

1 **Assessing the impact of stratospheric aerosol injection**
2 **on U.S. convective weather environments**

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5 **Key Points:**

- 6 • SAI may prevent future increases in the magnitude of thermodynamic parameters
7 relevant to the formation of severe weather over the U.S.
- 8 • Future changes in wind shear, a kinematic parameter, is driven largely by changes
9 in tropical precipitation whether or not SAI is deployed.
- 10 • Internal decadal-scale climate variability is likely to impact future projections of
11 regional changes in convective weather environments.

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Abstract

Continued climate warming, together with the overall evaluation and implementation of a range of climate mitigation and adaptation approaches, has prompted increasing research into proposed solar climate intervention (SCI) methods, such as stratospheric aerosol injection (SAI). SAI would use aerosols to reflect a small amount of incoming solar radiation away from Earth to stabilize or reduce future warming due to increasing greenhouse gas concentrations. Research into the possible risks and benefits of SAI relative to the risks from climate change is emerging. There is not yet, however, an adequate understanding of how SAI might impact human and natural systems. For instance, little to no research to date has examined how SAI might impact environmental conditions critical to the formation of severe convective weather over the United States (U.S.). This study uses ensembles of Earth system model simulations of future climate change, with and without hypothetical SAI deployment, to examine possible future changes in thermodynamic and kinematic parameters critical to the formation of severe weather during convectively active seasons over the U.S. Results show that simulated forced changes in thermodynamic parameters are significantly reduced under SAI relative to a no-SAI world, while simulated changes in kinematic parameters are more difficult to distinguish. Also, unforced internal climate variability is likely to significantly modulate the projected forced climate changes over large regions of the U.S.

1 Introduction

Global carbon dioxide (CO₂) emissions have increased every decade since the 1960s and are projected to continue to increase over at least the next several decades (Friedlingstein et al., 2022; Jiang & Guan, 2016; Peters et al., 2012). It is therefore very unlikely that global climate warming will be limited to 1.5 or even 2°C above pre-industrial temperatures unless action is taken soon to drastically reduce emissions (IPCC, 2021). In fact, climate warming is projected to be over 2°C by the end of the century under moderate and current policy-relevant emissions scenarios, surpassing what is considered to be a safe threshold of warming (IPCC, 2021; Riahi et al., 2017; UNEP, 2022). Climate impacts such as drought intensification (Mukherjee et al., 2018; Strzepek et al., 2010), increases in extreme precipitation (M. R. Allen & Ingram, 2002; Donat et al., 2016; Dougherty & Rasmussen, 2020; Prein et al., 2017) and continued sea ice loss (Stroeve et al., 2012) are projected to worsen over the coming decades (IPCC, 2021). Future changes

44 also include the potential for increases in the frequency and intensity of severe convective
45 weather over large portions of the United States (U.S.) (Diffenbaugh et al., 2013;
46 Hoogewind et al., 2017; Lepore et al., 2021; K. L. Rasmussen et al., 2017; Seeley &
47 Romps, 2015; Tippett et al., 2015; Trapp et al., 2007, 2009, 2019).

48 Given slow progress toward reducing fossil fuel emissions and the urgency to limit
49 continued temperature warming, the U.S. National Academies of Science, Engineering and
50 Medicine (NASEM) recently recommended the formation of a transdisciplinary research
51 program to identify the potential benefits and risks of solar climate intervention (SCI)
52 relative to the risks posed by climate change (NASEM, 2021). Most SCI approaches
53 would cool the planet by reflecting a small amount of incoming solar radiation away from
54 Earth, potentially minimizing some of the worst consequences of anthropogenic climate
55 change while buying more time for mitigation and the deployment of CO₂ removal
56 technologies. Stratospheric aerosol injection (SAI) is one proposed form of SCI that would
57 involve, perhaps, the injection of sulfur dioxide (SO₂) into the stratosphere, which would
58 react with hydrogen and oxygen to form highly reflective sulfate aerosols (Crutzen, 2006;
59 Rasch et al., 2008; Richter et al., 2022).

60 Several Earth-system models have been used to simulate a future climate with SAI under
61 different climate change scenarios (Kravitz et al., 2011; Richter et al., 2022; Tilmes et al.,
62 2018; Vioni et al., 2023). Research to date has included examining changes in global and
63 regional temperature and precipitation (Hueholt et al., 2023; Richter et al., 2022; Tilmes
64 et al., 2018), atmospheric circulation patterns (Bednarz et al., 2022), extreme temperature
65 and precipitation events (Barnes et al., 2022; Ji et al., 2018), and ecological responses
66 (Zarnetske et al., 2021), in addition to potential deployment technologies (Lockley et al.,
67 2022; Smith & Wagner, 2018). Such studies have demonstrated that SAI could potentially
68 be deployed to stabilize or reduce global mean temperature to a specific temperature
69 target (Richter et al., 2022; Tilmes et al., 2018; Vioni et al., 2021); however, research has
70 also indicated that regional impacts of SAI could be both positive and negative. For
71 example, major African river basins may have enhanced drought risk because SAI is
72 projected to cause precipitation decreases that overcompensate for projected increases due
73 to climate warming (Abiodun et al., 2021). On the other hand, future projections indicate
74 that SAI has the potential to reduce Greenland ice sheet mass loss (Moore et al., 2019)
75 and minimize the loss of Arctic sea ice (Lee et al., 2023).

76 While research on the potential impacts of SAI has been increasing and broadening in
77 recent years, current research remains scattered and ad hoc, so a holistic understanding of
78 how SAI would impact Earth and human systems is limited (NASEM, 2021). For
79 instance, while there have been studies documenting the impact of climate change on the
80 large-scale environments in which severe weather (as defined by Galway, 1989) forms
81 (Diffenbaugh et al., 2013; Franke et al., 2023; Hoogewind et al., 2017; Lepore et al., 2021;
82 K. L. Rasmussen et al., 2017; Seeley & Romps, 2015; Trapp et al., 2007, 2009; Chen et al.,
83 2020), there are no studies that have examined the potential impact of SAI on those
84 environments. The topic is of relevance given increasing economic impacts and more
85 frequent billion dollar U.S. severe weather disasters in recent decades (NCEI, 2022).

86 Large-scale parameters and proxies have been used to identify what environmental
87 conditions are favorable to the formation of severe weather, largely in order to improve
88 short-term predictability and overcome discontinuities and inconsistencies in limited
89 observational records (e.g., Doswell et al., 1996; E. N. Rasmussen & Blanchard, 1998;
90 Brooks et al., 2003; Craven & Brooks, 2004). More recently, such parameters and proxies
91 have also been used to predict how the behavior of severe weather might change on longer
92 time scales, such as through the end of the century (e.g., Diffenbaugh et al., 2013; Franke
93 et al., 2023; Hoogewind et al., 2017; Lepore et al., 2021; K. L. Rasmussen et al., 2017;
94 Trapp et al., 2007). In part, this is because integrating convection-permitting models over
95 long periods of time is computationally expensive, and these parameters and proxies are
96 resolvable using coarser resolution Earth-system models.

97 Parameters commonly analyzed include convective available potential energy (CAPE),
98 convective inhibition (CIN), and the wind shear from the surface to ~ 6 km (S06). With
99 climate change, the magnitudes of both CAPE and CIN are projected to increase in the
100 U.S. east of the Rocky Mountains in both the spring and summer (Diffenbaugh et al.,
101 2013; Franke et al., 2023; Hoogewind et al., 2017; Lepore et al., 2021; K. L. Rasmussen et
102 al., 2017; Trapp et al., 2007; Chen et al., 2020). Increases in the magnitude of CAPE and
103 CIN have been attributed to increases in temperature and moisture throughout the
104 troposphere (K. L. Rasmussen et al., 2017, see also Fig. S2) and decreases in low-level
105 relative humidity (Chen et al., 2020). Wind shear (S06) is also generally projected to
106 decrease in both the spring and summer seasons across the U.S., especially east of the
107 Rockies (Trapp et al., 2007; Hoogewind et al., 2017; Lepore et al., 2021), a change that

108 largely reflects decreases in the zonal wind at ~ 6 km (Diftenbaugh et al., 2013; Franke et
109 al., 2023).

