

THESIS

THE IMPACT OF STRATOSPHERIC AEROSOL INJECTION: A REGIONAL CASE STUDY

Submitted by

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ABSTRACT

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The detrimental effects of anthropogenic climate change have become ubiquitous as global greenhouse gas emissions concentrations continue to increase. As a result, research into proposed climate intervention (CI) techniques to offset some of the most damaging effects of climate change is increasing, with the idea that CI could provide more time for humanity to pursue decarbonization. One of the most researched CI techniques is stratospheric aerosol injection (SAI), which would reflect a small portion of sunlight away from Earth to reduce or lower temperature increases. While many studies have analyzed SAI's potential global impacts on climate variables, such as temperature and precipitation, relatively few have examined regional impacts on variables more intimately tied to human well-being, such as crop productivity. Thus, using climate model data, we analyze the projected impacts of one future climate change and three SAI scenarios on four Global South regions already socioeconomically vulnerable to climate change: South Asia (SAS), East Asia (EAS), South Central America (SCA), and West Africa (WAF). We find that, in the SAI scenarios, heat extremes are reduced and wet season precipitation, soil moisture and crop productivity increase relative to the climate change scenario in all four regions. Further, SAI clearly ameliorates crop productivity losses produced by climate change in WAF and SCA, with less clear benefits in SAS and EAS. Our study indicates the potential for SAI (in the scenarios examined here) to alleviate some of climate change's adverse impacts on human welfare.

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CHAPTER 1

INTRODUCTION

Fossil fuel burning from anthropogenic industrial activities has led to substantial increases in atmospheric concentrations of greenhouse gases (GHGs), such as carbon dioxide (CO₂) and methane. From about ~10,000 years ago until ~1850, atmospheric CO₂ concentrations remained close to 280 parts per million (Joos et al., 2004); in contrast, the 2024 global mean CO₂ concentration was 424.61 ppm (Lan and Keeling, n.d.).

Scientists have been aware of the relation between atmospheric GHG concentrations and climate for over a century. In 1896, Swedish scientist Svante Arrhenius mathematically quantified the effect of GHG concentrations on surface temperatures (Arrhenius, 1896). Scientific concern regarding climate change due to anthropogenically-induced increases in GHG concentrations became truly rooted in the public's consciousness in the 1980s. In the summer of 1988, climate scientist James Hansen testified before the U.S. Congress that he was 99% confident that recent warming was due to GHG emissions (Saravanan, 2021). In that same year, the Intergovernmental Panel on Climate Change (IPCC), an organization of the United Nations, was formed. The IPCC consists of international scientists who produce reports assessing climate change research for use by policymakers. Six reports have been produced since 1990. In these reports, the IPCC provides extensive, policy-neutral assessments of the physical science behind climate change, its present and projected future societal impacts, and possible adaptation and mitigation pathways (IPCC, n.d.).

Scientific certainty in the attribution of climate change to anthropogenic forcings has grown enormously since the first IPCC assessment report in 1990. For instance, in that first report the IPCC concluded that it could take another decade or more before an anthropogenic warming signal might be detected, and a 1992 supplemental report concluded any observed warming to that point in time could be due to natural climate variability (IPCC, 1992). In contrast, in its latest report, the IPCC stated that fossil fuel burning has “unequivocally” caused 2011-2020 global mean temperatures to rise 1.1°C above 1850-1900 levels (IPCC, 2023). Scientists worldwide have researched climate change’s projected detrimental impacts, such as heat waves, fires, droughts, floods, disease spread, and crop failures (e.g., Bevacqua et al., 2020; Anderson et al., 2020; Tripathy et al., 2023; IPCC, 2023).

The scale of political and industrial initiatives to reduce GHG emissions, however, has not matched the extent of scientific concern. While this is mainly due to the enormous socioeconomic and lifestyle changes required to reduce emissions, inaction has been further exacerbated efforts to cast doubt on the certainty of climate change and its anthropogenic cause, for instance by the fossil fuel industry to protect monetary interests (Oreskes and Conway, 2011). Thus, human and ecological damage from climate change has grown considerably in recent years. Scientists have directly attributed the severity of recent hurricanes, droughts, floods, heat waves, etc. to climate change (e.g., Risser and Wehner, 2017; Frame et al., 2020; Zachariah et al., 2023; You et al., 2024). The 2023 global mean temperature was an unprecedented 1.45°C hotter than preindustrial, 1850-1900 levels (Perkins-Kirkpatrick et al., 2024). This record was broken by that of 2024, which likely surpassed 1.5°C above preindustrial (ECMWF, 2025; Madge, 2025). Global mean temperatures are projected to reach ~2.5°C above preindustrial by 2100 under IPCC’s intermediate SSP2-4.5 emissions scenario (O’Neill et al., 2017; Hausfather, 2025).

