

# Assessing the Impact of Solar Climate Intervention on Future U.S. Weather Using a Convection-Permitting WRF Model

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**Abstract.** A primary solar climate intervention (SCI) strategy is stratospheric aerosol injection (SAI). SAI would increase the number of small reflective particles (aerosols) in the upper atmosphere to reduce climate warming by reflecting more incoming solar radiation away from Earth. Research on SCI is growing quickly, but no studies to date have examined the impact of SCI on severe storms using a mesoscale weather model. In this study, we develop a novel framework using the convection-permitting (4-km resolution) Weather Research & Forecasting (WRF) model to assess the potential impact of SCI on future convective weather over the contiguous United States (CONUS). We conduct three types of simulations for the March-August 2011 period, during which widespread convective outbreaks occurred across the CONUS: (1) a control simulation driven by ERA-5 reanalysis; (2) a Pseudo-Global Warming (PGW) simulation representing a future with increasing greenhouse gas concentrations but without SCI; and (3) a novel Pseudo-SAI (PSAI) simulation representing a future with SCI. Future climate perturbations applied to the PGW and PSAI boundary conditions are derived from ensemble-mean differences between baseline and future scenarios in Community Earth System Model (CESM) experiments with and without SCI. These perturbations are taken from two CESM projects featuring different scenarios: the Geoengineering Large Ensemble (GLENS) and the Assessing Responses and Impacts of Solar Climate Intervention on the Earth System with Stratospheric Aerosol Injection (ARISE). The PSAI simulation includes an additional aerosol optical depth perturbation to represent the shortwave radiative impact of SAI. This paper presents the novel experimental design and modeling framework, and shares preliminary results that highlight the feasibility and scientific potential of this approach for assessing potential weather-scale impacts of SCI. In particular, we show that global warming leads to an increase in extreme precipitation and more frequent deep convection over the Eastern U.S., both of which can be mitigated by SAI deployment.

**Short summary.** We develop a novel framework using the convection-permitting Weather Research and Forecasting (WRF) model to assess how stratospheric aerosol injection, a solar climate intervention strategy, affects future convective weather over the contiguous U.S. Results demonstrate the feasibility and scientific potential of this approach for evaluating weather-scale impacts and suggest that such intervention may mitigate changes in temperature, precipitation, and convective activity due to warming.

## 32 **1 Introduction**

33 To potentially avoid some of the worst impacts of global warming, there is increasing interest and research on climate  
34 intervention (CI) methods. Significant concerns exist over the possible adverse effects that CI approaches may have if  
35 implemented, so it is important to understand their potential impacts. Solar Climate Intervention (SCI), also referred to as solar  
36 geoengineering or solar radiation management, has been the subject of growing scientific investigation in the context of climate  
37 change (e.g., NASEM 2021; Patrick et al. 2022; The Royal Society 2025). A primary SCI strategy considered is stratospheric  
38 aerosol injection (SAI), which would increase the number of small reflective particles (aerosols) in the upper atmosphere to  
39 reduce climate warming by reflecting more incoming solar radiation away from Earth.

40 The natural analogue to SAI is a large volcanic eruption that creates a stratospheric aerosol layer, and the Earth cools as  
41 a result (e.g., Budyko, 1977; Robock, 2000). If SAI was pursued, an idea is that aerosol precursors (e.g., SO<sub>2</sub>) could be injected  
42 into the stratosphere with strategic design for injection locations (i.e., latitudes and altitudes), aerosol amounts, and timing  
43 (MacMartin et al., 2017; Tilmes et al., 2017; Vioni et al., 2019; Vioni et al., 2020), all depending on the intended  
44 temperature target (how much to cool the planet or reduce the rate of future warming). MacMartin et al. (2014) developed a  
45 feedback-control algorithm to regularly modify the amount of solar irradiance reduction needed to meet the chosen global  
46 mean temperature objective, which was further expanded to achieve multiple climate objectives simultaneously (Kravitz et  
47 al., 2016; Kravitz et al., 2017). However, conclusions about the effectiveness and risks of SAI are uncertain, and they are  
48 dependent upon the specifics of the modelling scenario (MacMartin et al., 2016; NASEM, 2021). To-date, most assessments  
49 of SAI typically consider just one scenario with one particular injection strategy (where and when to inject).

50 Significant progress in assessing the impacts of SAI on the Earth system and understanding their underlying mechanisms  
51 has been achieved through initiatives like the Geoengineering Model Intercomparison Project (GeoMIP; Kravitz et al., 2015;  
52 Vioni et al., 2024), the Geoengineering Large Ensemble project (GLENS; Tilmes et al., 2018), and the Assessing Responses  
53 and Impacts of Solar climate intervention on the Earth system project (ARISE; Richter et al., 2022). GeoMIP explores a range  
54 of idealized and scenario-based SAI experiments using prescribed aerosol or radiative forcing perturbations, while GLENS  
55 and ARISE employ feedback-controlled sulfur dioxide injection strategies designed to maintain global temperature targets  
56 under increasing greenhouse gas forcing. Together, these coordinated modeling efforts have revealed several robust features  
57 of the climate response to SAI. For example, previous studies have shown that SAI can suppress the intensification of the  
58 global hydrological cycle under global warming and moderate climate hazards in most regions (Simpson et al., 2019; Cheng  
59 et al., 2019; Irvine and Keith, 2020). A number of assessments have also been conducted on the impact of SAI on the polar  
60 vortex and tropospheric North Atlantic Oscillation (NAO) (Simpson et al., 2019; Banerjee et al., 2020), tropospheric air  
61 pollution (Xia et al., 2017), stratospheric ozone loss (Tilmes et al., 2021; Robrecht et al., 2021), the ocean and the cryosphere  
62 (Fasullo et al., 2018; Jiang et al., 2019; Morrison et al., 2024), ecosystems (Hueholt et al., 2024), wildfire risk (Touma et al.,  
63 2023), biogeochemistry (Yang et al., 2020), and climate impacts regionally (e.g., Pinto et al., 2020; Da-Allada et al., 2020).

64 Yet, no studies to date (to our knowledge) have examined the impact of SAI on mesoscale processes and hazardous convective  
65 weather.

66 Hazardous convective weather, including severe thunderstorms, tornadoes, strong winds and large hail, is a prominent  
67 source of natural disasters and losses across the world, including the contiguous United States (CONUS) (NCEI, 2024; Munich,  
68 2024). Potential future changes in frequency and intensity of severe weather have drawn considerable attention due to the  
69 economic and societal implications of such changes. Climate models forced by increasing greenhouse gas concentrations  
70 suggest that convection and severe weather will increase in a warmer climate from enhanced convective available potential  
71 energy (CAPE)—a measure of atmospheric instability that promotes cloud formation and thunderstorm development (e.g.,  
72 Diffenbaugh et al., 2013; Rasmussen et al., 2017). Figure S1 in the supplementary material, diagnosed from ARISE Shared  
73 Socioeconomic Pathway 2-4.5 (SSP2-4.5) future projections with and without SAI, indicates a significant increase (up to 12%)  
74 in the number of days with environments favorable for the formation of severe thunderstorms (NDSEV; a combined proxy  
75 critical for the occurrence of several convective storms) under climate change, including potentially intensified convective  
76 weather over much of the southeast and eastern U.S. This increase is mostly avoided when SAI is deployed as in ARISE (Fig.  
77 S1). Glade et al. (2023) revealed that while the forced changes in thermodynamic parameters like NDSEV, CAPE and  
78 Convective Inhibition (CIN) are significantly reduced under SAI relative to climate change, future changes in kinematic  
79 parameters such as wind shear are less certain.

80 While global climate models are useful to examine future projected changes in the large-scale severe thunderstorm  
81 environment (Fig. S1), coarse-resolution models do not adequately represent the fine-scale cloud and mesoscale processes  
82 critical for understanding the physical mechanisms that may result in a changing convective population. In contrast, high-  
83 resolution (e.g., horizontal grid spacing of ~4 km) convection-permitting models (CPMs) do not rely on convective  
84 parameterizations to represent the evolution and life cycle of convective clouds and allow for a more accurate representation  
85 of surface fields (Prein et al., 2015), such as topography (Rasmussen et al., 2011) and the diurnal cycle of precipitation  
86 (Rasmussen et al., 2017). Research at the interface of climate and mesoscale processes has motivated efforts to conduct  
87 convection-permitting climate model simulations that more accurately represent cloud and mesoscale processes under varying  
88 climate states, including recent progress in global convection-permitting climate modeling (Stevens et al. 2019; Palmer and  
89 Stevens 2019; Senior et al., 2021). Dynamical downscaling, which utilizes initial and boundary conditions from global climate  
90 model projections or reanalysis datasets to drive regional CPMs, has been found to reasonably replicate the climatological  
91 distribution and variability of convective storms (Trapp et al., 2011; Gensini and Mote, 2014; Prein et al., 2017a) and  
92 precipitation (Liu et al., 2017). One widely used form of dynamical downscaling is the pseudo global warming (PGW)  
93 technique, which has been successfully used to demonstrate the impact of climate change on convective weather around the  
94 world (Schär et al., 1996; Sato et al., 2007; Hara et al., 2008; Kawase et al., 2009; Lackmann, 2013; Rasmussen et al., 2011;  
95 Rasmussen et al., 2014; Rasmussen et al., 2017; Liu et al., 2017; Trapp and Hoogewind, 2016; Prein et al., 2017a; Prein et al.,  
96 2017b; Viceto et al., 2017; Gutmann et al., 2018; Rasmussen et al., 2023; Cui et al., 2024; Dominguez et al., 2024). The PGW

97 approach is typically paired with a control simulation driven by reanalysis data to represent present-day conditions. Global  
98 climate model projections are used to calculate the climate change signal as the climatological difference between a future  
99 period and a baseline period. This “delta signal” is then added to the lateral and lower boundary conditions of the regional  
100 model, as well as to greenhouse gas concentrations. PGW simulations represent future thermodynamic environments while  
101 maintaining synoptic conditions that are very similar to those in the control run. Thus, the PGW method is particularly well-  
102 suited to address the question: “what will today’s weather look like in a future warmer climate?” (Rasmussen et al., 2017).  
103 This technique can be used to estimate the fine-scale processes and physical mechanisms that explain changes in the full  
104 spectrum of clouds and precipitation systems in a future climate. For example, it has been shown that in response to climate  
105 change there may be fewer weak storms but more strong storms over the contiguous U.S., which can be largely explained by  
106 changes in the thermodynamic environments (Rasmussen et al., 2017). Recent studies have also used this technique to study  
107 flash flood producing storms (Dougherty and Rasmussen, 2020; Dougherty and Rasmussen, 2021), including atmospheric  
108 rivers (Dougherty et al., 2020).