110 Combined proxies that consider the integrated effects of more than one convective
111 weather environment parameter have also been analyzed (Diftenbaugh et al., 2013;
112 Hoogewind et al., 2017; Lepore et al., 2021; Seeley & Romps, 2015; Trapp et al., 2007,
113 2009). Proxies that consider both the thermodynamic and kinematic characteristics of the
114 environments have been shown to better discriminate between environments conducive to
115 ordinary thunderstorms, supercells, and tornadic supercells than individual
116 thermodynamic or kinematic parameters alone (E. N. Rasmussen & Blanchard, 1998).
117 CAPES06, defined as the product of CAPE and S06, has been used to distinguish
118 significant severe storms from those that are less severe (Brooks et al., 2003;
119 E. N. Rasmussen & Blanchard, 1998). This proxy is often used in tandem with other
120 convective weather environment parameters to describe whether an environment is
121 favorable to the formation of severe weather on a given day (Diftenbaugh et al., 2013;
122 Hoogewind et al., 2017; Lepore et al., 2021; Seeley & Romps, 2015; Trapp et al., 2007).
123 The number of days with high magnitude CAPES06 are projected to increase with future
124 warming across the eastern U.S. (Seeley & Romps, 2015). Diftenbaugh et al. (2013)
125 suggests that CAPES06 is expected to increase across the eastern U.S. even though S06 is
126 projected to decrease, because decreases in S06 are expected to occur on days when
127 CAPE is already low.

128 Previous research examining projections of convective weather environments has mostly
129 considered high emissions trajectories that are not consistent with current climate
130 policies. In this study, the potential impact of climate warming on convective weather
131 environments in the U.S. is examined using a 10-member ensemble of Earth-system model
132 simulations under the Shared Socioeconomic Pathway 2-4.5 (SSP2-4.5) emissions scenario.
133 This is a “middle of the road” scenario more consistent with current climate policies. It
134 projects $\sim 2.7^\circ\text{C}$ of global warming by the end of the century (O’Neill et al., 2017) and
135 considers the slow development and deployment of sustainability practices such as CO_2
136 emissions reduction and removal technologies (IPCC, 2021; Riahi et al., 2017). In
137 addition, parallel climate change integrations with a hypothetical SAI deployment are
138 analyzed to document the potential impact of SAI on large-scale convective weather
139 environments, relative to the impacts from climate change alone. To our knowledge, this

140 is the first study to examine the potential influence of SAI on future convective weather
141 environments.

142 **2 Methodology**

143 **2.1 Model Information**

144 This study utilizes a set of parallel simulations of climate change with and without SAI;
145 specifically, the Assessing Responses and Impacts of Solar climate intervention on the
146 Earth system using stratospheric aerosol injection (ARISE-SAI; Richter et al., 2022).
147 These simulations were performed using the freely available Community Earth System
148 Model version 2 (CESM2), a fully coupled model with the Whole Atmosphere Community
149 Climate Model version 6 (WACCM6) as the atmospheric component (Danabasoglu et al.,
150 2020; Gettelman et al., 2019). WACCM6 is a high-top model with a well-represented
151 stratosphere that includes 70 vertical levels with a model top of 4.5×10^{-6} hPa (~ 130 km)
152 and a horizontal resolution of 1.25° longitude and 0.9° latitude (Danabasoglu et al.,
153 2020). ARISE-SAI consists of two 10-member ensembles of climate change with and
154 without SAI. Both ensembles follow the moderate SSP2-4.5 emissions scenario (O'Neill et
155 al., 2017). The ARISE-SAI climate change simulations consist of five members that run
156 from 2015-2100 and were carried out as a part of the Coupled Model Intercomparison
157 Project Phase 6 (Eyring et al., 2016). Five other ensemble members cover the period from
158 2015-2069 and were branched off from three existing historical CESM2-WACCM6
159 simulations (1850-2014) with the addition of a small temperature perturbation at the first
160 model time step (Richter et al., 2022).

161 The first five members of the ensemble with a hypothetical SAI deployment were
162 initialized in 2035 using the first five members of the climate change (SSP2-4.5) ensemble.
163 The last five members were initialized in a similar way, but with the addition of a small
164 temperature perturbation (Richter et al., 2022). Each of the 10 SAI simulations extend
165 through 2069, with SO_2 being injected into the stratosphere continuously beginning in
166 2035 in order to maintain global mean temperature at $\sim 1.5^\circ\text{C}$ above its pre-industrial
167 value. In addition, the ARISE-SAI injection strategy is designed to maintain the
168 equator-to-pole and interhemispheric temperature gradients to values consistent with
169 those observed at the 1.5°C temperature target (Kravitz et al., 2017; MacMartin et al.,
170 2014; Richter et al., 2022). The stabilizing influence of SAI is clear when examining not

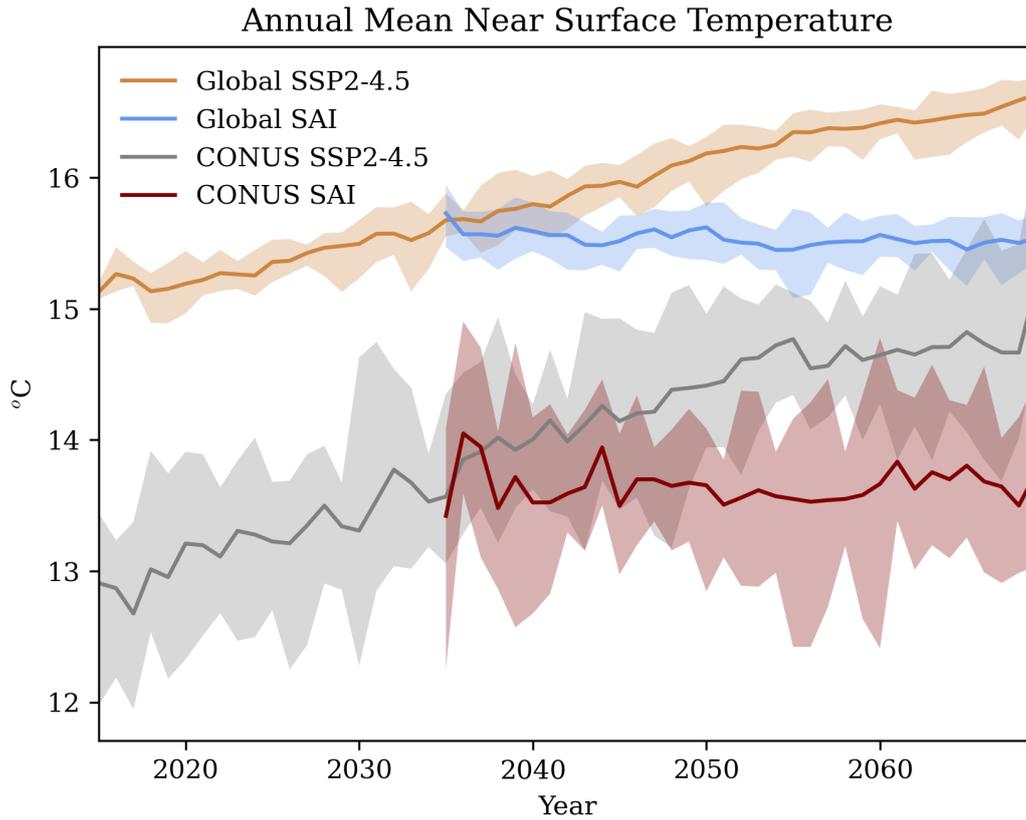


Figure 1: Annual mean near-surface (2 m) temperature from the SSP2-4.5 simulations (2015-2069) and the simulations where SAI is deployed (2035-2069). Results averaged over the globe are given by the tan (SSP2-4.5) and blue (SAI) lines, while those averaged over the contiguous U.S. are given by the gray (SSP2-4.5) and red (SAI) lines. Ensemble means are shown by the thick solid lines, while the minimum and maximum ranges of the individual ensemble members are shown by the corresponding color shading.