Thus, it is increasingly unlikely that the temperature rise will be limited to 1.5 or 2°C above preindustrial, targets formulated in the 2015 Paris Agreement to prevent the most pernicious impacts of climate change.

In this context, an increasing number of scientists have researched climate intervention (CI) as a possible way to mitigate climate change's adverse impacts while humanity continues economic decarbonization efforts. CI techniques can be broadly grouped into two categories (NASEM, 2021). The first is carbon dioxide removal (CDR). Some CDR methods use technology to remove CO₂ from the ambient air. Others, using a combination of natural and technological processes, sequester carbon in the geosphere and biosphere (Hurrell et al., 2024). The second CI technique is solar CI, by which a small portion of incoming sunlight is reflected away from Earth to reduce average temperatures. One of the most researched solar climate intervention techniques is stratospheric aerosol injection (SAI), which reflects sunlight through the introduction of small aerosols into the stratosphere (Zhang et al., 2024). Scientific interest in SAI grew substantially after the famous atmospheric chemist Paul Crutzen (2006) argued that, because of slow progress in climate mitigation, SAI could potentially mitigate the seriousness of climate change. In the past few decades, despite numerous concerns regarding the SAI's morality, political practicality, and potential negative impacts on the Earth system (e.g., Halstead, 2018; Smith & Henly, 2021; Simpson et al., 2019; Bednarz et al., 2023), SAI-related research has greatly increased, an increase that has accompanied the increasing gravity of climate change.

Earth system model simulations have been analyzed to document and understand the possible future impacts of SAI. For instance, the Geoengineering Model Intercomparison Project (GeoMIP) comprises four different scenarios (Kravitz et al., 2011). In two of these, the solar constant is reduced to mimic SAI while the CO₂ atmospheric concentration increases at different

rates; in the other two, sulfate aerosols are injected into the stratosphere at varied locations and rates. Though not part of GeoMIP, another widely used simulation is the Geoengineering Large Ensemble (GLENS) (Tilmes et al., 2018). GLENS is based on the IPCC's RCP-8.5 emissions scenario, with SAI deployment beginning in 2020 and continuing through the century. Other SAI simulations have adjusted the number, timing, latitude, and altitude of injection locations, as well as the amount of aerosols injected (e.g., Tilmes et al., 2017; Lee et al., 2021; Lee et al., 2023; Goddard et al., 2023).

The simulation used in the present work is Assessing Responses and Impacts of Solar climate intervention on the Earth system with stratospheric aerosol injection (ARISE-SAI) (Richter et al., 2022). ARISE uses the SSP2-4.5 emissions scenario (Hausfather, 2025) as its baseline. There are three different SAI scenarios, all of which we utilize in this work. In one scenario (SAI-1.5), SAI deployment begins in 2035 and continues until 2070 to stabilize global average surface temperatures at 1.5 °C above preindustrial (Richter et al., 2022). In the SAI-1.0 scenario, the deployment years are the same as the SAI-1.5 scenario, but global average surface temperatures are lowered to 1 °C above preindustrial (MacMartin et al., 2022). In the SAI-DELAYED scenario, deployment begins in 2045 to lower global surface temperatures to 1.5 °C, although they actually lower to 1.37 °C in the model due to a computational error (Brody et al., 2024). These scenarios represent a range of possibilities with which to explore SAI's potential future impacts.

In this work, we contribute a novel analysis to the field of SAI research. Many past studies (e.g., Mamalakis et al., 2023, Simpson et al., 2019; Richter et al., 2022; Haywood et al., 2022; Zhang et al., 2024) have analyzed how SAI scenarios may impact future global mean temperature, precipitation and other climate fields. Other studies have focused on temperature

and precipitation extremes (e.g., Ji et al., 2018; Alamou et al., 2022) and drought (e.g., Liu et al., 2024). Only a small number of studies (e.g., Da-Allada et al., 2020; Grant et al., 2025) have examined SAI impacts from a regional perspective.