109 The purpose of this paper is to develop a novel modelling framework using the convection-permitting Weather Research  
110 and Forecasting (WRF) model (Skamarock et al., 2008) to assess the potential impact of SAI on hazardous convective weather  
111 over the CONUS. The PGW technique is a proven methodology that allows examination of how today’s weather might change  
112 under future climate states (Rasmussen et al., 2017; Liu et al., 2017). A novel aspect of this study is to conduct parallel pseudo-  
113 stratospheric aerosol injection (PSAI) simulations and compare the future changes in weather under climate change to those  
114 where SAI has been deployed. To our knowledge, no other studies have examined how SAI might impact fine-scale cloud and  
115 mesoscale processes and their thermodynamic environments in a future climate. This paper is organized as follows: Section 2  
116 provides an overview of the GLENS and ARISE data used to drive our convection-permitting model. Section 3 describes the  
117 WRF model and the detailed setup of PGW and PSAI simulations. Section 4 presents a few preliminary results that highlight  
118 the feasibility and scientific potential of this approach for assessing weather-scale impacts of SCI, followed by a summary and  
119 conclusions in Section 5.

## 120 **2 SAI simulations with Community Earth System Model (CESM)**

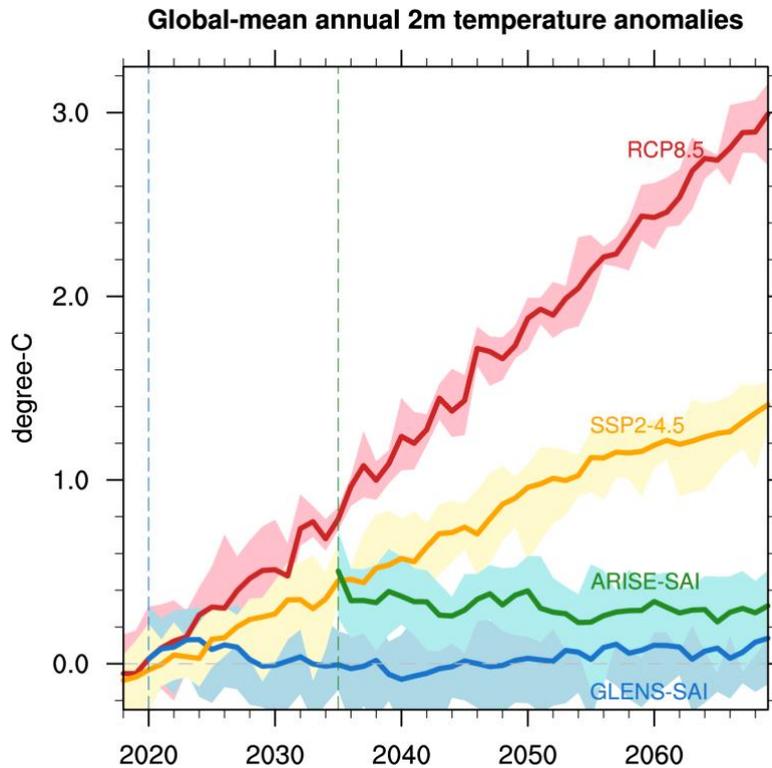
121 We utilize two CESM-SAI ensembles featuring different climate change and SAI scenarios to drive the WRF model: the  
122 GLENS (Tilmes et al., 2018) and ARISE (Richter et al., 2022) simulations, all conducted at a horizontal resolution of 1.25°  
123 longitude by 0.9° latitude. Table 1 lists the details for these ensembles. GLENS used the CESM version 1 (Hurrell et al., 2013)  
124 with the Whole Atmosphere Community Climate Model as its atmospheric component (CESM1-WACCM; Mills et al., 2017)  
125 to complete a 21-member ensemble of stratospheric sulfate aerosol geoengineering simulations between 2020-2099. The time-  
126 varying sulphur dioxide (SO<sub>2</sub>) injections, using the aforementioned feedback algorithm, occur at ~5 km above the tropopause  
127 at four locations (15°N/S and 30°N/S). The controller algorithm specifies the amount of SO<sub>2</sub> injected, updated annually based  
128 on the climate objectives (MacMartin et al., 2014; Kravitz et al., 2017). The climate objectives of GLENS were to maintain

129 the global-mean surface temperature, interhemispheric surface temperature gradient, and equator-to-pole surface temperature  
 130 gradient at 2020 values under the representative concentration pathway 8.5 (RCP8.5) scenario (Fig. 1; red and blue curves).

131 **Table 1.** CESM data that was utilized to generate regional climate simulation forcing terms.

Name	Model	Period	Ens.	Forcing	References
GLENS-RCP8.5	CESM1-WACCM	2010-2030	17	RCP8.5	Tilmes et al., (2018)
		2010-2098	4		
GLENS-SAI	CESM1-WACCM	2020-2099	21	RCP8.5 and SAI	
ARISE-SSP2-4.5	CESM2-WACCM	2015-2069	5	SSP2-4.5	Richter et al., (2022)
		2015-2100	5		
ARISE-SAI	CESM2-WACCM	2035-2069	10	SSP2-4.5 and SAI	

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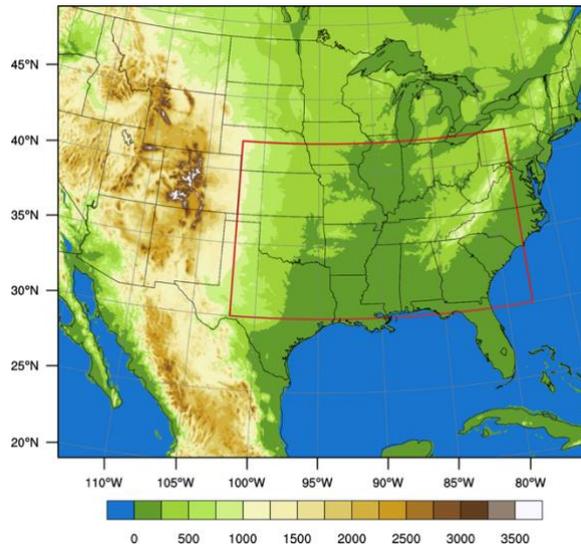
134 **Figure 1.** Global mean surface air temperature anomalies relative to the 2015–2024 baseline from CESM1-WACCM RCP8.5 (red curve),  
 135 CESM2-WACCM SSP2-4.5 (orange curve), and their respective GLENS-SAI (blue curve) and ARISE-SAI (green curve) simulations.  
 136 Shading represents the range of temperature anomalies (maximum to minimum across all available individual members). Vertical blue and  
 137 green lines indicate the start year of SAI for GLENS (2020) and ARISE (2035), respectively. Adapted from Tilmes et al. (2018) and Richter  
 138 et al. (2022).

139 The GLENS project assumes no climate mitigation through 2100; that is, SAI must increase in magnitude through the  
140 end of the century to counter warming from ever-increasing concentrations of greenhouse gases. The ARISE-SAI project uses  
141 a moderate SSP2-4.5 that more closely tracks current policy scenarios for climate mitigation. ARISE is a 10-member SCI  
142 ensemble with version two of the CESM (Danabasoglu et al., 2020), again with the Whole Atmosphere Community Model  
143 (CESM2-WACCM; Gettelman et al., 2019) as its atmospheric component. ARISE-SAI assumes that the world would not  
144 begin SAI until 2035 (when the CESM2 global surface temperature reaches  $\sim 1.5^{\circ}\text{C}$  above pre-industrial levels following the  
145 SSP2-4.5 scenario) and would only continue it until 2070, when carbon levels in the atmosphere reach “safer levels” due to  
146 mitigation and the implementation of carbon dioxide removal techniques (Figure 1; orange and green curves). Sulfur dioxide  
147 is injected at the same latitudes in both ARISE-SAI and GLENS-SAI simulations, with an injection altitude in the lower  
148 stratosphere near 21.5 km. Considering that GLENS and ARISE have different climate change scenarios (RCP8.5 and SSP2-  
149 4.5), strategic design and stratospheric aerosol loadings, there is no reason to assume that the impact of SAI will be the same  
150 between them. Therefore, the GLENS and ARISE ensembles span a range of SCI scenarios that we leverage for our project.

