.

334 For human systems, reducing the uncertainties about impacts is inherently difficult as  
335 human systems respond not only to abiotic variables but also other highly uncertain  
336 variables such as adaptations and technological advances (e.g., more efficient solar  
337 photovoltaics might offset some of the reductions in solar power generation that are  
338 expected from SAI (Smith et al. 2017; Baur et al. 2024)). The most studied Human Systems  
339 impact, the food system, focused on agricultural yield changes under SRM, typically via the  
340 chained model approach. The knowledge gaps for agriculture were similar to those  
341 mentioned above (light changes, carbon cycling, and model downscaling, (Tracy et al.  
342 2022)). Studies on other human systems were less frequent, which may be due to the  
343 difficulties listed above. For example, economic impact studies typically rely on integrated  
344 assessment models which use temperature as the main parameter. Studies have noted  
345 that such models ignore decoupling and nuances associated with SRM (Honegger et al.  
346 2021; Belaia et al. 2021). Other Human Systems impact studies relied on non-  
347 standardized, or novel, approaches. This includes sensitivity analyses on mortality  
348 (Eastham et al. 2018) or solar power calculations (Smith et al. 2017; Baur et al. 2024).  
349 Notably, other topics have yet to be studied, such as hydropower, wind power, and many  
350 staple crops. The conclusions from these limited studies are consequential for decision-  
351 makers. For example, the rare studies on energy systems suggest reduced solar power  
352 output (Smith et al. 2017; Baur et al. 2024; Murphy 2009), and one paper on malaria  
353 transmission suggests potential for increased malaria risks overall (Carlson et al. 2022).  
354

### 355 **Analog impact studies are an under-utilized research method**

356 A challenge to forecasting SRM impacts is the inability to corroborate models of a novel  
357 climate state with empirical evidence. Intentional experimentation of SRM at a scale large  
358 enough to induce measurable regional temperature change presents large ethical and  
359 technological barriers (Doherty et al. 2026). Several natural and anthropogenic events have  
360 occurred that offer potential analogs of SRM, such as large volcanic eruptions, smoke from  
361 large wildfires, and ship tracks. SRM analogs are not equivalent to SRM deployment  
362 scenarios as they are typically point source emissions over short time periods and in  
363 specific regions. Even so, the available analog literature shows that analog events have  
364 detectable global impacts as half of the studies (6 of 12) reported results on a hemispheric,  
365 zonal, or global scale. Like imperfect modeling of SRM, empirical analyses identify  
366 knowledge gaps and sensitivities but with the benefit of circumventing compounding

367 uncertainty from chained models, invalid parameterizations, or downscaling limitations.  
368 Analog studies also avoid additional risk as they utilize only past datasets.

369 Indeed, the limited number of published SRM analog studies identified important  
370 sensitivities. Many showed measurable and statistically significant decreases in regional  
371 and global precipitation following major volcanic eruptions (Trenberth and Dai 2007; Paik  
372 and Min 2017) and their results were used to test global models (Joseph and Zeng 2011;  
373 Haywood et al. 2013). Others identified impacts rarely studied in global models, such as  
374 changes in light quantity and the ratio of diffuse to direct light. Such changes are suspected  
375 to decrease global solar power generation by 4-10 % for every 1 % of solar reduction  
376 (Murphy 2009). These changes in sunlight could have non-linear effects on crop yields,  
377 (Proctor 2021) and one study suggested the reduction in total sunlight canceled the  
378 benefits of cooler temperatures and increased diffuse light for crop yields following  
379 volcanic eruptions (Proctor et al. 2018).

380 Studies that were not included in this review because they were not among the search  
381 results or did not explicitly discuss the applicability to SRM still offer important insight into  
382 physical and chemical processes that need to be improved in climate models (Eastham et  
383 al. 2025). For example, many volcanic studies focus on the impacts to stratospheric ozone  
384 and climate (Cole-Dai 2010; Angell 1997; Basha et al. 2023), (see the SI for a list of volcanic  
385 studies that did not meet the criteria for inclusion). Similarly, wildfires were not included in  
386 the search terms (see strengths and limitations below), but have been considered as an  
387 SRM analog with impacts on agriculture, (Hemes et al. 2020) and statistically significant  
388 change to global atmospheric temperatures (Li et al. 2026).