Our work centers on the impacts of various climate futures on human well-being. We analyze four Global South regions—South Asia, East Asia, South Central America, and West Africa. These regions’ inhabitants are especially exposed to climate change’s negative impacts due to socioeconomic difficulties, large populations, political instability, natural disasters, and the particularly intimate dependence on climatic conditions (on crop productivity, thermal comfort, etc.) (Barr et al., 2010; Fankhauser et al., 2014; SEDAC, n.d.; Lakhani, 2021; Gan, 2022; Khalid & Maishman, 2022; Zargar, 2022; FAO, 2024;). For these four regions, we examine changes in 2050-2069 temperature, precipitation, heat extremes, soil moisture, and crop productivity in one climate change and three SAI scenarios relative to a 2020-2039 base period.

Our study (Chapter 2) has been submitted for publication. Chapter 3 summarizes this work and considers possible future research avenues.

CHAPTER 2

THE IMPACT OF STRATOSPHERIC AEROSOL INJECTION: A REGIONAL CASE STUDY

2.1. INTRODUCTION

As the impacts of anthropogenic climate change become more prevalent and severe, an increasing number of scientists are researching climate intervention as a possible approach to rapidly lessen or even reduce the rate of warming (NRC, 2015; NASEM, 2021; UNEP, 2023a). One of the most studied climate intervention techniques is stratospheric aerosol injection (SAI). SAI involves the injection of sulfur dioxide or some other material, such as aluminum oxide (e.g., Vattioni et al., 2023), into the stratosphere to form aerosols, which reflect a small percentage of incoming shortwave radiation (Crutzen et al., 2006; Zhang et al., 2024; Haywood et al. 2025).

The possibility of employing SAI has engendered tremendous political, ethical, and environmental debate. Some argue that employing SAI to lower or stabilize Earth's surface temperature would dissuade humanity from aggressively pursuing greenhouse gas (GHG) emission cuts (Halstead, 2018). Others comment on the enormous political difficulties of establishing a worldwide system of governance and regulation of SAI (Smith and Henly, 2021) or the potential environmental consequences of actual deployment, such as the potential reduction of stratospheric ozone (e.g., Bednarz et al., 2023), the possibility of shifts in regional rainfall patterns (e.g., Simpson et al., 2019; Da-Allada et al., 2020; Krishnamohan et al., 2022), and the possibility of "termination shock" – the rapid climate change that would occur if SAI deployment was suddenly halted (e.g., Parker and Irvine, 2018).

These and other concerns are valid and warrant serious consideration and debate. Despite the numerous potential problems and risks of SAI, however, many have argued that its potential benefits are worth investigating (e.g., Crutzen, 2006; Kravitz et al., 2011; Simpson et al., 2019; Richter et al., 2022; Haywood et al. 2025) given the growing risks posed by anthropogenic climate change. In particular, the geopolitical challenges of reducing GHG emissions make it unlikely that global surface warming will be limited to 1.5° or even 2° C above the preindustrial baseline (IPCC, 2023), with warming of nearly 2.5° C or more likely given current emission rates (UNEP, 2023). Thus, it is very probable that adverse consequences of climate change, such as heat waves, floods, droughts, and crop failures, will become more frequent and severe in coming decades (Bevacqua et al., 2020; Anderson et al., 2020; Tripathy et al., 2023; IPCC, 2023).

Many previous studies have carried out global analyses of SAI impacts (e.g., Mamalakis et al., 2023, Simpson et al., 2019; Richter et al., 2022; Haywood et al., 2022; Zhang et al., 2024); here, we contribute a primarily regional analysis to this rapidly growing field of research. While it has been established that global-mean temperatures could potentially be stabilized or cooled under many SAI scenarios, and precipitation changes would lessen in many regions compared to future changes projected under climate change, specific impacts vary regionally (e.g., Richter et al., 2022; Kravitz et al., 2017). We analyze how different SAI scenarios might affect four Global South regions that may be particularly vulnerable to the harmful impacts of climate change: South Asia (SAS), East Asia (EAS), South Central America (SCA), and West Africa (WAF). The geographical boundaries of these “IPCC AR6 regions” combine areas with similar

climatological characteristics and projected changes in future climate (Iturbide et al., 2020).