### 151 **3 WRF model and experimental designs**

#### 152 **3.1 WRF description**

153 Previous efforts have created long-term, convection-permitting regional hydroclimate simulations using the WRF model by  
154 dynamically downscaling ERA5 reanalysis (Hersbach et al., 2020), including a 40-year dataset over the conterminous United  
155 States (CONUS404; Rasmussen et al., 2023) and 22-year simulations over South America conducted by the South America  
156 Affinity Group (SAAG; Dominguez et al., 2024). For this project, we use WRF version 4.1.5 (Skamarock et al., 2008), which  
157 is an updated version of that used in CONUS404 and identical to the one used in the SAAG simulations. We conduct all  
158 simulations over a domain of 1019x863 grid points, using 4-km horizontal grid spacing to encompass most of the CONUS,  
159 Southern Canada, Northern Mexico and nearby waters (Figure 2). The simulations include 61 vertically-stretched levels  
160 capped at 10 hPa. The major subgrid parameterizations include the Thompson microphysics scheme (Thompson et al., 2008),  
161 the Yonsei University (YSU) planetary boundary layer formulation (Hong et al., 2006), the Noah-MP land surface model (Niu  
162 et al., 2011), and the Rapid Radiative Transfer Model (RRTMG) for longwave and shortwave atmospheric radiation (Iacono  
163 et al., 2008).



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**Figure 2.** Domain of the 4-km WRF simulation with land surface elevation height (m). The red box denotes the eastern U.S. region used in subsequent analyses.

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Our control setup and parameterizations are identical to the setup used for the CONUS404. This configuration has been demonstrated to generally well reproduce the diurnal cycle of precipitation (Rasmussen et al., 2017; Scaff et al., 2020), mesoscale convective systems (Prein et al., 2017a), and state variables like temperature and moisture (Liu et al., 2017). In addition, the newly integrated Miguez-Macho groundwater scheme has been shown to significantly reduce the warm air temperature and low moisture biases (Barlage et al., 2021) that were evident during the late warm season in earlier CPM simulations over CONUS (Liu et al., 2017).

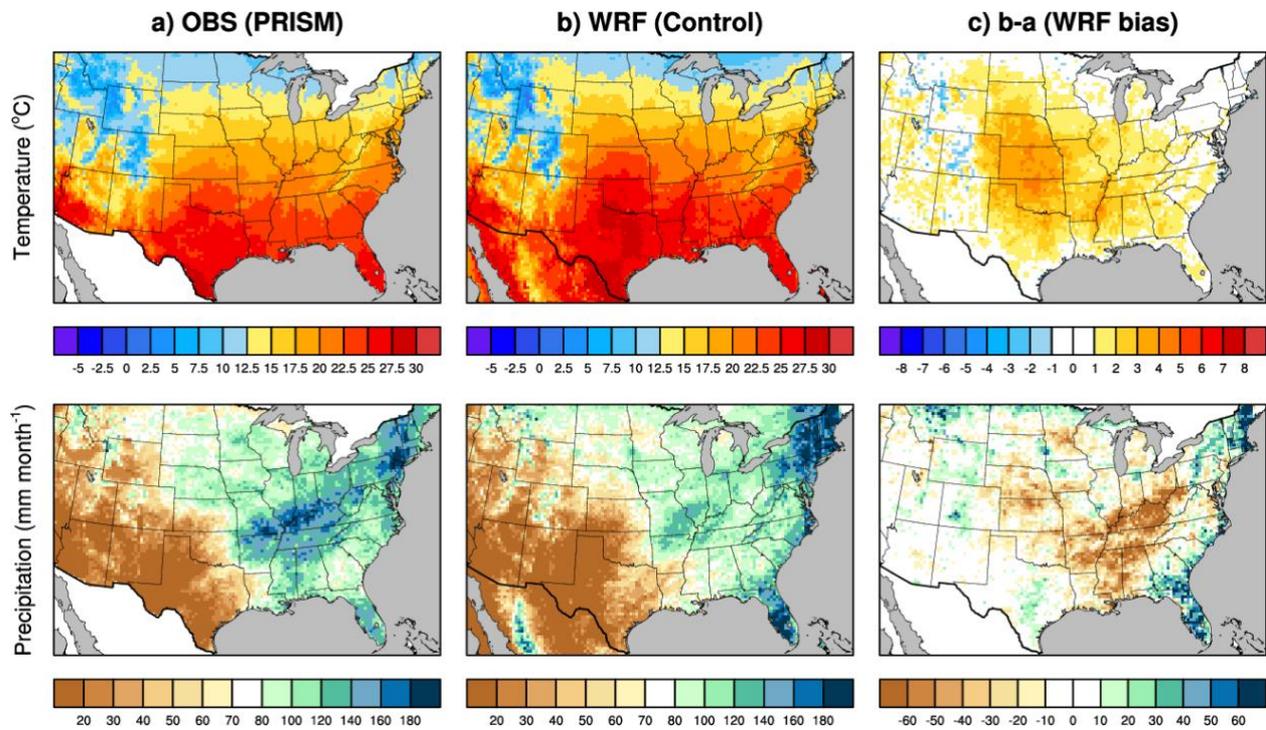
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**Figure 3.** March–August 2011 average temperature ( $^{\circ}\text{C}$ ) and precipitation ( $\text{mm}/\text{month}$ ) from (a) PRISM data, (b) WRF control simulations, and (c) their difference.

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This study focuses on the warm season (March–August) of 2011, which includes the U.S. tornado super outbreak that occurred from 25–28 April, resulting in 321 fatalities and an estimated \$14.3 billion in damages (NCEI, 2024). Using the ERA-5 reanalysis dataset (Hersbach et al., 2020) as the lower and lateral boundary conditions, we conduct a WRF control simulation over this period. Figure 3 compares the mean temperature and precipitation from the control with observations from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) dataset (Daly et al., 1997) at 4-km resolution. The WRF control simulation effectively captures both large-scale and fine-scale temperature and precipitation patterns, including localized cooler regions over the high-elevation western U.S. The model also realistically represents the enhanced precipitation on the windward sides of the Rocky Mountains and Appalachians and reduced on the leeward sides, a pattern shaped by underlying topography. On the other hand, the model still exhibits a warm and dry bias in the Central U.S., particularly during June–August, consistent with findings from Liu et al. (2017) and Rasmussen et al. (2023). Along the East Coast, especially in the Southeast, the model tends to overestimate summer precipitation—a feature also noted in both studies.

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### 3.2 PGW and PSAI experimental design

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To assess the impact of climate change and SAI on convective storms, two additional types of WRF simulations are conducted: (1) single-member PGW simulations forced with reanalysis plus a future climate perturbation from greenhouse gas forcing; and (2) single-member Pseudo SAI (PSAI) simulations developed herein that use reanalysis plus a term that incorporates the

191 impacts of both climate change and SAI from ARISE and GLENS. Both the ERA5 reanalysis and the ARISE and GLENS  
 192 model outputs are interpolated to the same 4 km WRF grid during preprocessing before being used to construct the boundary  
 193 conditions. Table 2 summarizes the lateral and lower boundary forcing for the suite of WRF simulations used in this study.  
 194 The GLENS and ARISE monthly mean climate forcing changes from the mid-century time frame (2060-2069) relative to the  
 195 present (2015-2024) are used to develop the PGW and PSAI forcings that drive the high-resolution convection-permitting  
 196 WRF simulations. The mid-century period is chosen to align with the ARISE-SAI simulations (which end in 2069). For the  
 197 GLENS simulations under the RCP8.5 scenario, a 21-member ensemble exists for simulations with SAI and a four-member  
 198 ensemble exists without SAI. For the ARISE simulations under the SSP2-4.5 scenario, 10-member ensembles exist for  
 199 simulations both with and without SAI (ARISE-SAI and ARISE-CTRL, respectively). These two ensembles are used to force  
 200 the PSAI and PGW runs under SSP2-4.5 (Table 1).

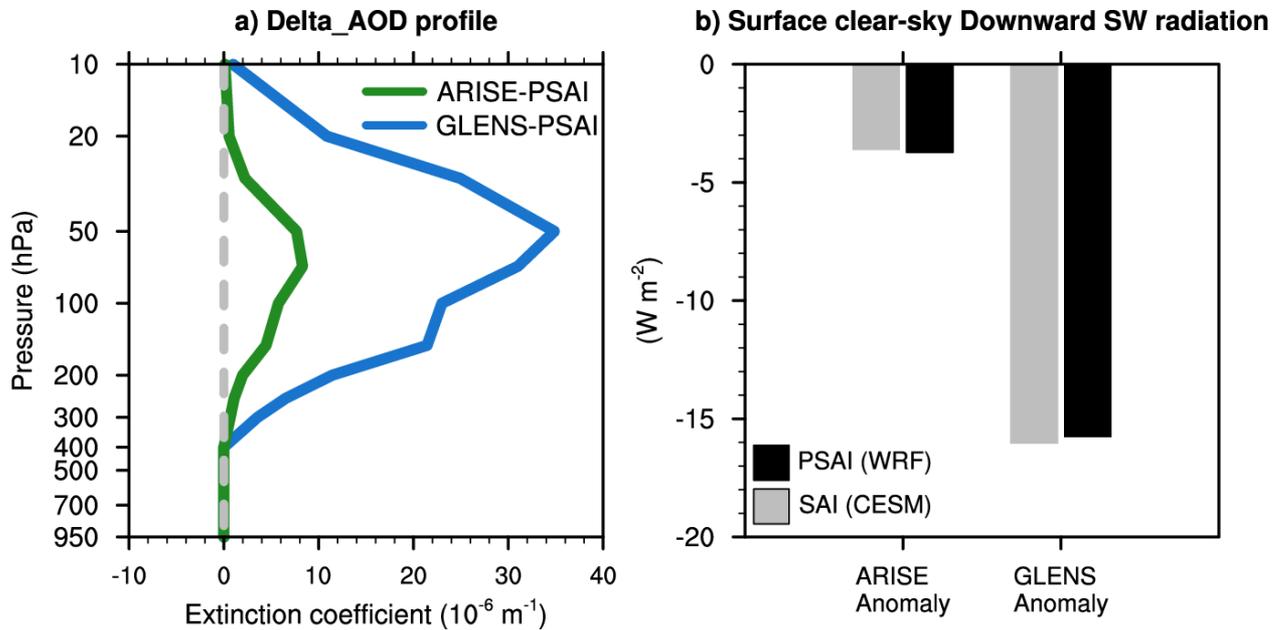
201 **Table 2.** Convection-permitting WRF ensemble experiments performed.