389 As interest in SRM field experimentation grows (Doherty et al. 2026), emphasis on  
390 empirical monitoring capability is needed (Waxman et al. 2026). Analog studies noted  
391 sparse observations in some regions or the need to fill data gaps with models (Zhao et al.  
392 2017; Trenberth and Dai 2007). One analog study found that large volcanic eruptions cause  
393 systematic biases in satellite observations of ocean carbon (Franz et al. 2024). This  
394 suggests that the observational networks required to monitor SRM impacts must be  
395 proactively tested, and issues identified, beforehand. Such efforts can be made today  
396 through SRM analog research. This point is especially important for currently understudied  
397 regions and/or regions where observation networks are less robust. While most analog  
398 studies reported regional results (9 of 12), they were mainly focused on North America (4),  
399 Asia (3), or Europe (2) by authors affiliated with those regions. For many regions, focused  
400 analog research has yet to be conducted, and authors in those regions are also  
401 underrepresented across SRM research. New studies will benefit from locally affiliated  
402 researchers with contextual knowledge.

403 Overall, despite the significant insight that empirical analog studies provide, they are rare  
404 and represent a decreasing fraction of the SRM impacts literature as model studies rapidly  
405 increase (Figure 1A). Indeed, a majority of recent SRM research grants went toward climate  
406 modeling (Sanborn and Sapinski 2026).

## 407 **Strengths and limitations of this study**

408 Although this review has limitations, it is the most comprehensive review to date of  
409 research on potential impacts of SRM on abiotic conditions, ecosystems &  
410 biogeochemistry, and human systems. A limitation of this review is that it only presents  
411 studies published through May 2024. Our search results identified several dozen  
412 conference abstracts and preprints of studies from the past five years that would have met  
413 our inclusion criteria had they been published in a peer-reviewed journal. That said, based  
414 on their titles, the unpublished records we excluded did not appear to address the  
415 fundamental limitations of chained modeling approaches identified here and few appeared  
416 to focus on Human Systems. Thus, we are confident that the trends, knowledge gaps, and  
417 research priorities described here still hold. A second limitation is that, due to the large  
418 variety of terms used to describe SRM, it is possible that some relevant studies of SRM  
419 impacts were missed by our search terms. However, since we screened all citations in  
420 review articles (which increased the number of included studies by approximately 10%), we  
421 are confident that our review includes a large majority of relevant studies. Finally, this  
422 review did not seek to capture research on important social dimensions of SRM, including  
423 but not limited to governance, justice, public opinion, and costs (see the SI for SRM-related  
424 publications that did not focus on the impacts reviewed here).

425

## 426 **Looking forward**

427 Taken together, the results of this review reinforce longstanding calls for greater use of  
428 empirical evidence to complement SRM modeling studies (Robock et al. 2013). While  
429 climate models remain indispensable for exploring hypothetical deployment pathways and  
430 global responses, this review shows that downstream impacts on natural and human  
431 systems are often constrained by coarse spatial resolution, divergent regional responses  
432 across models, and compounding uncertainty in chained modeling approaches. These  
433 limitations are particularly consequential for impacts that matter most for decision-  
434 making, which are inherently regional, context-specific, and mediated by social and  
435 ecological processes. As others have noted, inter-model agreement alone does not  
436 guarantee accuracy in the absence of observational constraints (Visioni et al. 2021).  
437 Improving the robustness of SRM impact assessments will require targeted efforts to test

438 models against empirical evidence, especially in the context of stratospheric composition  
439 (Eastham et al. 2025) where new ‘surprises’ are still being discovered (Murphy et al. 2023).