171 only the time series of global 2 m temperature change (Hueholt et al., 2023; Richter et al.,
 172 2022), but also that for the contiguous U.S (CONUS) (Figure 1).

173 **2.2 Convective Weather Environment Parameters and Proxies**

174 CAPE (J kg^{-1}) and CIN (J kg^{-1}) are thermodynamic parameters which consider the
 175 temperature and moisture content of the atmosphere (Doswell & Rasmussen, 1994).
 176 CAPE is a measure of potential energy that is defined by the vertical integral of buoyancy
 177 from the level of free convection to the equilibrium level, and is analogous to updraft

178 velocity (Doswell & Rasmussen, 1994; E. N. Rasmussen & Blanchard, 1998; Trapp et al.,
179 2007). CIN represents the negative buoyancy and is indicative of the potential to suppress
180 convective motions (E. N. Rasmussen & Blanchard, 1998). CAPE and CIN were
181 calculated as the most-unstable parcel in the lowest 3000 m of the atmosphere (MUCAPE
182 and MUCIN), which is a useful method for capturing cases of elevated instability, while
183 being effective at identifying low-level or surface-based instability when present (Doswell
184 & Rasmussen, 1994).

185 S06 (m s^{-1}) is a kinematic parameter that is representative of the change in the
186 horizontal wind vector from ~ 10 m above ground-level to approximately 6 km altitude.
187 This measure of wind shear is used to diagnose whether or not an environment is
188 favorable to the formation of significant severe thunderstorms (Brooks et al., 2003;
189 E. N. Rasmussen & Blanchard, 1998). In particular, small magnitudes of S06 are typically
190 associated with the development of relatively small, short-lived single-cell thunderstorms,
191 while larger magnitudes of S06 are typically associated with the potential for development
192 of supercell thunderstorms, which are longer-lived, more organized, and more intense
193 (Weisman & Klemp, 1982).

194 The combination of CAPE and 0-6 km wind shear (CAPES06; $\text{m}^3 \text{s}^{-3}$) is a good
195 discriminator for significant severe thunderstorm events (Brooks et al., 2003; Marsh et al.,
196 2007; E. N. Rasmussen & Blanchard, 1998; Trapp et al., 2007). CAPES06 is considered
197 simply as the product of CAPE and S06. Some previous studies have weighted S06 more
198 heavily than CAPE (Brooks et al., 2003; Seeley & Romps, 2015), but Seeley and Romps
199 (2015) note that varying the weight of S06 in calculations of CAPES06 did not have a
200 large impact on future projections of favorable convective weather environments.

201 While results are presented as spatial maps over the CONUS, area-averaged statistics over
202 the Southeast and Midwest regions are also computed. The Southeast is defined as the
203 grid points bounded by 39° - 48° N and 255° - 274° W, while the Midwest is defined as the
204 region within 30° - 39° N and 255° - 280° W (Figure S1). While all seasons and other regions
205 over the U.S. were examined, the analysis here is restricted to the Southeast region during
206 the boreal spring season (MAM) and the Midwest region during the boreal summer
207 season (JJA). These regions and seasons were chosen subjectively based on the
208 climatological seasonal distributions of both convective weather environments and severe
209 weather events (e.g., Kelly et al., 1985; Doswell et al., 2005; Brooks et al., 2007; Taszarek

210 et al., 2020). The representation of convective weather environments in both the
211 Community Atmosphere Model version 6 (CAM6) (Danabasoglu et al., 2020), an
212 atmosphere only model, and CESM2-CAM6, a fully coupled Earth-system model, have
213 been validated against the fifth generation of the high resolution global reanalysis dataset
214 produced by ECMWF (ERA5) (Franke et al., 2023; Li et al., 2020; Chen et al., 2020).
215 CAM6 is the low-top version of WACCM6, where the two models have the same vertical
216 structure up to 87 hPa and nearly identical parameterizations (Danabasoglu et al., 2020).
217 These validations have shown that both CAM6 and CESM2-CAM6 are able to well
218 represent convective weather environments over the eastern CONUS, as well as the
219 synoptic features (Li et al., 2020) and the influence of large-scale modes of variability,
220 such as the El Niño Southern Oscillation (ENSO; Franke et al., 2023).

221 Most previous studies that have considered convective weather environment parameters
222 have calculated these indices using model output at 00 Z, which is known to represent the
223 time when MUCAPE is maximized in the central to eastern U.S. (e.g., Trapp et al., 2007;
224 Diffenbaugh et al., 2013; Seeley & Romps, 2015). However, only daily mean data are
225 available for all 10 of the ARISE-SAI ensemble members. To assess the suitability of using
226 daily averaged data, 00 Z data were extracted from one ensemble member from the
227 CESM2 Large Ensemble (CESM2-LE; Rodgers et al., 2021) and results were compared to
228 those computed from the daily averaged data from the same simulation. The CESM2-LE
229 is a 100-member ensemble that runs from 1850-2100 and follows the SSP3-7.0 emissions
230 scenario, which warms more and has slower development of mitigation and adaptation
231 practices relative to SSP2-4.5 (O'Neill et al., 2017). The CESM2-LE utilizes the low-top
232 atmospheric component of CESM2 (CAM6; Rodgers et al., 2021).

233 The time evolutions from 2015-2069 of MUCAPE, MUCIN, S06, and CAPES06 computed
234 at 00 Z were compared to those computed as a daily mean quantity. The analysis was
235 based on anomalies relative to 2015-2034 climatologies. The time evolution of CAPES06
236 anomalies for the Southeast in MAM and the Midwest in JJA indicates high correlation
237 between the sub-daily and daily mean anomalies in both regions ($r = 0.988$ and $r =$
238 0.946) (Figure 2). Correlations between sub-daily and daily mean anomalies are similarly
239 high for MUCAPE, MUCIN and S06 (not shown). Thus, while differences exist in the
240 absolute magnitude of the convective weather environment parameters when computed
241 from sub-daily relative to daily mean data (especially for MUCIN, which is maximized at
242 night rather than in the afternoon due to nocturnal stability in the boundary layer), the

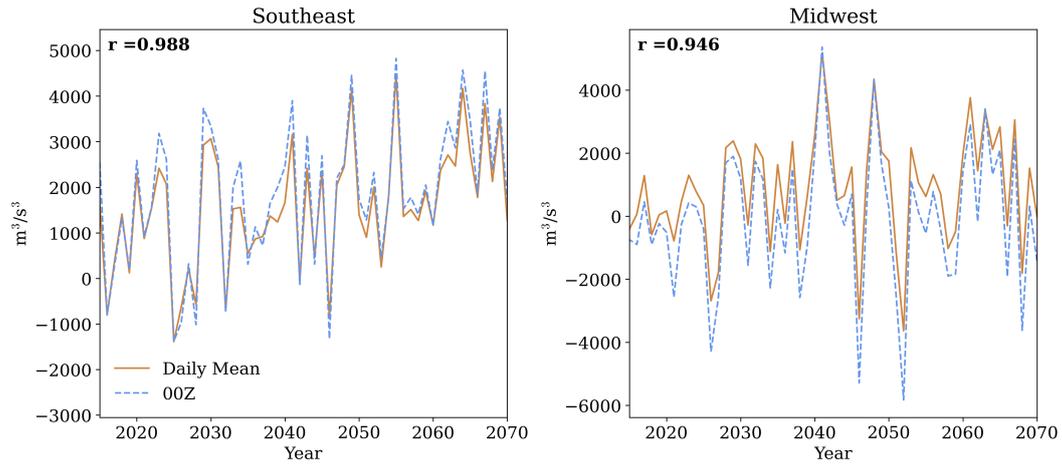


Figure 2: Time series of CAPES06 anomalies in the Southeast in MAM and in the Midwest in JJA from 2015-2070 from one member of the CESM2 Large Ensemble. Anomalies are relative to the 2015-2034 mean. The tan line represents CAPES06 anomalies calculated from daily mean data, while the blue dashed line represents CAPES06 anomalies from 00 Z data only. The correlation between the two time series is the r-value in the top left of each graph.