Experiments	Lateral and lower boundary forcing	Period
Control	ERA5	March-August 2011
GLENS-PGW	ERA5 + GLENS-RCP8.5 <sub>2060-2069</sub> - GLENS-RCP8.5 <sub>2015-2024</sub>	
ARISE-PGW	ERA5 + ARISE-SSP2-4.5 <sub>2060-2069</sub> - ARISE-SSP2-4.5 <sub>2015-2024</sub>	
GLENS-PSAI	ERA5 + GLENS-SAI <sub>2060-2069</sub> - GLENS-RCP8.5 <sub>2015-2024</sub>	
ARISE-PSAI	ERA5 + ARISE-SAI <sub>2060-2069</sub> - ARISE-SSP2-4.5 <sub>2015-2024</sub>	

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 203 For each simulation in Table 2, we calculate the average monthly mean values for horizontal wind, geopotential,  
 204 temperature, relative humidity, sea surface temperature, soil temperature, and sea level pressure for the periods from 2015-  
 205 2024 and 2060-2069 and take the difference to calculate the change (delta term) over this period, as has been done in previous  
 206 PGW simulations (e.g., Liu et al., 2017). Brogli et al. (2023) examined various PGW approaches and found that modifying  
 207 relative humidity, rather than specific humidity, helps avoid unrealistic precipitation bands along the model boundary.  
 208 Consistent with their recommendation, we perturb relative humidity while leaving specific humidity unchanged.

209 We also calculate the delta term for the lake ice concentration and lake surface temperature, using the output from the  
 210 CESM land model output. Figures S2 and S3 show the delta changes for these variables for the GLENS and ARISE PGW and  
 211 PSAI simulations, respectively. These deltas are then added to the ERA5 reanalysis for March-August 2011 (when significant  
 212 convection was observed over most of the CONUS) to investigate how a future climate state might impact the occurrence of  
 213 severe weather (Table 2). PSAI and PGW simulations both use lower and lateral boundary conditions from their corresponding  
 214 future simulations (Table 2 and previous descriptions). For these simulations, delta changes in greenhouse gas (GHG)  
 215 concentrations from RCP8.5 and SSP2-4.5, including CO<sub>2</sub>, N<sub>2</sub>O, CH<sub>4</sub>, CFC11, CFC12, are applied to the GLENS and ARISE  
 216 PGW and PSAI scenarios, respectively.

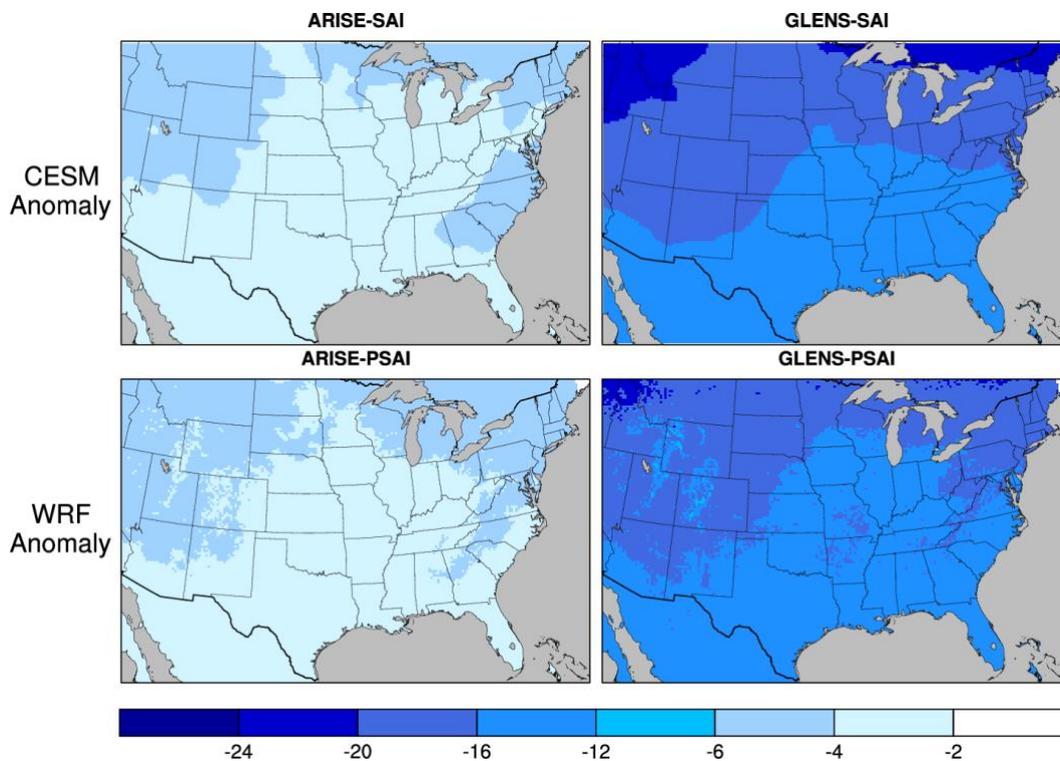
217 Aerosol changes associated with SAI are also required for the PSAI simulations. The WRF model allows us to prescribe  
 218 climatological aerosol radiative properties, such as aerosol optical depth (AOD), in its shortwave radiation scheme—the Rapid  
 219 Radiative Transfer Model (RRTMG; Iacono et al., 2008). This capability enables us to implement the average monthly  
 220 differences in aerosol extinction coefficients between 2015–2024 and 2060–2069 from the GLENS and ARISE simulations.  
 221 By setting `aer_opt` to 1, the model reads aerosol optical data (stored in `aerosol.formatted`) based on Tegen et al. (1997). We  
 222 adjust the values for type 6 (stratospheric aerosols), taken from CESM, while setting all other aerosol types to zero. Although  
 223 the WRF aerosol forcing input has a coarser resolution ( $4^\circ \times 5^\circ$  lat-lon grid) compared to CESM ( $0.9^\circ \times 1.25^\circ$  lat-lon grid), the  
 224 delta AOD exhibits minimal spatial variability, which mitigates potential issues. Figure 4 presents the U.S. averaged aerosol  
 225 extinction coefficient profiles for GLENS-PSAI (blue curve) and ARISE-PSAI (green curve). The aerosol forcing peaks in  
 226 the lower stratosphere, near 50 hPa, with the GLENS forcing exceeding the ARISE forcing by more than threefold—consistent  
 227 with the warming offset required (Figure 1). Notably, our WRF simulations only account for the radiative effects of  
 228 stratospheric aerosols: we set aerosol forcing below 400 hPa to zero. Given that the aerosols associated with SAI are primarily  
 229 confined to the stratosphere (Fig. 4a), we make the assumption that the aerosols have relatively few impacts on the cloud  
 230 microphysics of tropospheric storm systems. This assumption allows for the direct modification of the shortwave radiation  
 231 (e.g., reducing the incoming solar radiation) without needing to explicitly simulate aerosol-cloud interactions.



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 233 **Figure 4.** a) Vertical profile of March–August aerosol optical depth (AOD) forcing in WRF GLENS-PSAI (blue) and ARISE-PSAI (green)  
 234 simulations.  $\Delta$ AOD, calculated as the 2060–2069 SAI simulations minus the 2015–2024 climatology, is set to zero below 400 hPa to isolate  
 235 stratospheric aerosol effects. The vertical dashed line indicates the zero-extinction coefficient. b) Surface clear-sky downward shortwave  
 236 radiation anomalies in CESM-SAI and WRF-PSAI simulations. CESM anomalies (2060–2069) are relative to the 2015–2024 baseline, while  
 237 WRF anomalies are relative to the control simulation. Averages in a) and b) are calculated for the WRF domain.

238 Figure 4b compares the surface clear-sky downward shortwave radiation anomalies averaged over the WRF domain  
 239 between CESM-SAI and WRF-PSAI simulations for the two SAI scenarios. The reduction in shortwave radiation is  $\sim 3.6$  W/m<sup>2</sup>  
 240 in ARISE-SAI and  $\sim 16$  W/m<sup>2</sup> in the GLENS-SAI, consistent with the different AOD forcings. Our simplified AOD  
 241 modification successfully reproduces the magnitudes of the shortwave reduction observed in CESM-SAI simulations. Figure  
 242 5 shows the spatial pattern of surface clear-sky downward shortwave radiation anomalies, indicating large reductions over  
 243 higher latitudes. The PSAI simulations, again, well resemble the changes in CESM-SAI. A more complex test, which involved  
 244 manually calculating the radiative scattering properties from the CESM and applying them to WRF alongside delta changes  
 245 in the aerosol extinction coefficient, did not reveal significant differences in the results.