440 Our findings point to the need for a more deliberate, multi-method research strategy that  
441 integrates climate modeling with analog studies, targeted observations, laboratory  
442 experiments, and/or intermediate-scale modeling frameworks (for example, Sun et al.  
443 2026). Analog approaches are uniquely positioned to reveal sensitivities in natural and  
444 human systems that are difficult to assess through models alone. At the same time, no  
445 single method is sufficient to characterize the risks and trade-offs of SRM in a novel climate  
446 state. Progress will therefore depend on coordinated use of multiple approaches,  
447 expanded observational capacity, and greater regional and institutional diversity in SRM  
448 impacts research. Together, these steps would help move the field beyond reliance on a  
449 narrow set of model-accessible variables toward a more decision-relevant understanding  
450 of SRM’s potential impacts and uncertainties.

451

## 452 Methods

### 453 Search strategy

454 We conducted this review in accordance with the PRISMA 2020 Guidelines.(Page et al.  
455 2021) In July 2024, we used EBSCO and Google Scholar to identify relevant publications.  
456 Search terms included the "impact" or "effect" of "geoengineering", "stratospheric aerosol  
457 injection", "marine cloud brightening", "cirrus cloud thinning", "eruption", "volcano", or  
458 "Pinatubo" on "agriculture", "agricultural", "crop", "food", "health", "disease", "mortality",  
459 "infectious", "photovoltaic", "renewable", "hydropower", "wind", "solar power", "solar  
460 energy", "energy potential", "cyclone", "storm", "hurricane", "weather", "extreme", "typhoon",  
461 "monsoon", "sea ice", "sea level", "sea surface temperature", "ice sheet", "ocean",  
462 "biodiversity", "ecosystem", "ecology", "ecological", "vegetation", "species", "biome", "coral",  
463 "photosynthesis", "deposition", "acid rain", "ozone", "feedback", "albedo", "carbon",  
464 "tradeoff", and "trade-off". The specific searches and number of results are available in the  
465 SI.

466 Google Scholar and EBSCO removed duplicates as search results were saved. The  
467 resulting records were imported into a Zotero collection. We used the Duplicate Items  
468 function in Zotero and a manual inspection of the collection to identify duplicate records  
469 that had not been identified and removed by Google Scholar or EBSCO. Where possible,  
470 duplicates were merged. For sets of duplicates that Zotero would not merge due to the

471 degree of differences among the records, we retained the most complete record. We then  
472 imported all unique records with complete citations into an Excel sheet for screening.

## 473 Screening criteria

474 We excluded each unique record if it was (1) not peer-reviewed, (2) not about SAI, MCB,  
475 CCT, or using a natural analog to study SRM, (3) about SAI, MCB, CCT or a natural analog,  
476 but *not* about impacts (defined as those related to food, water, energy, health, ecosystems,  
477 and/or impacts on biophysical systems or conditions that affect any of those issue areas,  
478 (4) not in English or Spanish, (5) published after May 31, 2024, or (6) not available in full text  
479 via subscriptions, author requests, or purchase.

## 480 Data extraction

481 The following information was recorded for each record that met the inclusion criteria:

- 482 • type of study: literature review, modeling study, and/or observations from a natural  
483 analog. Analog studies were only included if they explicitly sought to understand  
484 potential impacts of SRM via observations from an analogous event.
- 485 • form(s) of SRM studied: SAI, MCB, CCT, or proxies such as solar dimming or surface  
486 albedo.
- 487 • names and/or brief descriptions of the model(s) and scenario(s) used. See the  
488 Supplementary Information for descriptions of the most common scenarios.
- 489 • counterfactual scenario(s) used in the study, defined as any scenario to which an  
490 SRM scenario was compared.
- 491 • region(s), ecosystem(s), and crop(s) of focus, if any. Papers that studied specific  
492 locations were placed into one or more broad regions modified from the United  
493 Nations' SDG regional framework by splitting North America, Europe, and Greenland  
494 into separate regions and adding four regions of interest in SRM research:  
495 Antarctica, the Arctic/high northern latitudes, the tropics, and ocean basins. Papers  
496 that included any observations or model results at hemispheric, zonal, or global  
497 scale, or that provided at least one global map for any result, were also categorized  
498 as global.
- 499 • specific quantitative metrics of the effects of SRM on Abiotic Conditions,  
500 Ecosystems & Biochemistry, or Human Systems at Earth's surface. For ozone,  
501 observations or modeling results at any altitude were included, since ozone is  
502 relevant to biological systems via its influence on surface UV. Indices of  
503 atmospheric circulation and teleconnections such as the Hadley and Walker  
504 circulations, El Nino-Southern Oscillation (ENSO), North Atlantic Oscillation (NAO),  
505 Intertropical Convergence Zone (ITCZ), as well as the Atlantic Meridional