243 changes over time of the parameters computed from daily mean data, as well as the
 244 differences between the SAI and no-SAI simulations, are very similar to the temporal
 245 changes of the parameters computed from 00 Z data only. Using the daily mean data that
 246 is available from all 10 ARISE-SAI ensemble members for a better estimation of the
 247 forced changes in climate, as well as to better examine how the forced changes might be
 248 modified by decadal and multi-decadal internal climate variability.

249 **3 Results**

250 **3.1 Forced Responses**

251 Differences in future projections with and without SAI are evident in many convective
 252 weather environment parameters averaged over the Southeast and Midwest regions
 253 (Figure 3). Without SAI deployment, MUCAPE increases throughout the time period
 254 relative to the base period (2015-2034), but with SAI deployment MUCAPE stabilizes
 255 (Figure 3a, 3e). Similarly, climate change causes an increase in the magnitude of MUCIN
 256 (increasingly negative values) in both regions while SAI stabilizes MUCIN near 2035 levels

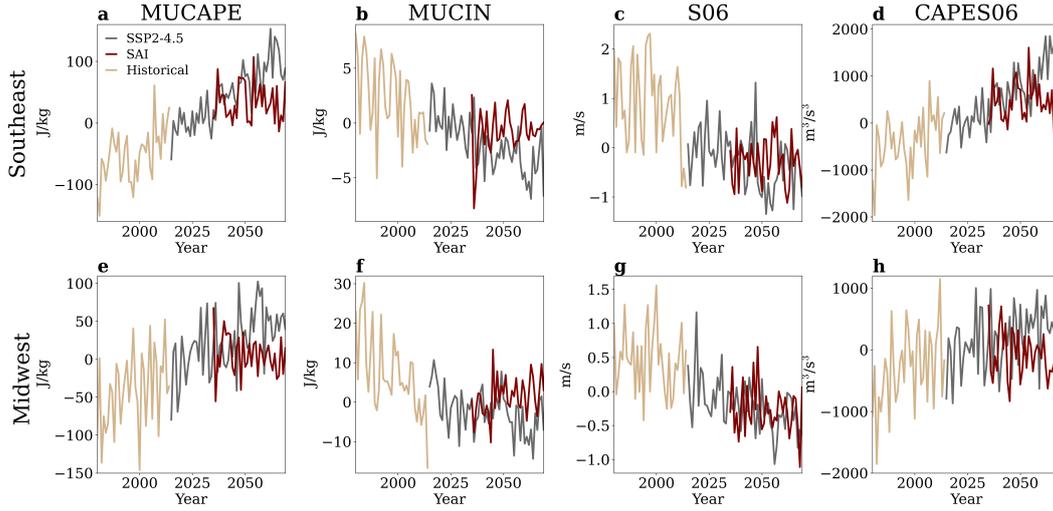


Figure 3: Time series showing MUCAPE (J kg^{-1}) (a and e), MUCIN (J kg^{-1}) (b and f), S06 (m s^{-1}) (c and g), and CAPES06 ($\text{m}^3 \text{s}^{-3}$) (d and h) anomalies relative to the 2015-2034 mean for the Southeast in MAM (top row) and the Midwest in JJA (bottom row) from 1980-2069. The tan line represents the three-member ensemble mean from CESM2(WACCM6) historical runs, the gray line represents the 10-member ensemble mean from the SSP2-4.5 simulations, and the red line represents the 10-member ensemble mean from the simulations with SAI deployment beginning in 2035.

257 in these simulations (Figure 3b, 3f). S06 decreases in magnitude throughout the time
 258 period in the no-SAI simulations, but the influence of SAI on wind shear is less clear
 259 (Figure 3c, 3g). The sign of future greenhouse-gas induced changes in MUCAPE, MUCIN
 260 and S06 are in general agreement with previous studies (Diffenbaugh et al., 2013; Lepore
 261 et al., 2021; Trapp et al., 2009; K. L. Rasmussen et al., 2017), although magnitudes differ,
 262 partly because earlier studies examined climate change scenarios other than SSP2-4.5 and
 263 with a variety of model frameworks. Projected increases in the magnitude of CAPES06,
 264 which are dominated by increases in MUCAPE with continued climate warming (Figure
 265 3d, 3h) are also in line with earlier studies (Diffenbaugh et al., 2013; Seeley & Romps,
 266 2015; Trapp et al., 2007). It thus follows that changes in CAPES06 mirror the simulated
 267 changes to MUCAPE in the SAI runs, with anomalies stabilizing to approximately 2035
 268 levels (Figure 3d, 3h).

269 The underlying climatological (2015-2034) spatial distributions of these parameters from
 270 the ARISE-SAI simulations (Figure 4) provide context for projected changes with and

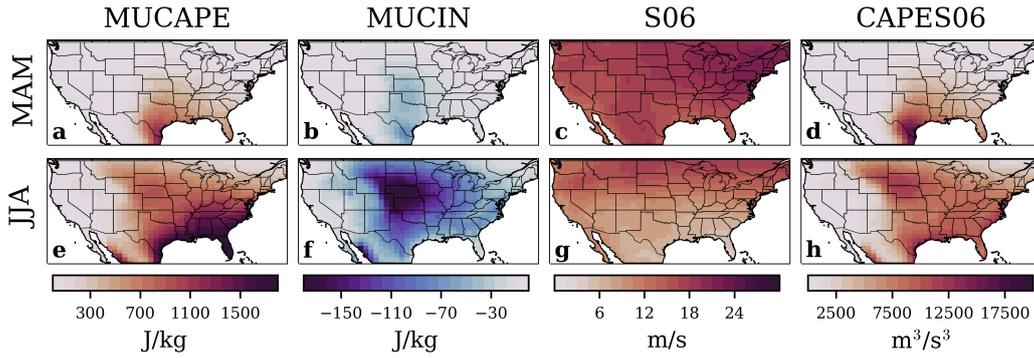


Figure 4: Climatological MUCAPE (a and e), MUCIN (b and f), S06 (c and g) and CAPES06 (d and h) for MAM (top row) and JJA (bottom row) over 2015-2034 for the SSP2-4.5 simulations.

271 without SAI, and they are in good agreement with observations (e.g., Franke et al., 2023;
 272 Li et al., 2020; Chen et al., 2020; K. L. Rasmussen et al., 2017). In MAM, maximum
 273 values of MUCAPE are found over the south-central U.S., especially just west of the Gulf
 274 of Mexico (Figure 4a). The area of maximum MUCAPE becomes much larger in JJA,
 275 with large values generally east of the Rockies and the greatest magnitudes over the far
 276 southern U.S. (Figure 4e). The changes between MAM and JJA are especially notable
 277 over the Northern Plains and the Midwest, where MUCAPE in the summer has
 278 magnitudes near those of the Southeast in MAM (Figure 4e).