246 The PSAI simulation is driven by lateral and lower boundary forcing, local GHGs, and the radiative effect of stratospheric  
 247 aerosols. To assess their relative contributions, we conduct one-month sensitivity tests by rerunning the PSAI simulation with  
 248 either  $\Delta$ AOD or  $\Delta$ GHGs set to zero. The differences from the full PSAI simulation isolate the impacts of aerosol and GHG  
 249 forcing, respectively. Results show that the aerosol forcing accounts for nearly all of the reduction in clear-sky surface  
 250 downward shortwave radiation, while local GHGs and boundary conditions contribute minimally (not shown). These  
 251 experiments, importantly, suggest that aerosols in the WRF simulations exert similar effects as in CESM, supporting the  
 252 validity of our PSAI approach.



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 254 **Figure 5.** (Top) Surface clear-sky downward shortwave radiation anomalies ( $W m^{-2}$ ) for 2060–2069 relative to the 2015–2024 baseline  
 255 climatology in ARISE-SAI (left) and GLENS-SAI (right) simulations. (Bottom) Same as the top row, but for ARISE-PSAI and GLENS-  
 256 PSAI simulations.

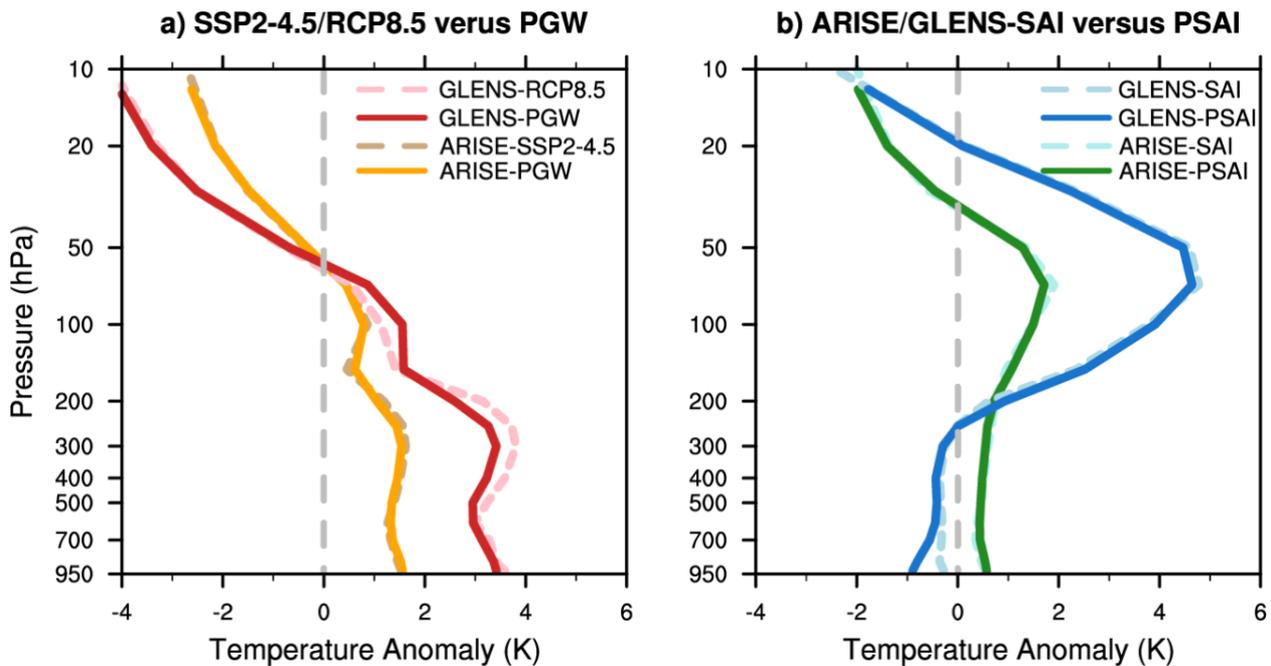
## 257 **4 Climate change and SAI impact over the CONUS**

258 To assess how convective storms may evolve under future climate change and SCI scenarios, we apply the established PGW  
259 framework together with the new PSAI approach introduced in this study, enabling direct comparison between present-day  
260 and future storms. In this section, we present a few high-level analyses of temperature, precipitation, and convection,  
261 highlighting the feasibility and scientific potential of this approach for assessing the weather-scale impacts of SCI. More  
262 detailed analyses of these simulations are the topic of ongoing research. We begin by examining large-scale environmental  
263 changes across models and scenarios. CESM anomalies are calculated as the difference between the 2060–2069 average in  
264 future projections and the 2015–2024 baseline climatology. WRF anomalies represent the deviations of the PGW and PSAI  
265 simulations relative to their corresponding control baselines.

### 266 **4.1 Temperature**

267 Figure 6 shows the vertical profiles of March-August temperature anomalies averaged over the Eastern U.S. (30°-42°N, 78°-  
268 102°W). This period includes the record-breaking April 2011 tornado outbreak, which is the focus of our case study, and  
269 broadly represents the warm season when convective storms are most frequent in this region. In response to increased  
270 greenhouse gases, the tropospheric temperature rises while the stratospheric temperature decreases relative to the baseline  
271 climatology, consistent with the known vertical temperature response to anthropogenic climate change (e.g., Figure 10.8 in  
272 IPCC AR5). The RCP8.5 scenario, with higher future concentrations of greenhouse gases, exhibits greater tropospheric  
273 warming and stratospheric cooling compared to SSP2-4.5. All these features in CESM are well reproduced in the PGW  
274 simulations for both scenarios (Fig. 6a).

275 When SAI is deployed, stratospheric aerosols absorb both shortwave and longwave radiation and also reflect sunlight,  
276 resulting in significant warming in the lower stratosphere, with greater magnitudes in GLENS-SAI than ARISE-SAI (Fig. 6b),  
277 consistent with the aerosol forcing differences between the two scenarios (Figure 4a). In the middle stratosphere, greenhouse  
278 gas-induced cooling persists. In the troposphere, aerosol-induced cooling counteracts greenhouse gas-induced warming,  
279 leading to much weaker warming in ARISE-SAI and even slight cooling in GLENS-SAI relative to the 2015-2024 baseline.  
280 The weak warming observed in ARISE-SAI can be attributed to the temperature target being 1.5°C above pre-industrial levels,  
281 which is close to the projected 2030 values under SSP2-4.5 (Figure 1). Interestingly, even though our approach accounts only  
282 for the shortwave radiative effect of stratospheric aerosols, the temperature anomalies in CESM-SAI are effectively reproduced  
283 by WRF-PSAI for both scenarios (Figure 6b).



284

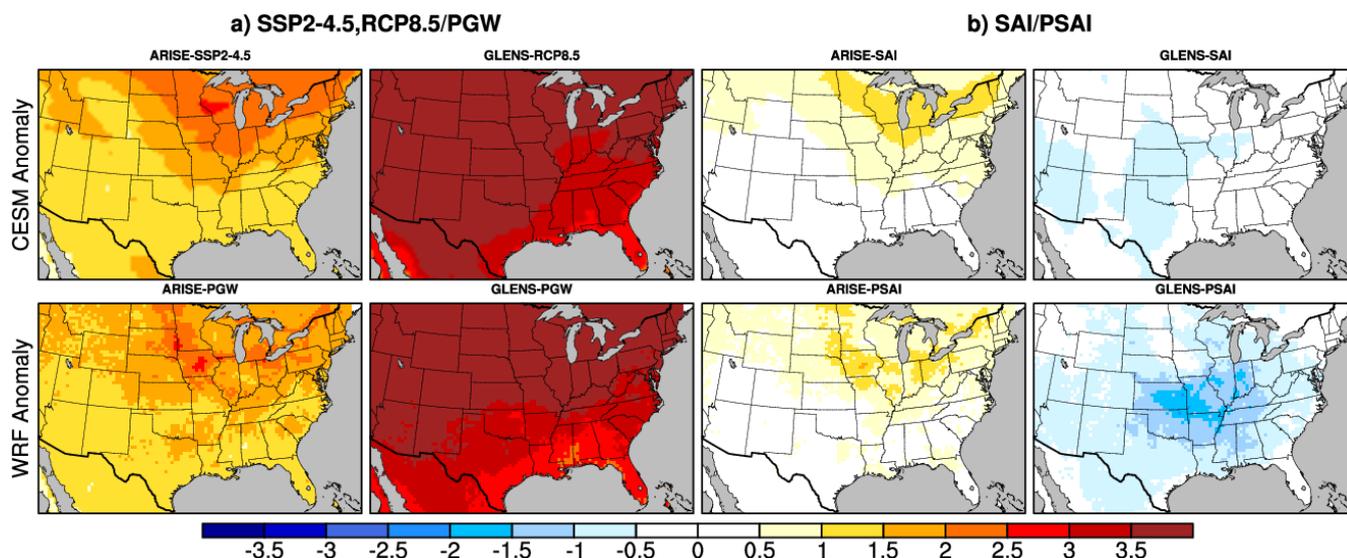
285 **Figure 6.** a) Eastern U.S. average temperature anomalies ( $^{\circ}\text{C}$ ) for 2060–2069 relative to the 2015–2024 baseline climatology from CESM1-  
 286 WACCM RCP8.5 (dashed red) and CESM2-WACCM SSP2-4.5 (dashed orange) simulations, with the corresponding GLENS-PGW (solid  
 287 red) and ARISE-PGW (solid orange) WRF simulations overlaid. b) Same as a), but for temperature anomalies in GLENS-SAI (dashed blue)  
 288 and ARISE-SAI (dashed green) simulations, overlaid by the corresponding GLENS-PSAI (solid blue) and ARISE-PSAI (solid green) WRF  
 289 simulations. The Eastern U.S. is defined by the latitude-longitude bounds  $30^{\circ}\text{--}42^{\circ}\text{N}$  and  $78^{\circ}\text{--}102^{\circ}\text{W}$  (red box in Fig. 2).