Less economically developed countries, such as those in the regions studied here, suffer disproportionately from the effects of anthropogenic climate change (e.g., World Bank, 2013; Bathiany et al, 2018; Jafino et al., 2020). One reason for this is the vulnerability of such countries to worsening heat waves, floods, tropical cyclones, and other climate-related events (Bowen et al., 2012). As subsistence agriculture is particularly prominent in many less economically developed countries, their citizens' well-being depends more intimately on climatic conditions (Fankhauser et al., 2014). In addition, such countries have relatively low levels of technological, institutional and economic capacity that would allow for effective adaptation to climate change (Barr et al., 2010). The Socioeconomic Data and Applications Center (SEDAC) at NASA (n.d.) has generated population projection data for various IPCC climate change scenarios. We used SEDAC's data for the IPCC's Shared Socioeconomic Pathway (SSP) 2-4.5 moderate emissions scenario (O'Neill et al., 2017) to determine the projected percentage changes in future regional populations. The projected populations of SAS, SCA, and WAF all exceed the world average change of 24.1% by the year 2070, with the largest change in the population of WAF (Table 1). In EAS, population is projected to decrease, although the region remains a tremendously populated area in 2070, comprising 12.8% of the total world population. The population burden in these regions means that any socioeconomic difficulties already present will likely be worse in the future due to climate change.

Table 1. Projected changes in population growth for this study’s four regions, as well as worldwide totals, from 2020 to 2070.

Region	2020 pop. (millions)	% of 2020 world pop.	2070 pop. (millions)	% of 2070 world pop.	% change (2070 pop. – 2020 pop.)
SAS	1531.4	20.5	1954.1	21.0	27.6
EAS	1522.4	20.3	1188.0	12.8	-22.0
SCA	94.3	1.3	118.5	1.3	25.6
WAF	369.4	4.9	806.8	8.7	118.4
World	7482.8	100	9283.9	100	24.1

A critical challenge will be ensuring food security for the inhabitants of these regions. In 2022, the percent of the population that could not afford a healthy diet was 16.3%, 26.3%, 53.1%, and 69.3% for Eastern Asia, Central America, Southern Asia, and Western Africa, respectively (FAO, 2024). Climatological factors such as droughts and heatwaves have also driven food insecurity in these regions (Zakari et al., 2014; Singh, 2016; Alpízar et al., 2020; Xu et al., 2024). Projected population growth, as well as climate-change-induced crop failures from plant diseases (Singh et al., 2023) and drought and temperature extremes (Lesk et al., 2022; Rezaei et al., 2023), further threaten future food security.

These four regions have also been ravaged by extreme weather events in recent years. For instance, in March-May 2022, India and Pakistan suffered an extremely intense, long-lasting heat wave, with surface air temperatures reaching up to 50°C locally, making it perilous for people to go outdoors (Zargar, 2022). Zachariah et al. (2023) concluded that climate change made this heat wave 30 times more likely, and Nath et al.

(2024) determined that climate change made the median value of the heat wave likelihood 41 times greater. During the monsoon season (June-October) of the same year, a combination of torrential rains and melting glaciers gave rise to a flood in Pakistan affecting 33 million people, resulting in over 1,000 deaths and approximately \$15 billion USD in damages (World Bank, 2022). Otto et al. (2023) concluded that climate change increased the rainfall in Pakistan by up to 50%, and You et al. (2024) found that, while natural variability played a role, the influence of anthropogenic warming was evident via intensified moisture transport and convection.

From May to October 2022, Nigeria experienced extreme flooding that killed over 600 people, displaced over a million, and wrecked thousands of homes (Khalid and Maishman, 2022). Zachariah et al. (2022) found that climate change made the event 80 times more probable and that the precarious economic, political, and infrastructural conditions exacerbated its effects. In summer 2022, Sichuan, a province in southwestern China, suffered a multi-month heatwave that severely disturbed the economy, resulting in multiple factory shutdowns and city blackouts (Gan, 2022). In August 2023, Hebei, a province in northeastern China, experienced its heaviest rainfall in 140 years (the aftermath of a tropical cyclone), displacing over a million people (McCarthy et al., 2023). In 2020, Central America was hit by two devastating hurricanes, Eta and Iota, within two weeks. In Honduras, one of the poorest Latin American countries, the hurricanes' destruction to land and infrastructure impacted over 4 million people (Lakhani, 2021).

In this paper, we examine the projected and possible impacts of anthropogenic climate change and several SAI scenarios on these four world regions by analyzing changes in temperature, precipitation, heat extremes, soil moisture, and crop productivity.