279 Similar to MUCAPE, the magnitude of MUCIN increases greatly from MAM to JJA
 280 (Figure 4b, 4f), although again note the magnitudes of the climatological values from
 281 daily mean data are larger than in previous studies that have utilized data from the
 282 afternoon only. In particular, the largest magnitudes of MUCIN are concentrated over
 283 Texas, Oklahoma and Kansas in MAM, but by JJA the largest magnitudes are shifted to
 284 the central Great Plains. S06 is positive over the entire U.S. during both seasons,
 285 although it is larger in spring than summer (Figure 4c, 4g). In both seasons, maximum
 286 values of wind shear are over the northern third of the U.S. The distribution of CAPES06
 287 largely mirrors the distribution of MUCAPE in both MAM and JJA (Figure 4d, 4h),
 288 although CAPES06 has a more uniform distribution across the eastern half of the U.S. in
 289 JJA compared to MUCAPE (4d, 4h).

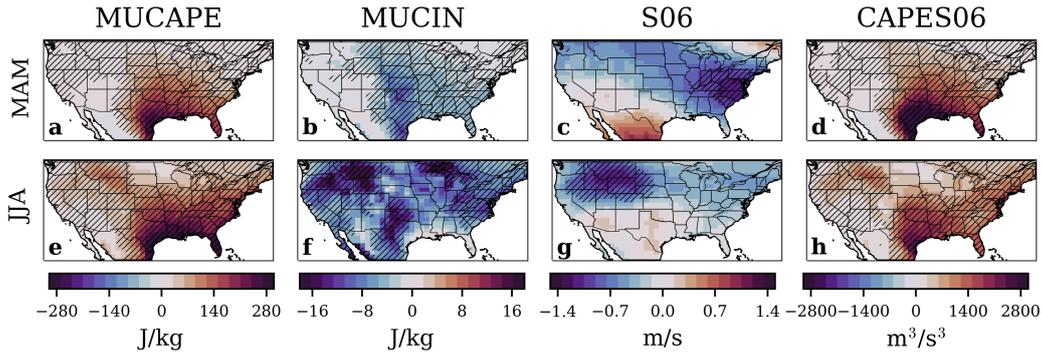


Figure 5: The differences between 2060-2069 (SSP2-4.5) and 2015-2034 (SSP2-4.5) ensemble mean MUCAPE, MUCIN, S06, and CAPES06, in MAM (top row) and JJA (bottom row). Stippling indicates statistical significance at the $\alpha=0.05$ level.

290 To examine how climate change affects these environmental parameters, the average
 291 changes in the last decade of the ARISE-SAI simulations (2060-2069) are examined
 292 relative to the climatological period (2015-2034; Figure 5). In the spring and summer,
 293 MUCAPE, MUCIN, and CAPES06 are all projected to increase in magnitude with
 294 climate change (Figure 5). Over most regions, these increases are statistically significant
 295 at the $\alpha=0.05$ level for the two-sample t-test (to account for issues related to multiple
 296 testing across the U.S. domain, the method outlined in Wilks (2016) was used to control
 297 the false discovery rate). Wind shear (S06) is projected to decrease in magnitude during
 298 MAM across much of the U.S., with decreases largest in the eastern U.S. (Figure 5c). S06
 299 is also projected to decrease in the summer months, with the largest decreases in the
 300 northwest U.S. where convective activity is not as significant historically (Figure 5g).
 301 While decreases in wind shear are evident across much of the U.S., the magnitude of the
 302 decrease is relatively small compared to the magnitude of the underlying climatology
 303 (Figure 4c, 4g, 5c, 5g): climatological S06 values exceed 20 m s^{-1} across much of the U.S.,
 304 while projected changes by 2060-2069 exceed 1 m s^{-1} over only limited regions (Figure 5c,
 305 5g). Projected increases in MUCAPE, MUCIN and CAPES06, as well as projected
 306 decreases in S06, are broadly consistent with previous literature (Difffenbaugh et al., 2013;
 307 Franke et al., 2023; Hoogewind et al., 2017; Lepore et al., 2021; K. L. Rasmussen et al.,
 308 2017; Seeley & Romps, 2015; Trapp et al., 2007, 2009).

309 In the SAI simulations, future changes in the magnitudes in MUCAPE, MUCIN and
310 CAPES06 are generally much smaller and less statistically significant across the U.S.
311 (Figure 6) than in the no-SAI simulations (Figure 5). This suggests that if SAI were to be
312 deployed, the convective weather environment parameters analyzed here would not change
313 appreciably from today, although that conclusion may be specific to the ARISE-SAI
314 simulations. Future changes in S06 with SAI, however, are generally similar to those
315 projected in the no-SAI simulations. For instance, the spatial patterns of projected
316 decreases in S06 with SAI are similar to those without SAI in MAM (Figure 5c, 6c),
317 although regions of maximum decrease differ. Since an objective of the ARISE-SAI
318 experiment is to not only keep global average temperature near its 2035 value but also to
319 preserve the equator-to-pole temperature gradient (Richter et al., 2022), it is difficult to
320 simply attribute the S06 decreases in the no-SAI simulations (Figure 5c) to changes in the
321 thermal wind balance, as has been done previously (Trapp et al., 2007; Seeley & Romps,
322 2015). The results suggest that there could be a different mechanism driving future
323 changes in S06 that has not previously been identified. This aspect is further explored in
324 the Discussion section.

325 Another way to examine the impacts of SAI on convective weather environment
326 parameters relative to the effects from increasing greenhouse concentrations alone is to
327 directly difference the SAI and no-SAI simulations. Here this is done for differences
328 averaged over the 2060-2069 decade. For MUCAPE, MUCIN, and CAPES06, the
329 differences follow a similar spatial pattern and magnitude, but are of the opposite sign, to
330 the projected future changes in the no-SAI simulations (Figure 5 and 7). Further, the
331 differences between the SAI and no-SAI simulations for MUCAPE, MUCIN and
332 CAPES06 are widely statistically significant across the eastern U.S. for 2060-2069, while
333 the differences for S06 are not (Figure 7).

334 In addition to examining changes in each convective weather environment parameter
335 separately, understanding their co-variability can provide insight into the potential change
336 in the distributions of convective modes and frequency with and without SAI
337 (Difffenbaugh et al., 2013; Lepore et al., 2021; K. L. Rasmussen et al., 2017). To this
338 point, bivariate distributions of convective weather environment parameters from
339 2060-2069 were created from daily data for the SAI and no-SAI simulations, respectively.
340 For each individual ensemble member, daily mean values of MUCAPE, MUCIN and S06
341 were collected for each gridpoint over the Southeast in MAM and the Midwest in JJA.

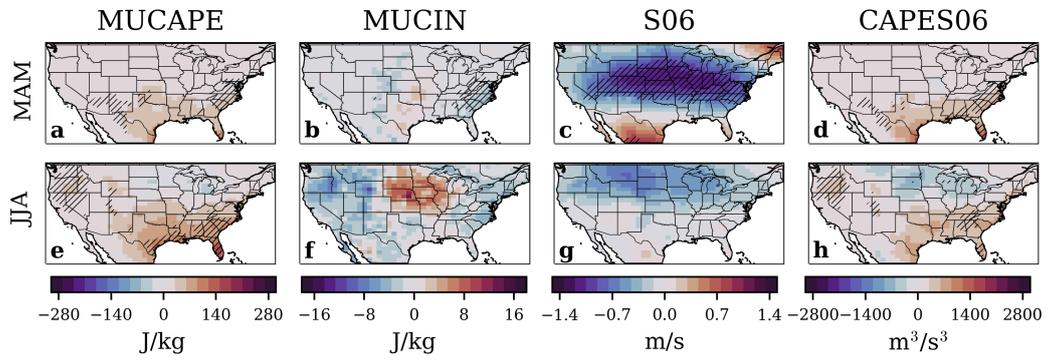


Figure 6: Differences between 2060-2069 (SAI) and 2015-2034 (SSP2-4.5) ensemble mean MUCAPE, MUCIN, S06, and CAPES06, in MAM (top row) and JJA (bottom row). Stippling indicates statistical significance at the $\alpha=0.05$ level.