290

291 Figure 7 illustrates the spatial variability of surface air temperature anomalies for the CESM and WRF simulations.  
 292 Without SAI, temperatures increase by approximately  $1\text{--}1.5^{\circ}\text{C}$  under SSP2-4.5 and exceed  $3.5^{\circ}\text{C}$  under RCP8.5, with more  
 293 pronounced warming at higher latitudes. The WRF-PGW simulation effectively captures this warming, further providing finer-  
 294 scale details. When SAI is implemented, most of the warming is mitigated in ARISE-SAI, and GLENS-SAI even shows slight  
 295 cooling. The WRF-PSAI simulation also reproduces this trend, with GLENS-PSAI displaying greater cooling over the Central  
 296 U.S. than GLENS-SAI, as also seen in the vertical profile (Fig. 6b, solid blue curve).

296

297 It is important to note that CESM and WRF are two different models with distinct physical configurations. The similar  
 298 temperature responses observed in both suggest that WRF can effectively reproduce CESM’s climate response when provided  
 299 with consistent boundary conditions and radiative forcings, supporting the validity of our experimental approach. Differences  
 300 between the models may stem from their respective physical parameterizations and from the different ways in which SAI is  
 301 implemented. In addition, it is unclear to what extent the model biases may influence the accuracy of the projected future  
 302 changes and contribute to the differences between CESM and WRF. Further investigation is thus warranted to better  
 understand the mechanisms behind these differences, including potential links to biases in the basic state (Figure 3).



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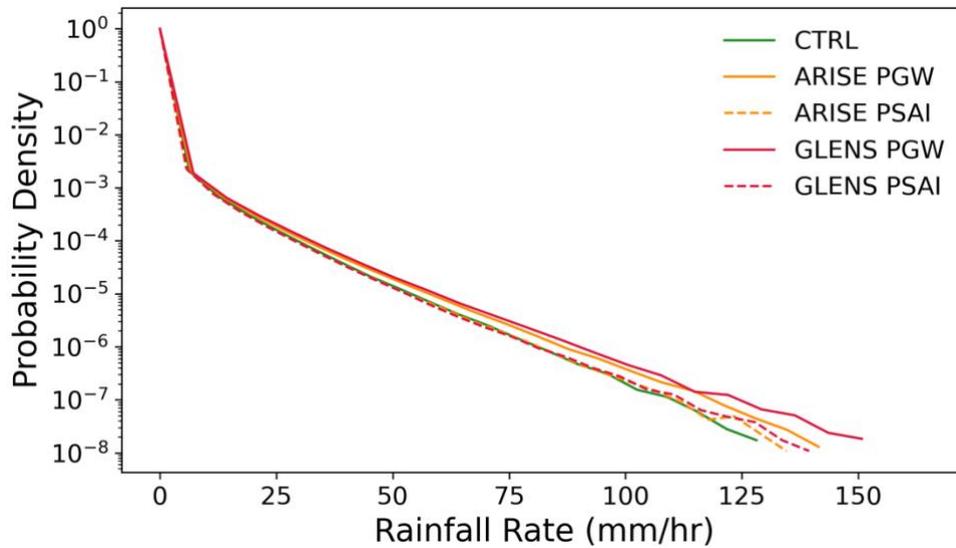
304 **Figure 7.** a) Surface air temperature anomalies (°C) for 2060–2069 relative to the 2015–2024 baseline climatology from (top) CESM2-  
 305 WACCM SSP2-4.5 and CESM1-WACCM RCP8.5 simulations, and (bottom) the corresponding ARISE-PGW and GLENS-PGW WRF  
 306 simulations. b) Surface air temperature anomalies for 2060–2069 relative to the 2015–2024 baseline from (top) ARISE-SAI and GLENS-  
 307 SAI simulations, and (bottom) the corresponding ARISE-PSAI and GLENS-PSAI WRF simulations.

#### 308 4.2 Precipitation

309 Figure S4 shows the spatial variability of mean precipitation anomalies in the CESM and WRF simulations. Without SAI, an  
 310 increase in precipitation is evident over the eastern United States, particularly under the more extreme GLENS-RCP8.5  
 311 scenario. With SAI, this increase is reduced (for example, ARISE-SAI) or nearly eliminated (GLENS-SAI). The WRF  
 312 simulations generally reproduce this behavior, although with finer-scale but noisier patterns and larger magnitudes. We also  
 313 note that the region where GLENS-PSAI exhibits additional cooling (Fig. 7) coincides with an area of enhanced precipitation,  
 314 suggesting a possible connection.

315 Converging evidence from previous PGW studies indicates that extreme precipitation across the U.S. will become more  
 316 intense, and in many cases, more frequent in a warming future (e.g., Prein et al., 2017b; Gutmann et al., 2018; Cui et al., 2024).  
 317 Figure 8 presents the probability density function (PDF) of hourly precipitation over the Eastern U.S. during March–August  
 318 2011 for the control, PGW, and PSAI simulations, highlighting substantial sensitivity to different scenarios. Notably, both  
 319 PGW scenarios exhibit a higher likelihood of extreme precipitation events compared to the control, indicating an increase in  
 320 extreme precipitation intensity under future climate conditions. This effect is more pronounced in GLENS-PGW (RCP8.5)  
 321 than in ARISE-PGW (SSP2-4.5). With the implementation of SAI, the PDFs for extreme precipitation become much closer to  
 322 the control, suggesting that the projected increase in extreme precipitation is mitigated, with an exception at the highest rainfall  
 323 rates (Fig. 8). This result is consistent with previous studies based on global climate models (e.g., Curry et al., 2014; Simpson  
 324 et al., 2019; Tye et al., 2022).

325 CESM2 provides hourly precipitation output which we analyze and compare with the WRF simulations (not shown). The  
 326 2060–2069 projection without SAI exhibits similarly enhanced extreme precipitation compared to the baseline (2015–2024),  
 327 resembling ARISE-PGW. With SAI implementation, the PDF shifts closer to the baseline, similar to ARISE-SAI. However,  
 328 CESM2’s hourly precipitation remains about an order of magnitude lower, with a maximum below 20 mm/hr. This is consistent  
 329 with previous findings that high-resolution models tend to produce stronger precipitation than low-resolution models (e.g.,  
 330 Rauscher et al., 2016; Herrington and Reed, 2020), highlighting WRF’s capability in explicitly simulating fine-scale  
 331 convective precipitation processes.  
 332

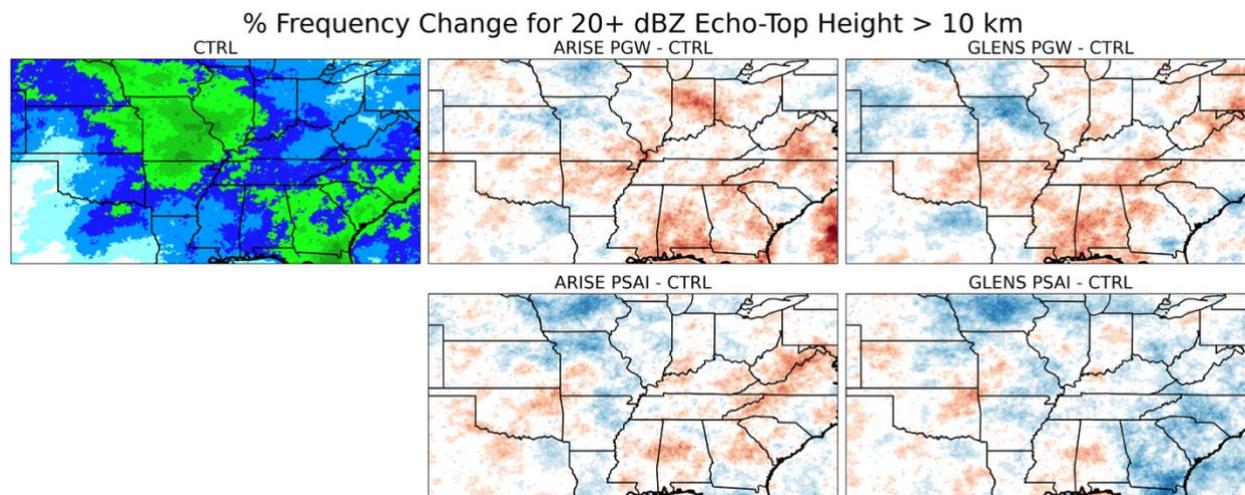


333  
 334 **Figure 8.** Probability density function (PDF) of the Eastern U.S. precipitation spectrum over March-August 2011, in the control, PGW and  
 335 PSAI simulations.