2.2. MATERIALS AND METHODS

Our analysis is based on numerical simulations performed with the Community Earth System Model, version 2 (CESM2) with the Whole Atmosphere Community Climate Model, version 6 (WACCM6) as its atmospheric component (Danabasoglu et al., 2020). WACCM6 was run with a latitude and longitude grid of 0.9 and 1.25 degrees, respectively (Brody et al., 2024), and 70 vertical layers extending up to about 140 km. WACCM6 has been shown to effectively simulate stratospheric dynamics and chemistry (including aerosol creation) when compared to observations of volcanic eruptions (Gettelman et al., 2019). The simulations analyzed in this study also used the Community Land Model 5 (CLM5), which simulates temperate and tropical corn, temperate and tropical soybean, rice, cotton, spring wheat, sugarcane, miscanthus, and switchgrass (Lawrence et al., 2019; Lombardozzi et al., 2020).

We consider three SAI scenarios under the "Assessing Responses and Impacts of Solar Climate Intervention on the Earth System with Stratospheric Aerosol Injection" (ARISE-SAI) simulations (Richter et al., 2022). Each SAI scenario, consisting of ten ensemble members, uses the SSP2-4.5 emissions scenario to simulate policymakers' stated intentions regarding GHG emission cuts (Hausfather, 2025). To stabilize or cool global temperatures while simultaneously minimizing other disruptions to the climate system, ARISE-SAI uses an algorithm called the "controller" (Kravitz et al., 2017). Sulfur dioxide is injected at 30°N, 15°N, 15°S, and 30°S, all at 180°E longitude, to achieve three temperature targets: global mean temperature, the north-to-south-pole (inter-hemispheric) temperature gradient, and the equator-to-pole temperature gradient. Maintenance of the temperature gradients is fundamental so that atmospheric dynamical

circulations are altered as little as possible. The controller analyzes these metrics every year and adjusts the injection amounts in the four locations accordingly.

In CESM2(WACCM6) under SSP2-4.5, Earth is projected to reach a global-mean temperature of 1.5°C above pre-industrial levels during 2020-2039. Thus, in the SAI-1.5 scenario, injections begin in 2035 and continue through 2069 to maintain the global-mean temperature at 1.5°C, even as GHG emissions continue increase (Richter et al., 2022). In the SAI-1.0 scenario, injections also begin in 2035 but are larger in magnitude to cool the planet to 1.0°C (MacMartin et al., 2022). In the SAI-DELAYED scenario, the global mean temperature target is once again 1.5°C, but injections do not begin until 2045; thus, injection quantities are greater than in SAI-1.5 to counteract the additional global warming that occurs over 2035-2045. We note that, due to an error when running the simulations, SAI-DELAYED overshoots its temperature target (1.5°C) and cools the planet to 1.37°C (Brody et al., 2024). The delayed start scenario was constructed because of the possibility that humanity might not be ready to deploy SAI as soon as 2035 (Brody et al., 2024).

As mentioned, each SAI scenario is simulated with increasing GHG concentrations over time that follow SSP2-4.5, which specifies that annual CO₂ emissions peak mid-century and then decrease (O'Neill et al., 2017). We refer to this as the “climate change” scenario, and we compare each SAI scenario to it. We use 2020-2039 under SSP2-4.5 as the base period, following Richter et al. (2022). Our focus is on mid-century changes averaged over a twenty-year period (2050-2069) to enhance the magnitude of the climate change and SAI signals (Hueholt et al., 2023). We used a program called "regionmask", compatible with Python (Hauser et al., 2024), to analyze AR6 regions (Iturbide et al., 2020). We also used the Python program “xclim” to analyze simulated changes in maximum annual temperatures (TXx) and the annual

number of warm spell days, as measured by the Warm Spell Duration Index (WSDI, Zhang et al., 2011).

2.3 RESULTS

2.3.1 GLOBAL CHANGES

While we primarily focus on regional analyses of possible climate futures, global maps facilitate a more comprehensive understanding of regional climate change patterns. Figures 1 and 2 show annual-mean surface temperature and precipitation changes in the SAI and climate change scenarios (see also Richter et al., 2022; Visionsi et al., 2023; Brody et al., 2024). Compared to the base period (2020-2039), average annual-mean surface temperatures increase by mid-century (2050-2069) under the climate change scenario (Fig. 1a) almost everywhere except for the North Atlantic. The latter is due to a slowing of the Atlantic Meridional Overturning Circulation in the CESM2 (Gu et al., 2024). Polar amplification, particularly in the Northern Hemisphere due to such factors as the ice-albedo feedback, is also evident, as has been found in CMIP6 models in general (Södergren and McDonald, 2022). Large warming is noted in the tropical eastern Pacific, consistent with projections in CMIP6 models (e.g., Cai et al., 2021) that the El Niño phase of the El Niño Southern Oscillation (ENSO) will become more prevalent under climate change.