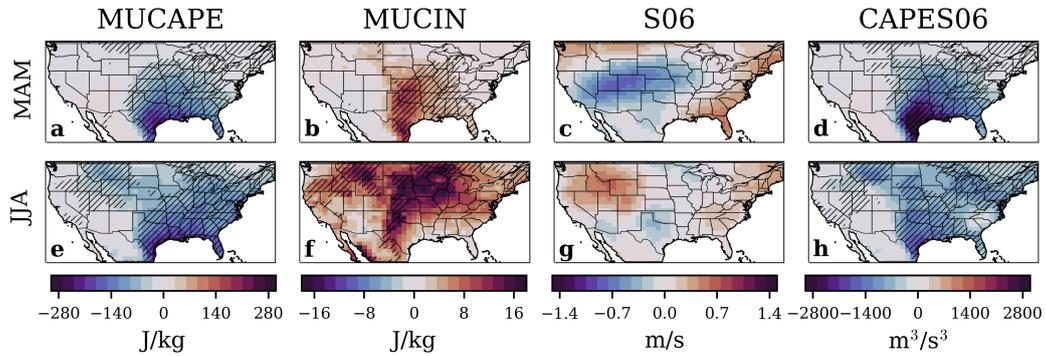


Figure 7: Differences between SAI and SSP2-4.5 ensemble means for 2060-2069 in MAM (top row) and JJA (bottom row). Stippling indicates statistical significance at the $\alpha=0.05$ level.

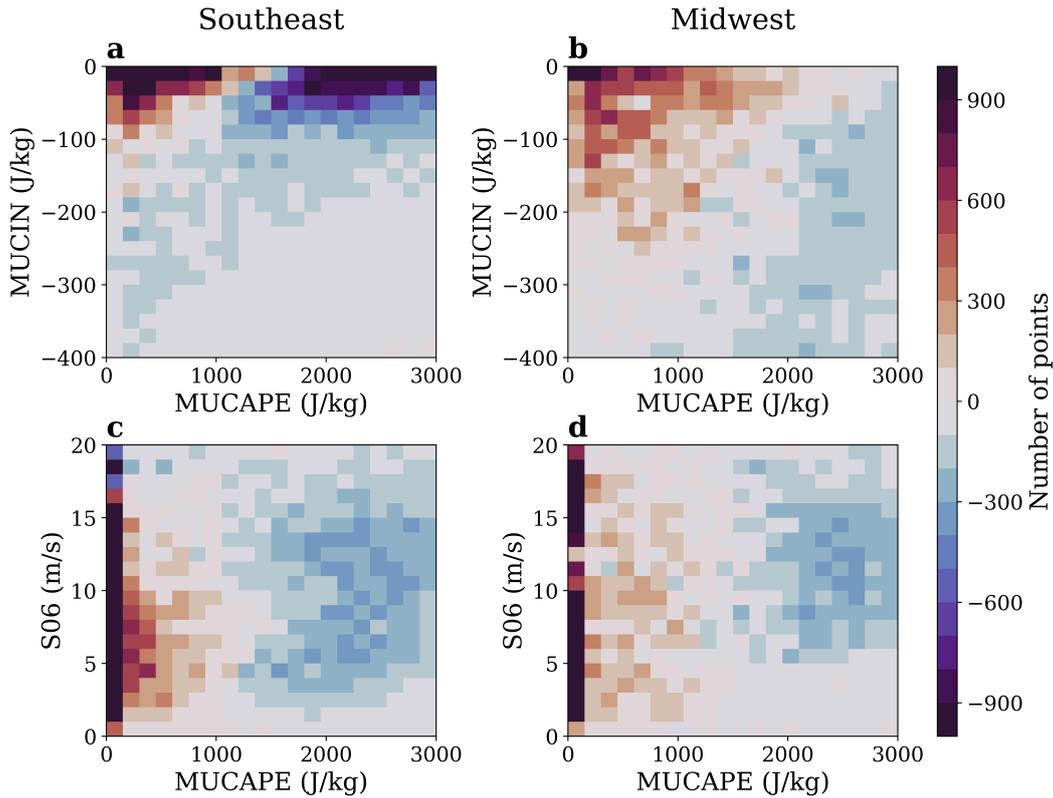


Figure 8: The difference between the SAI and no-SAI simulations (i.e., SAI - SSP2-4.5) for the bivariate distribution of MUCAPE (x-axis) and MUCIN (y-axis) for the Southeast in MAM (a) and the Midwest in JJA (b) over 2060-2069. (c) shows the difference between the SAI and no-SAI simulations for the bivariate distribution of MUCAPE (x-axis) and S06 (y-axis) for the Southeast in MAM, while (d) shows the same, but for the Midwest in JJA. Red (blue) pixels represent bins where there are more (less) days with corresponding MUCAPE and MUCIN (MUCAPE and S06) values in the simulations with SAI.

342 Distinct bivariate distributions (MUCAPE versus MUCIN, and MUCAPE versus S06)
 343 were then plotted for the difference of the SAI and no-SAI simulations (Figure 8).
 344 Positive numbers indicate that the SAI simulations had more days in a given bin than the
 345 no-SAI simulations, whereas negative numbers indicate the opposite.

346 In the Southeast in MAM and the Midwest in JJA, there are more days with low
 347 magnitudes of MUCAPE and MUCIN in the SAI simulations than in the no-SAI
 348 simulations, indicating that projected increases in the number of days with increased
 349 MUCAPE and MUCIN magnitudes under SSP2-4.5 could be largely avoided with SAI

350 (Figure 8a, 8b). The shift in the distribution of these parameters is due to decreases in
351 both MUCAPE and MUCIN, which is evident in the straight diagonal region that
352 separates the red and blue points. The difference in the shape of the distributions
353 between the Southeast in MAM (Figure 8a) and the Midwest in JJA (Figure 8b) is largely
354 due to the climatology of MUCIN, where values have much higher magnitudes in the
355 Midwest in JJA (Figure 4b, 4f).

356 The difference between the SAI and no-SAI simulations for the daily bivariate distribution
357 of MUCAPE and S06 is illustrated in Figure 8c and 8d. While the simulations suggest
358 fewer days with high MUCAPE if SAI were to be deployed, the number of days with high
359 shear is comparable between the SAI and no-SAI simulations. Thus, with SAI, there may
360 be fewer days with high magnitude MUCAPE and S06, but the number of days with
361 low-to-moderate MUCAPE and high shear may be similar with and without SAI (Figure
362 8c, 8d).

363 The analyses in Figure 8 also begin to highlight the potential role of unforced, internal
364 climate variability in projected future changes in convective weather environments with
365 and without SAI. The potential for internal variability to significantly modulate projected
366 forced changes in climate is known to be significant (e.g. Deser et al., 2012; Deser, 2020;
367 Schwarzwald and Lenssen, 2022). Motivated by these and similar studies, the next section
368 goes beyond descriptions of only forced changes in climate warming in order to more
369 completely examine the range of plausible future convective weather environments with
370 and without SAI.