506 Overturning Circulation (AMOC) were also recorded, because these phenomena  
507 affect temperature and precipitation patterns over broad regions.

- 508 • impact categories for which the paper’s results were relevant. For example, a paper  
509 reporting the impacts of SRM on sea surface temperature and sea level rise-  
510 equivalent melting rates of an ice sheet would be marked as providing information  
511 relevant to the “marine ecosystems,” “cryosphere,” and “sea level” impact  
512 categories.
- 513 • author affiliations were extracted via Lens.org.

## 514 **Augmenting the dataset**

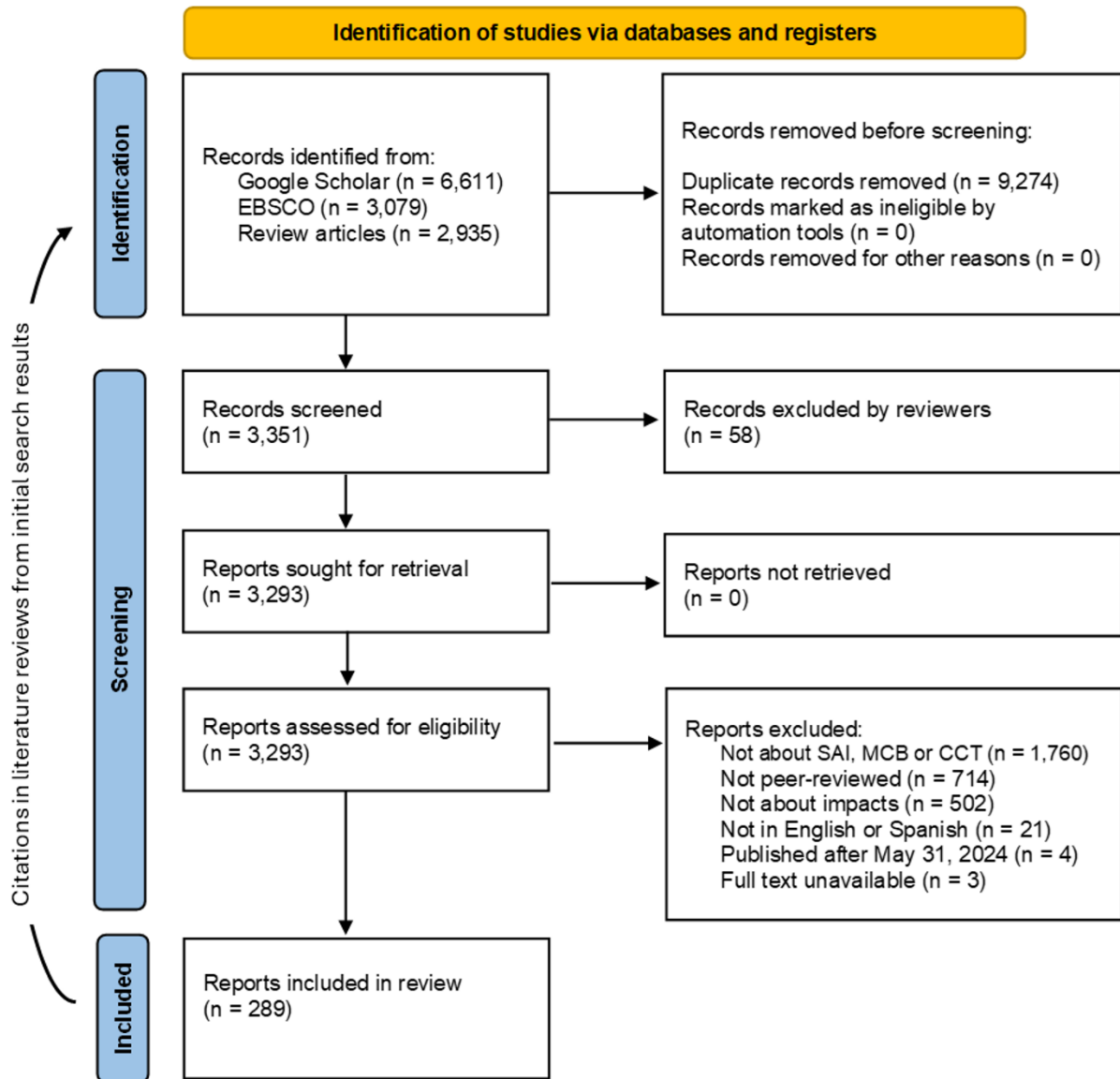
515 After screening and reviewing articles identified through our EBSCO and Google Scholar  
516 searches, we downloaded all citations from the literature reviews into Zotero. We then  
517 repeated the process described above to identify and remove duplicates, screen unique  
518 records, and review included articles. We summarized the process and results using the  
519 Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework  
520 (Figure 3).