Figure 1b and 1c, which depict mid-century changes from the base period in SAI-1.5 and SAI-DELAYED, respectively, are generally similar. Both SAI scenarios result in warming of the tropical eastern Pacific, though it is smaller in magnitude than in the climate change scenario (Fig. 1a). Under SAI-1.0 (Fig. 1d), significant cooling is present nearly everywhere except a few oceanic regions. This is consistent with having a global-

mean temperature target (1.0°C) cooler than the average global-mean temperature of the base period (1.5°C).

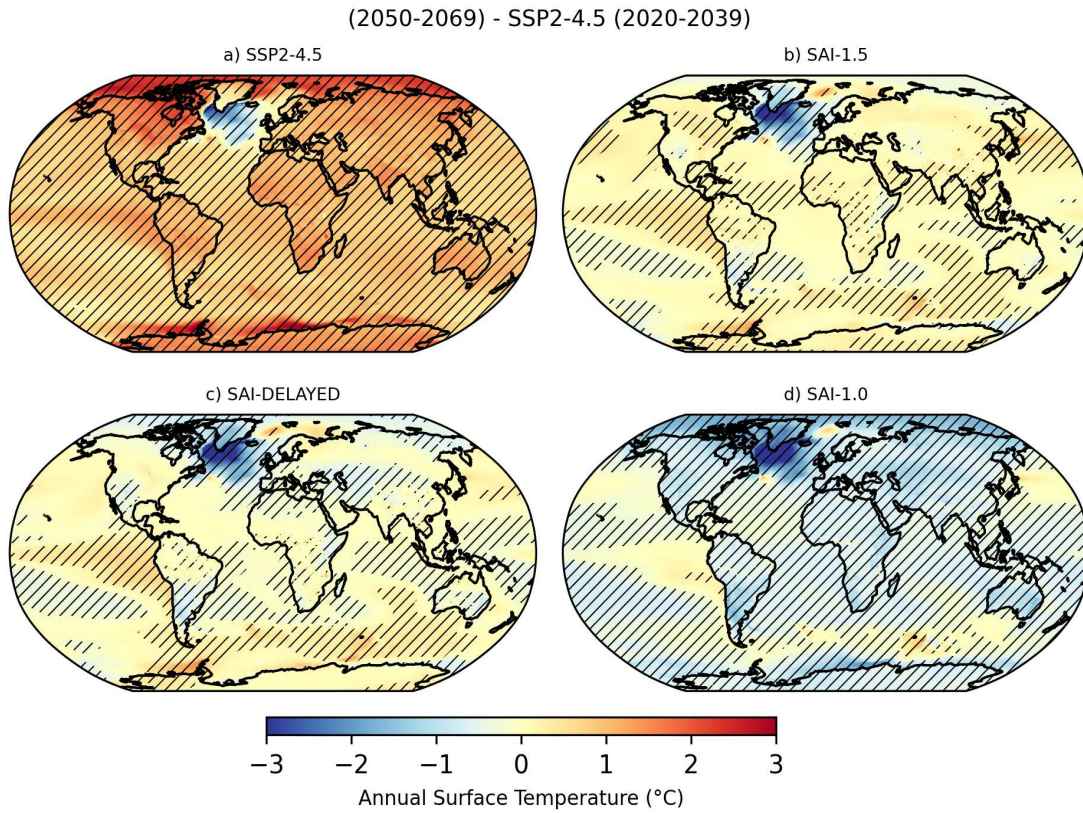


Figure 1. A comparison of changes in mean annual surface temperature under the three SAI and climate change scenarios relative to the base period. Hatching indicates statistically significant changes (at the 99% confidence level using a Welch t-test (West, 2021)) in the distribution of ensemble members relative to the base period. Figure 1a and 1b are as in Richter et al. (2022); Figure 1d is as in Visioni et al. (2023).