371 **3.2 The Role of Internal Climate Variability**

372 Other studies have examined the impact of internal climate variability on the behavior of
373 severe weather related phenomena. However, they have tended to focus on
374 sub-seasonal-to-interannual variations, such as those associated with the Madden Julian
375 Oscillation (Baggett et al., 2018; Thompson & Roundy, 2013) or the El Niño Southern
376 Oscillation (ENSO) phenomenon. For instance, J. T. Allen et al. (2018) examined the role
377 of ENSO in modulating the annual cycle of tornadoes over the U.S., while Tippett et al.
378 (2022) studied how ENSO and the phase of the Arctic Oscillation (AO) impacted the
379 predictability of the tornado environment index. What has not been often considered,
380 however, is the potential role that lower frequency (e.g., decadal) internal climate

381 variability could play in future projections of severe weather. Ensemble simulations from
382 climate and Earth system models indicate that even though the forced response to
383 increasing greenhouse gas concentrations shows warming across the U.S. and other land
384 regions, decadal and longer-timescale internal climate variability has the potential to
385 significantly enhance or dampen the forced response (Deser et al., 2012; Hawkins &
386 Sutton, 2009; Kay et al., 2015). It is thus relevant to consider how internal climate
387 variability may impact future projections of convective weather environments both with
388 and without SAI.

389 Histograms of changes in MUCAPE and CAPES06 by 2060-2069 relative to the reference
390 period (2015-2034) show that while the forced response (ensemble mean) increases in
391 magnitude under SSP2-4.5, changes in individual no-SAI simulations could be notably
392 smaller or larger due to unforced variations in climate (Figure 9; gray bars). Specifically,
393 individual ensemble members project changes in MUCAPE that depart as much as 60 J
394 kg^{-1} from the ensemble mean increase of 107 J kg^{-1} by 2060-2069 over the Southeast in
395 MAM (Figure 9a). Similar results are evident for CAPES06. For instance, while the
396 ensemble-mean projected change in CAPES06 is an increase of $392 \text{ m}^3 \text{ s}^{-3}$ across the
397 Midwest in JJA, one member projects a decrease of $226 \text{ m}^3 \text{ s}^{-3}$ by mid-century (Figure
398 9h). Such results confirm the large role that internal climate variability will likely play in
399 the future evolution of climate, a point also emphasized recently by Franke et al. (2023)
400 who examined future decadal trends in convective environment variables using the
401 CESM2 Large Ensemble under SSP3-7.0 (Rodgers et al., 2021).

402 A similarly wide range of possible changes in MUCAPE, MUCIN and CAPES06 are also
403 evident in the SAI simulations (Figure 9; red hatched bars). Thus, while the forced
404 signals in the convective weather environment parameters examined here are distinct in
405 future worlds with and without SAI, internal climate variability could produce similar
406 climate outcomes in the decades ahead (Keys et al., 2022). For example, an ensemble
407 member in the no-SAI simulation projects that MUCIN decreases in magnitude by 5.2 J
408 kg^{-1} in the Midwest in JJA by 2060-2069, while a member in the SAI simulation projects
409 an 8.5 J kg^{-1} increase in MUCIN over the same period (Figure 9f). Additionally, the
410 distribution of possible future changes in S06 with and without SAI are very similar
411 across ARISE-SAI ensemble members when averaged over the Southeast and Midwest
412 regions, as is the case for the ensemble-mean changes (Figure 9c, 9g). This further

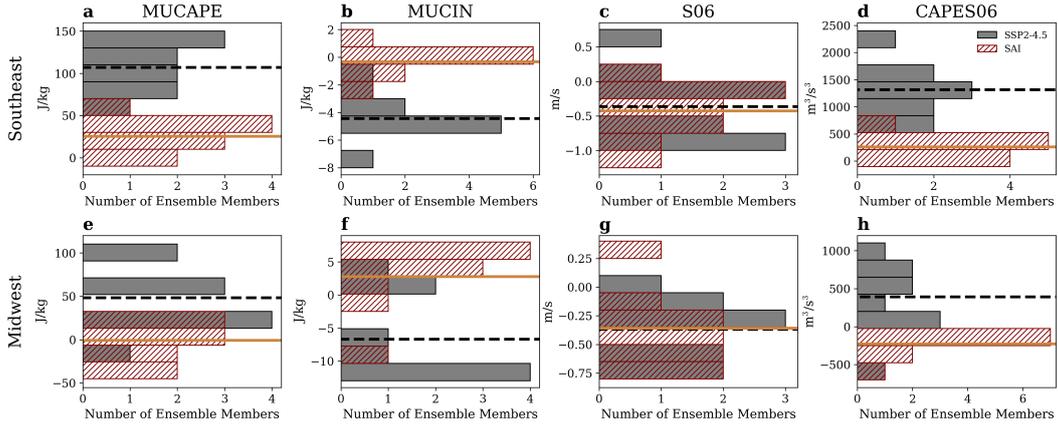


Figure 9: Histograms of the 10 ensemble members of the SSP2-4.5 (gray bars) and SAI (red hatched bars) simulations, illustrating the change in MUCAPE, MUCIN, S06, and CAPES06 for 2060-2069 relative to the 2015-2034. The black dotted and solid tan lines represent the ensemble mean values of the SSP2-4.5 and SAI simulations, respectively. Results are for the Southeast in MAM (a-d) and the Midwest in JJA (f-h).

413 supports the idea that the thermal wind relationship may not be the primary mechanism
 414 governing future changes in the deep-layer tropospheric wind shear over the U.S.

415 To further illustrate the extent to which internal climate variability can produce a climate
 416 outcome that differs significantly from the forced response alone, the ensemble member
 417 with the maximum change in CAPES06 by 2060-2069 when averaged over the Southeast
 418 in MAM is contrasted against the ensemble member with the smallest change. The spatial
 419 patterns of change for each of these two ensemble members is shown in Figure 10, along
 420 with the ensemble mean changes. By subtracting the latter from the total changes in
 421 CAPES06, the regional changes due only to internal climate variability are revealed. The
 422 main point is that internal climate variability may either significantly enhance the forced
 423 response due to climate change (Figure 10c) or suppress it (Figure 10f) on decadal time
 424 scales. It is also notable that the magnitudes of the changes due solely to internal climate
 425 variability are spatially coherent over large regions, and they are of similar magnitude to
 426 the force changes (e.g., Deser et al., 2020).

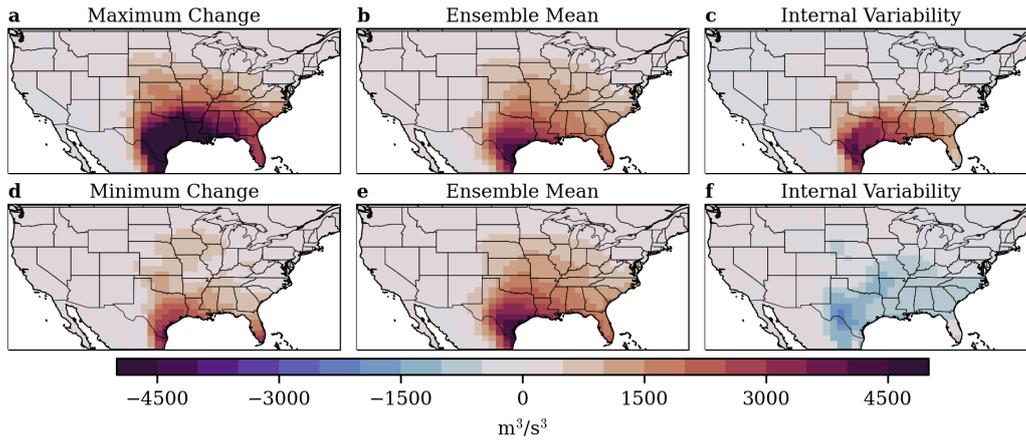


Figure 10: The ensemble members with the maximum (a) and minimum (b) changes in CAPES06 by 2060-2069 relative to 2015-2034 over the Southeast in MAM in the SSP2-4.5 simulations, calculation described in text. The forced response, or ensemble mean, is shown in (b) and repeated in (e). The change in CAPES06 due only to internal variability is shown for the ensemble member with the maximum and minimum change in (c) and (f), respectively.