521

522

523 **Figure 3. Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram**  
 524 **illustrating the identification, screening, and selection of publications and modified to show the use of**  
 525 **citations from literature reviews to identify additional relevant records (n = number of publications).**

526



527

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### 778 **Author Contributions**

779 ZCJD: writing, analysis, and interpretation. LAM: systematic review and study design as  
780 well as support of writing, analysis and interpretation. BB: study design and systematic  
781 review as well as writing support. SSS: systematic review support and writing review. LD:  
782 study design, and support of writing, analysis and interpretation.

### 783 **Data availability**

784 The datasets generated and analyzed in this study are included in the supporting  
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790 **Supplementary Information**

791 **Contents**

792 Description of XLSX file “Supplementary Info SRM Impacts Data Sheets” ..... 29  
793 Table S1: Common SRM and baseline (counterfactual) scenarios..... 30  
794 Table S2: Descriptions and criteria for impact categories ..... 32  
795 References for Supplementary Information ..... 35

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798 **Description of XLSX file “Supplementary Info SRM Impacts Data Sheets”**

799 The separate XLSX file “Supplementary Info SRM Impacts Data Sheets” has  
800 datasheets with 1) “ReadMe” information, 2) the data recorded from each of the 289  
801 publications included in the review, 3) a list of volcanic studies that did not meet the  
802 criteria for inclusion in this review but that may be of interest to readers, 4) a list of  
803 publications that were about SRM but not about the impacts that were the focus of this  
804 review, and the number of results for each set of searches conducted in 5) Google  
805 Scholar and 6) EBSCO.

806 **Table S1: Common SRM and baseline (counterfactual) scenarios**

807 For descriptions of less common baseline scenarios such as SRES, SSP, and  
 808 ScenarioMIP, we refer readers to IPCC (2000, 2023) and Tebaldi et al. (2021).