### 336 4.3 Echo-top height

337 Echo-top height is a commonly used metric to describe the vertical range of the precipitation reflectivities (Wilson and  
 338 Megenhardt, 1997) and is often used as an indicator of both storm height and intensity. For example, storms with the strongest  
 339 updrafts tend to produce higher echo tops and are associated with higher lightning flash rates compared to weaker storms  
 340 (Deierling and Petersen, 2008). Here we investigate changes in convection under climate change and SAI by examining the  
 341 percentage frequency echo-top heights exceeding 10 km, based on radar reflectivity values of at least 20 dBZ, across different  
 342 climate scenarios (Figure 9). From March to August, this frequency generally ranges between 0.5 and 3.5%, with higher values  
 343 over the central U.S., particularly over the Midwest and Southeast (green shades), indicating frequent deep convection (Houze  
 344 et al., 2015). Climate change leads to increases in the frequency of deep convection across most of the eastern U.S., with a  
 345 very similar pattern between GLENS-PGW and ARISE-PGW (top right panel). In contrast, this increase is largely reduced or  
 346 transitions to a decrease in the PSAI simulations. This pattern is evident when comparing ARISE-PGW (SSP2-4.5) with

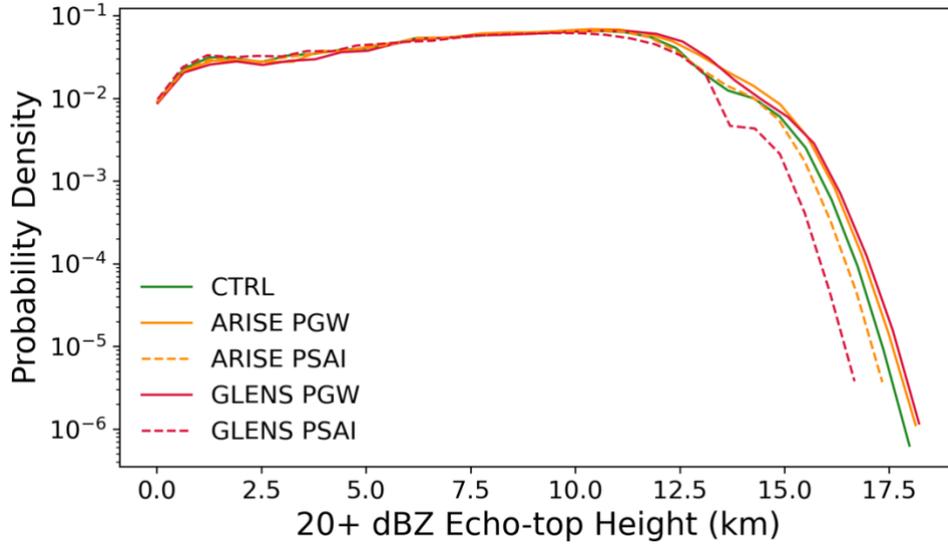
347 ARISE-PSAI and even more pronounced between GLENS-PGW and GLENS-PSAI. Together, these results suggest that  
348 climate warming enhances deep convection consistent with prior studies (Trapp et al., 2007; Rasmussen et al., 2017), while  
349 SAI may suppress it, implying a potential mitigating effect on convective intensity.



350

351 **Figure 9:** Percentage frequency for 20+ dBZ Echo-Top height larger than 10km for (left) Control and (top middle and right) PGW and  
352 (bottom) PSAI anomalies. The frequency is calculated based on hourly data for March-August 2011.

353 Figure 10 further presents the probability density function of 20+ dBZ echo-top height frequencies over the eastern U.S.  
354 Most convection occurs below 1 km, while between 1–12 km, the frequency remains nearly constant. Beyond 12–13 km, the  
355 probability declines sharply, resembling an exponential drop-off. Both PGW scenarios exhibit slightly higher probabilities of  
356 echo tops exceeding 12 km, indicating an increase in deep convection under climate warming. In contrast, PSAI simulations  
357 show a reduction in high echo tops compared to both the control and PGW scenarios, suggesting that SAI may suppress  
358 extreme convection. There is more reduction in GLENS-PSAI than in ARISE-PSAI because the temperature target is lower  
359 in GLENS-SAI (year 2020) than in ARISE-SAI (1.5°C above pre-industrial level, around 2035). A similar analysis using 40+  
360 dBZ echo-top heights reveals comparable changes (not shown).



361

362 **Figure 10:** Probability density function (PDF) of the fractional occurrence for 20+ dBZ Echo-Top height larger than 10km over the Eastern  
 363 U.S. over March-August 2011, in the control, PGW and PSAI simulations.

364 **4.4 Convective population**

365 Rasmussen et al. (2017) examined the convective population change under climate change using 13-year PGW simulations  
 366 and found that the lower reflectivity ranges occur less frequently, while higher reflectivity ranges are more common in both  
 367 the CONUS domain and the U.S. Great Plains. Here we do a similar analysis and focus on boreal spring (March, April, May)  
 368 when severe convective storms occur mostly frequently. In particular, hourly composite reflectivity data from each simulation  
 369 set is used to calculate the frequency of occurrence in six reflectivity ranges defined as weak convection (0-10, 10-20 dBZ),  
 370 moderate convection (20-30, 30-40 dBZ), and strong convection (40-50, 50+ dBZ). The change in frequency of occurrence  
 371 for each reflectivity range can be calculated using the following formulas:

372

373 
$$\Delta CONV_{PGW} = \frac{\sum RR_{PGW} - \sum RR_{CTRL}}{\sum RR_{CTRL}} \times 100 \quad (1)$$

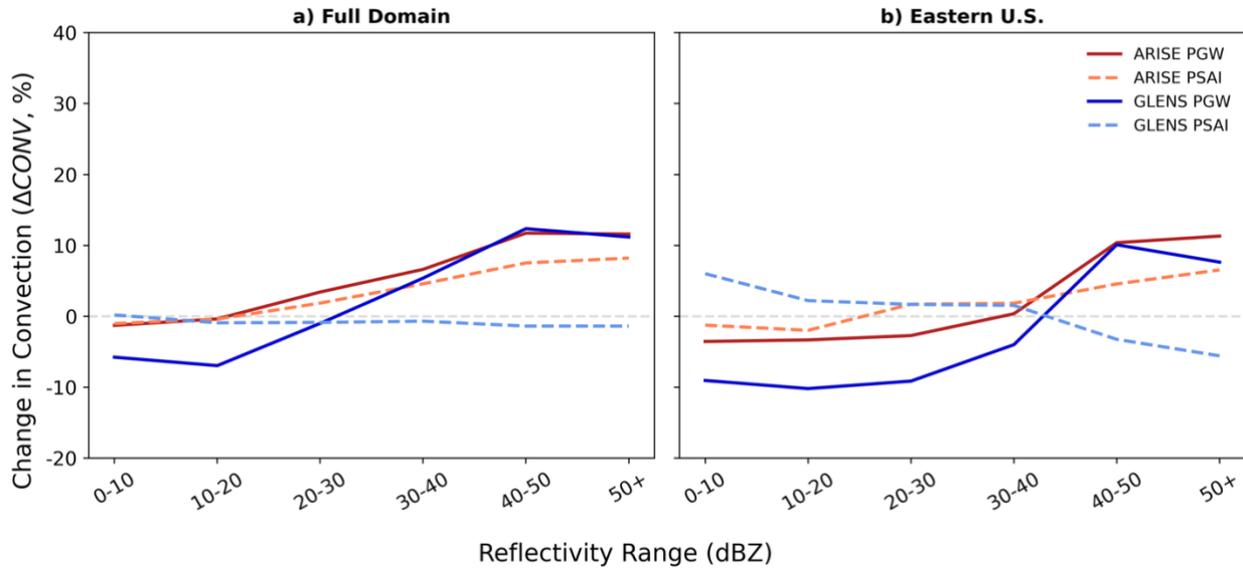
374

375 
$$\Delta CONV_{PSAI} = \frac{\sum RR_{PSAI} - \sum RR_{CTRL}}{\sum RR_{CTRL}} \times 100 \quad (2)$$

376 Here, RR denotes the radar reflectivity range calculated from each of the WRF simulations.

377 Figure 11 shows the changes in occurrence of each reflectivity range in the full domain (a) and in the eastern U.S. (b).  
 378 For both regions GLENS-PGW (solid blue) shows less frequent convection for 20- dBZ and more frequent convection for 40+  
 379 dBZ. A similar change is also observed for ARISE-PGW (solid brown) over the eastern U.S., in agreement with previous  
 380 findings. ARISE-PSAI (dashed orange) generally exhibits a similar change to ARISE-PGW, but with smaller magnitude. In  
 381 contrast, the changes in GLENS-PSAI (dashed light blue) and GLENS-PGW are very different. For example, over the eastern

382 U.S., GLENS-PSAI exhibits an increase in the frequency of convection for 20- dBZ and a decrease for 40+ dBZ, opposite to  
 383 that in its corresponding GLENS-PGW. When considering the entire CONUS, GLENS-PSAI is very close to the baseline,  
 384 only showing slightly less frequent occurrences for 40+ dBZ. The convective population changes in PGW and PSAI  
 385 simulations closely follow the changes in thermodynamic environments. In particular, Rasmussen et al. (2017) found that  
 386 climate change leads to larger values of both CAPE and CIN, a feature also observed in Chen et al. (2020) and Franke et al.  
 387 (2024). This suggests that the future atmosphere under climate change may support more vigorous convective storms but also  
 388 requires more energy to initiate given increases in lower-level static stability. As a result, the convective population exhibits  
 389 fewer weak to moderate storms and more storms that are intense.