4 Discussion

In ARISE-SAI, projected future changes in MUCAPE, MUCIN, and CAPES06 are smaller with simulated SAI deployment than what is projected with climate change alone (Figure 5, 6). This is consistent with lower temperatures and dew points on average throughout the troposphere in MAM and JJA in an SAI future (Figure S2). It thus follows that the SAI simulations have fewer co-occurrences of high magnitude MUCAPE and MUCIN in the future (Figure 8a, 8b), whereas changes in the bivariate distribution of MUCAPE and S06 are primarily driven by smaller values of MUCAPE in a future with SAI (Figure 8c, 8d).

Future differences in tropospheric wind shear are more difficult to understand than SAI-induced changes in thermodynamic parameters. Under climate change with and without SAI, S06 is expected to decrease across much of the convectively active regions in the U.S. in the spring and summer seasons (Figure 5c, 5g, 6c, 6g). Although the decreases are small in magnitude relative to the climatology (Figure 4c, 4g), similar decreases have been documented in other studies of future climate change. Trapp et al. (2007), for

442 instance, concluded that future decreases in tropospheric wind shear are consistent with
443 decreases in the middle latitude thermal wind, as would be expected as the
444 equator-to-pole temperature gradient decreases over the 21st century (Cohen et al., 2014;
445 Francis & Vavrus, 2012). However, changes in S06 with SAI are broadly consistent with
446 those in the no-SAI simulations examined here (Figure 5c, 5g, 6c, 6g), even though
447 ARISE-SAI is configured so that the equator-to-pole temperature gradient remains near
448 its 2035 value when SAI is deployed (Richter et al., 2022).

449 While a detailed analysis of the changes in wind shear are beyond the scope of this study,
450 note that precipitation is projected to increase over the eastern equatorial Pacific during
451 the seasons examined here under both the SAI and no-SAI simulations, although the
452 increases projected with SAI are smaller in magnitude (Figure S3; see also Richter et al.,
453 2022). Simpson et al. (2019) also indicated that precipitation is projected to increase in
454 magnitude in the eastern equatorial Pacific in a future with SAI. Further, they examined
455 the precipitation response to the addition of stratospheric heating in the absence of a
456 greenhouse gas forcing, and found that precipitation is also projected to increase in the
457 eastern equatorial Pacific. This suggests that precipitation changes in this region are
458 influenced by dynamical responses that may result from the introduction of aerosols into
459 the stratosphere. Upper-level divergence due to tropical convective heating in the
460 equatorial Pacific can be the source of anomalous vorticity that drives the propagation of
461 Rossby wave trains that impact the extratropics (Qin & Robinson, 1993; Sardeshmukh &
462 Hoskins, 1988). This idea is broadly consistent with the spatial patterns of 300 hPa winds
463 in both the SAI and no-SAI simulations, with alternating bands of increasing and
464 decreasing winds emanating from the eastern tropical Pacific (Figure S4). In other words,
465 future changes in S06 in the SAI and no-SAI simulations may be driven by changes in
466 tropical precipitation and associated large-scale climate circulations, which are similar
467 whether or not SAI is deployed.

468 A novel aspect of this study is the use of individual ensemble members to examine the
469 variability around the forced responses to climate change and SAI in large-scale convective
470 weather environment parameters relevant to severe weather (Figure 9). Recall that each
471 individual ensemble member represents an equally-plausible climate outcome in the
472 decades ahead (e.g., Deser et al., 2020). The results illustrate the large-role internal
473 climate variability will likely have, especially on regional scales. This also means that
474 future convective weather environments in an SAI world could be indistinguishable from a

475 world without SAI, even though the forced responses are distinguishable. Note that a
476 10-member ensemble is likely insufficient to statistically capture the full breadth of
477 possible outcomes (Deser et al., 2012; Franke et al., 2023). There are also shortcomings in
478 the ability of Earth-system models to accurately represent internal climate variability
479 (Orbe et al., 2020; O'Reilly et al., 2021).

480 Other limitations of this study include the fact that the use of large-scale parameters to
481 assess how the behavior of severe weather may change in the future is itself a caveat, since
482 a favorable environment does not imply that convection will actually occur. Further, this
483 method assumes that the frequency of convective initiation will not change with climate
484 warming (Hoogewind et al., 2017; Trapp et al., 2007, 2009), and that the rate of initiation
485 would not be affected by SAI deployment. Convective initiation is dependent on a variety
486 of factors such as orography and large-scale dynamics, the latter of which have the
487 potential to be impacted by climate warming and potential SAI deployment. The
488 representation of convective initiation is also likely sensitive to model configuration
489 (Carlson et al., 1983; Trapp et al., 2007).

490 **5 Conclusion**

491 The potential impact of SAI on future convective weather environments across the U.S.
492 Midwest and Southeast was evaluated in one climate change scenario, with and without
493 SAI deployment. The ARISE-SAI simulations indicate that, with climate change,
494 thermodynamic parameters such as MUCAPE and MUCIN are projected to increase in
495 magnitude across the U.S. in the spring and summer, and that these increases could be
496 mostly avoided if SAI were to be deployed. Future changes in kinematic parameters, such
497 as S06, appear to be primarily driven by changes in precipitation over the eastern tropical
498 Pacific, which are similar between climate change simulations with and without SAI.
499 Results further indicate that internal climate variability has the potential to significantly
500 impact future projections of U.S. convective weather environments regionally, with
501 spatially-coherent changes of similar magnitude to the forced responses.

502 Future work could examine how model-specific biases impact future projections of
503 convective weather environments with and without SAI. For instance, the exact
504 ARISE-SAI scenarios examined here were recently completed using the first version of the
505 U.K. Earth System Model (Archibald et al., 2020; Sellar et al., 2019; Henry et al., 2023).

506 It would also be insightful to examine Earth-system model simulations with different SAI
507 deployment goals and timelines (e.g., MacMartin et al., 2022), as well as simulations
508 under different climate change scenarios, such as the Stratospheric Aerosol Geoengineering
509 Large Ensemble Project (Tilmes et al., 2018). Use of the output from Earth-system
510 models to force high-resolution, regional climate models to explicitly examine how
511 projected changes in the large-scale environment impact the distribution of convective
512 modes could provide additional understanding as to how SAI deployment impacts
513 convective weather (Ashley et al., 2023; Gensini et al., 2023; Gensini & Mote, 2015;
514 K. L. Rasmussen et al., 2017; Trapp et al., 2019).

515 **6 Open Research**

516 The original ARISE-SAI data set from which the data in this work was derived (all SAI
517 members and 5 no-SAI members) are located on the NCAR Climate Data Gateway
518 (Richter, 2022a, <https://doi.org/10.5065/9kcn-9y79>). The remaining 5 no-SAI members
519 are available from the NCAR Climate Data Gateway at (Richter, 2022b,
520 <https://doi.org/10.26024/0cs0-ev98>). All ARISE-SAI data may also be accessed from
521 Amazon Web Services (NCAR, 2022, registry.opendata.aws/ncar-cesm2-arise/). The
522 complete CESM2 (WACCM6) Historical runs from which the data in this work was
523 derived are available at Earth System Grid (Danabasoglu, 2019,
524 <https://doi.org/10.22033/ESGF/CMIP6.11298>).

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