<b>Name</b>	<b>Description</b>	<b>Reference</b>
piControl	Preindustrial control	Taylor et al. (2012)
1pctCO2	1% yr <sup>-1</sup> increase in CO <sub>2</sub> until quadrupled above preindustrial levels	Taylor et al. (2012)
abrupt4xCO2	Abruptly quadruple CO <sub>2</sub> above preindustrial levels, then hold fixed	Taylor et al. (2012)
RCP4.5	Changes in global population, GDP, energy consumption, energy production, land use, and emissions that stabilize radiative forcing at 4.5 W m <sup>-2</sup> in 2100	Thomson et al. (2011)
RCP8.5	Changes in global population, GDP, energy consumption, energy production, land use, and emissions that stabilize radiative forcing at 8.5 W m <sup>-2</sup> in 2100	Riahi et al. (2011)
G1	Balance abrupt4xCO2 via solar irradiance reduction (dimming)	Kravitz et al. (2011)
G1ocean-albedo	Balance abrupt4xCO2 via ocean albedo increase	Kravitz et al. (2013)
G2	Balance 1pctCO2 via solar irradiance reduction (dimming)	Kravitz et al. (2011)
G3	Keep top of atmosphere radiative flux at 2020 levels against a background of RCP4.5 via stratospheric sulfate aerosols	Kravitz et al. (2011)
G4	Inject 5 Tg SO <sub>2</sub> into lower stratosphere per year against a background of RCP4.5	Kravitz et al. (2011)
G4cdnc	Increase cloud droplet number concentration in marine low clouds by 50% against a background of RCP4.5	Kravitz et al. (2013)
G4sea-salt	Inject sea salt aerosols into tropical marine boundary layer to achieve effective radiative forcing of -2.0 W m <sup>-2</sup> against a background of RCP4.5	Kravitz et al. (2013)
G4SSA	Inject a prescribed distribution of 8 Tg SO <sub>2</sub> stratospheric aerosols per year against a background of RCP6.0	Tilmes et al (2015)
G5 (also called G3-SSCE or SALT)	Keep top of atmosphere radiative flux at 2020 levels against RCP4.5 via sea salt injection into marine low clouds	Alterskjær et al. (2013); Niemeier et al. (2013)

G6sulfur	Reduce forcing from ScenarioMIP Tier 1 high forcing scenario to the medium forcing scenario with stratospheric sulfate aerosols	Kravitz et al (2015)
G6solar	Reduce forcing from ScenarioMIP Tier 1 high forcing scenario to the medium forcing scenario with solar irradiance reduction	Kravitz et al (2015)
GLENS	Inject SO <sub>2</sub> from 2020 to 2099 to maintain global mean surface temperature and interhemispheric and equator-to-pole surface temperature gradients at 2020 values against a background of RCP8.5	Tilmes et al. (2018)
ARISE-SAI-1.5	Inject SO <sub>2</sub> to keep global mean surface air temperature near 1.5°C above its pre-industrial value against a background of SSP2-4.5	Richter et al. (2022)
ARISE-SAI-1.0	Inject SO <sub>2</sub> to keep global mean surface air temperature near 1.0°C above its pre-industrial value against a background of SSP2-4.5	Richter et al. (2022)

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810 **Table S2: Descriptions and criteria for impact categories**

811 For each publication included in the review, we marked the types of impacts for which  
 812 its results were relevant, according to the following criteria. Some categories can  
 813 overlap, depending on the measure in question. For example, a publication that  
 814 reported sea level-equivalent melt rates from the Greenland Ice Sheet would be marked  
 815 as being relevant to the Sea Level and Cryosphere categories.