390

391 **Figure 11:** March–April–May changes in the occurrence of each reflectivity range over the full domain (left) and the Eastern U.S. (right).  
 392 The total number of occurrences within each reflectivity bin is summed over each domain, and  $\Delta\text{CONV}$  is computed following Eqs. (1) and  
 393 (2). This metric represents the percentage change in convective population in the PGW and PSAI simulations relative to the control  
 394 simulation, shown as a function of radar reflectivity range (dBZ).

395 As a potential climate mitigation method, SAI may be employed to counteract some of the effects of global warming.  
 396 Glade et al. (2023) suggested that SAI not only reduces the GHG-induced warming but also effectively minimizes future  
 397 changes in thermodynamic environmental parameters, such as CAPE and CIN, that are relevant to convection. Recall that the  
 398 temperature target of ARISE-PSAI is 1.5°C and thus there is still a global warming effect relative to the 2015–2024 baseline.  
 399 As a result, the distribution of CAPE and CIN in ARISE-PSAI still resembles ARISE-PGW but with smaller magnitude, which  
 400 leads to similar but smaller changes in convective populations. In contrast, GLENS-PSAI exhibits slightly cooling relative to  
 401 the baseline, opposite to the warming evident in GLENS-PGW (Figures 6 and 7). Consequently, changes in the population of  
 402 convection in GLENS-PSAI are opposite to those in GLENS-PGW.

## 403 5 Summary and discussion

### 404 5.1 Summary

405 Climate intervention has been proposed as a possible method to help counteract some of the future consequences of  
406 anthropogenic climate change. As one primary solar climate intervention strategy, many studies of SAI have focused on its  
407 benefits and risks relative to the risks posed by climate change. These studies, however, have almost exclusively used climate  
408 models, and no studies to date have examined how SAI may influence convective weather and mesoscale processes. The goal  
409 of this work is to begin to bridge this gap by developing a novel modeling framework using a regional convection-permitting  
410 model to investigate the possible impacts of SAI on severe weather in the U.S. We conduct PSAI and PGW simulations to  
411 mimic future climate change with and without SAI deployment, and we show some early analyses of temperature, precipitation  
412 and convection over the U.S. Our primary purpose is to introduce and demonstrate the methodology for evaluating convective  
413 storms under the PGW and PSAI frameworks rather than to analyze individual storm events. For this reason, the March–  
414 August 2011 period is used to provide a statistical representation of environmental and storm-related changes without  
415 cataloging each severe convective event that occurred over this period. The main results are summarized as follows:

- 416 1. Building on previous PGW approaches, this paper develops a novel PSAI method using WRF. Global climate model  
417 SAI simulations with CESM are used to generate delta terms and which are then applied to the lower and lateral  
418 boundary conditions for WRF. Stratospheric AOD changes in the global model are further applied to WRF to ensure  
419 that the radiative effects of SAI are well captured. Six-month simulations for the warm season (March – August) of  
420 2011 were then conducted.
- 421 2. The PSAI and PGW simulations capture the large-scale environmental changes evident in the CESM SAI and climate  
422 change simulations. In particular, the temperature anomalies in the PSAI and PGW runs well match those in the  
423 corresponding CESM simulations, confirming the viability of our methodology. Further, these results suggest that  
424 once the boundary forcings are prescribed and radiative forcings are properly configured, the WRF model can be  
425 used to study the impact of SAI on convective weather.
- 426 3. Our PSAI and PGW simulations reveal that future spring and summer extreme precipitation over the CONUS is likely  
427 to increase under climate change, as indicated in earlier studies, but that such increases could be largely avoided if  
428 SAI was deployed. This is also broadly consistent with the coarser-grid precipitation changes evident in the CESM  
429 simulations (e.g., Tilmes et al., 2019; Richter et al., 2022).
- 430 4. Climate change leads to increases in the frequency of deep convection over much of the eastern U.S., which may be  
431 largely mitigated by SAI deployment. Moreover, composite analysis of the convective population reveals a decreasing  
432 frequency of weak echoes (0–20 dBZ) and an increasing frequency of intense reflectivities (above 40 dBZ) in the  
433 future. This shift in convective characteristics may again be reduced or even fully offset under SAI deployment.

434

## 435 5.2 Discussion

436 Our PSAI and PGW approaches differ from direct dynamical downscaling of global climate models, which often carry inherent  
437 biases that are passed down to regional simulations. In contrast, our control simulation is driven by ERA5 reanalysis and thus  
438 more closely reflects observed climate conditions, despite its own limitations. Direct downscaling also inherits substantial  
439 internal variability from global models, complicating the separation of the forced response unless multiple ensemble members  
440 are conducted. This requirement makes it more computationally expensive than PGW-based methods. However, PGW cannot  
441 simulate synoptic-scale variability and may underperform in regions where dynamical eddy processes are important (Hall et  
442 al., 2024). Since the PSAI method is developed based on the PGW framework, it inherits both its advantages and limitations.  
443 Further studies are needed to evaluate PSAI in comparison with direct downscaling of SAI to evaluate their respective  
444 strengths.

445 One caveat of our PSAI approach is that it accounts only for the direct shortwave radiative effects of stratospheric  
446 aerosols, without representing their longwave influence. Nevertheless, the model well captures the lower stratospheric heating  
447 seen in global climate models (Fig. 6b), suggesting that while shortwave perturbations are essential, the omission of longwave  
448 effects may be less critical. Our approach excludes near-surface aerosol anomalies because it is unclear whether these signals  
449 arise from stratospheric aerosol descent or other processes, and they are therefore not included in the WRF-PSAI forcing.  
450 However, further investigation is warranted to assess the potential role of aerosol-radiation and cloud interactions in the  
451 troposphere, especially under conditions of stratosphere-troposphere exchange. Further, the WRF bias in environmental  
452 conditions may introduce uncertainty in the simulated storm activity and in the projected future changes with and without SAI.

453 Lastly, we emphasize that the primary goal of this paper is to introduce a methodology for assessing the impact of climate  
454 intervention on convective weather using regional models. In this study, the extension of the PGW framework to the SAI  
455 scenario is achieved by incorporating the CESM-derived aerosol optical depth forcing into the WRF simulations. The  
456 convection-permitting WRF model is particularly well-suited to capturing fine-scale mesoscale processes and physical  
457 mechanisms that drive changes in clouds and precipitation systems as it is also used for operational numerical weather  
458 prediction (e.g., high-resolution rapid refresh (HRRR) model). Our framework builds on this capability to utilize global climate  
459 model output to study future changes in weather under scenarios with and without SAI. More in-depth scientific results will  
460 follow. For example, we find that the changes in the occurrence of each reflectivity range exhibit clear seasonal variability  
461 (Figure S5). It will therefore be interesting to further investigate the seasonality of the results as well as the underlying  
462 mechanisms. In addition, we are conducting a parallel study focused on the influence of SAI on the super tornado outbreak of  
463 25-28 April 2011 (Summers et al. 2026), including additional ensembles forced by individual global climate model members  
464 of future projections to explore the role of internal climate variability. Further PGW and PSAI simulations are underway to  
465 extend the analysis over a longer period of record. We hope this framework provides a foundation for future investigations  
466 into the regional impacts of climate intervention on high-impact weather events.

467 *Code availability.* WRF version 4.1.5 that was used to carry out the simulations is archived on Zenodo at Sun et al. (2025a)  
468 under the UCAR Open Source License, which is equivalent to the BSD 3-Clause License.

469 *Data availability.* The CESM1-WACCM-RCP8.5, CESM2-WACCM-SSP4.5, and their corresponding GLENS-SAI and  
470 ARISE-SAI datasets used in this study are available via Zenodo (Sun et al., 2025b). Representative WRF output files used in  
471 the analysis are archived on Zenodo (Sun et al., 2025c). The WRF AOD forcing files are also archived on Zenodo (Sun et al.,  
472 2025d).

473 *Author contributions.* L.S., J.W.H., and K.L.R. designed the experimental setup. L.S. and K.L.R. led the model development  
474 and conducted the simulations. L.S., B.S. and E.A.S. performed the analysis and prepared the figures. L.S. wrote the  
475 manuscript. All authors contributed to in-depth discussions of data analysis and interpretation, and provided editorial feedback.

476 *Competing interests.* The contact author has declared that none of the authors has any competing interests.

477 *Acknowledgements.* We appreciate the thoughtful comments and suggestions from Long Cao, Chaochao Gao and one  
478 anonymous reviewer. This research was supported by the NOAA Earth Radiation Budget (ERB) program (Grant  
479 NA24OARX431C0055-T1-01). J.W.H. also acknowledges support from the LAD Climate Fund and Walter Scott, Jr. College  
480 of Engineering at Colorado State University. K.L.R. acknowledges support from the NOAA ERB program (Grant  
481 #NA24OARX431C0055-T1-01) and NSF (Grant #2312317). B.K. acknowledges support from the NOAA ERB program title  
482 “Dynamical Downscaling to Quantify Extreme Events Under Stratospheric Sulfate Aerosol Injection”. We thank Amazon  
483 Web Services (AWS) for providing computational resources, with special thanks to Joelle Rossback-Dahl and Joel Morgan  
484 (AWS), as well as the team from SilverLining for facilitating this support. We also appreciate the technical assistance from  
485 Jimy Dudhia, Changhai Liu, and Kyoko Ikeda (NCAR) during the WRF model setup.

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