<b>Impact category</b>	<b>Inclusion criteria for reported metrics</b>
Food	Measures explicitly tied to food, e.g., crop yield, calories, etc., but not precipitation, temperature, soil moisture, or other plant-relevant measures reported in papers that are not about crops
Health	Measures explicitly tied to human health, e.g. surface air quality (e.g., PM2.5, ozone), UV levels, disease transmission, wet bulb temperatures, heat waves, mortality, etc.
Water	Measures explicitly tied to water supply, e.g., water quality, water storage, aquifer recharge, etc., but not precipitation, ice sheet melting, soil moisture, or streamflow
Energy	Measures explicitly tied to energy systems, e.g., renewable energy generation potential
Dangerous Extreme Temperature	Measures of surface temperature that would be considered dangerous or extreme by the lay public and/or were explicitly tied in the publication to dangerous extremes for health or ecosystems, e.g., frequency of heatwaves, exceedance of dangerous wet bulb temps, dangerous thresholds of degree heating days (for coral reefs), dangerous rates of warming, etc.
Dangerous Extreme Precipitation	Measures of precipitation that would be considered dangerous or extreme by the lay public and/or were explicitly tied in the publication to dangerous extremes for health or ecosystems
Mean Temperature	Mean surface temperature averaged over any spatial or temporal scale, e.g., global, zonal, regional, annual, seasonal, monthly, etc.
Mean Precipitation	Mean precipitation averaged over any spatial or temporal scale, e.g., global, zonal, regional, annual, seasonal, monthly, etc.
Statistical Extreme Temperature	Indices of statistically anomalous surface temperature including but not limited to ETCCDI indices such as TXx, TNn, CSDI, WSDI, etc. (WMO et al., 2009)
Statistical Extreme Precipitation	Indices of statistically anomalous precipitation including but not limited to ETCCDI indices (WMO et al. 2009), rainfall above/below percentiles, duration of statistically anomalous rainfall or drought, etc.
Carbon Cycle	Measures related to the carbon cycle such as carbon storage, fluxes and feedbacks in vegetation, soils, land, ocean, e.g. GPP, NPP, respiration, etc. Some measures overlap with Plants.

Plants	Measures related to plant growth, other than temperature or precipitation, e.g., LAI, NDVI, GPP, NPP, photosynthesis, soil moisture, soil chemistry, etc. Only overlaps with food if measures are explicitly related to crop growth. Some measures overlap with Carbon Cycle.
Marine Ecosystems	Measures related to marine ecosystems, e.g., indices of coral bleaching, marine NPP, chlorophyll concentration, marine biodiversity, indices of ocean chemistry, sea surface temperature, etc.
Cryosphere	Measures related to ice sheets, sea ice, glaciers, or permafrost.
Terrestrial Ecosystems	Measures related to terrestrial ecosystems other than the Plants, Temperature, or Precipitation categories, e.g., streamflow, biodiversity, permafrost, wildfire, warming rates tied to geographic ranges, acid rain or sulfur deposition, etc. Only overlaps with Water if the result is explicitly tied to water supply. Measures related to permafrost overlap with Cryosphere.
Ozone	Measures of ozone at any altitude, e.g., stratospheric, total column, etc. Only overlaps with Health if explicitly tied to health outcomes.
Cyclone	Measures related to (extra)tropical cyclone frequency, intensity, storm track, storm surge, etc.
Monsoon	Measures related to monsoon timing, intensity, track, etc.
Sea Level	Measures related to sea level, including ice sheet surface mass balance, sea level equivalent melting rates, etc.
Light Quality	Measures of direct and/or diffuse radiation
AMOC	Indices of the Atlantic Meridional Overturning Circulation
Other Atmo Circ/Telecon	Indices of atmospheric circulations or teleconnections such as Walker circulation, Hadley circulation, North Atlantic Oscillation, Indonesian Throughflow, etc. ITCZ and ENSO are separate categories.
ITCZ	Indices of the Intertropical Convergence Zone
Sulfur Deposition	Measures of S deposition from sulfate aerosol SAI
Surface UV	Measures of UV or biologically active radiation at the surface
ENSO	Indices of the El Niño Southern Oscillation
Economic	Measures of economic damage from deploying or not deploying SRM, etc. Does not include the cost of SRM deployment.
Snow Cover	Measures of snow cover
Wind Speed	Measures of surface wind speeds
Surface Albedo	Measures of surface albedo related to the effects of SRM, e.g. from changes in snow or ice extent, vegetation cover, etc.
Air Quality	Measures of surface air quality
Storm Tracks	Measures of storm tracks
Perceived Failure	Measures of societal perceptions of the success or failure of SRM as a response to climate change

Convective	Measures of convective weather unrelated to monsoons or cyclones
Remote Sensing	Measures of the performance of remote sensing instruments
Sky Color	Measures of the color of the sky

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