In terms of future annual-mean precipitation changes, two of the most prominent features of the simulated climate change scenario (Fig. 2a) are the intensification of the ITCZ coupled with enhanced drying over the subtropical oceans, particularly in the Northern Hemisphere. These changes have been attributed to enhanced convection in a warmer, tropical climate and, by mass continuity, greater subsidence and drying in the adjacent sub-tropics (e.g., Held and Soden, 2006; IPCC, 2021; Zaitchik et al., 2023).

In contrast, to balance Earth’s energy budget under SAI, the decrease in incoming solar radiation is compensated by a decrease in evaporative cooling of the surface; thus, future precipitation changes overall are smaller (Simpson et al., 2019). Additionally, heating due to increased aerosol burdens in the stratosphere leads to increased atmospheric static stability, which produces weaker tropical convection and less subtropical subsidence (Ferraro et al., 2014). Simpson et al. (2019) summarize this finding by saying that “wet regions...become drier and dry regions...become wetter” under SAI relative to future hydrological cycle changes with climate change. These general changes are evident under the SAI-1.5, SAI-DELAYED and SAI-1.0 simulations examined here (Fig. 2b, c and d).

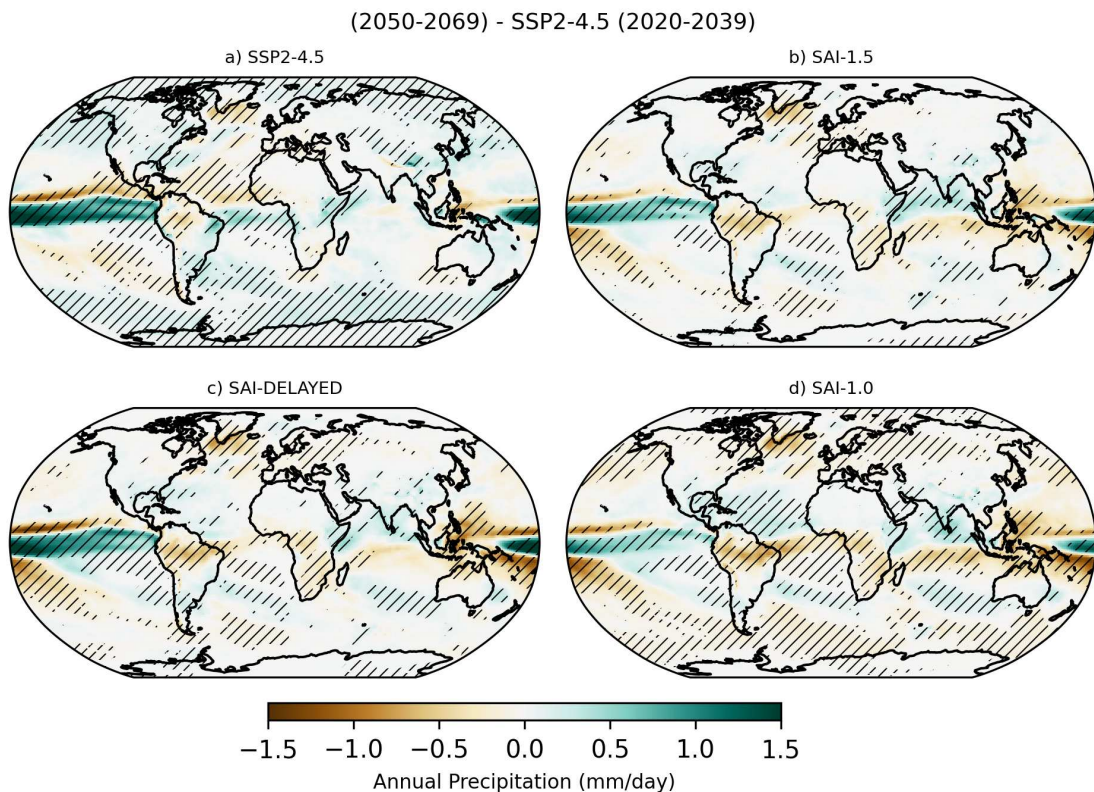


Figure 2. As in Figure 1, but for mean annual precipitation.

2.3.2 REGIONAL CHANGES

2.3.2.1 ANNUAL CYCLE

While many studies (e.g., Simpson et al., 2019; Haywood et al., 2022; Zhang et al., 2024) have examined changes in annual- or seasonal-average precipitation and temperature under climate change and SAI scenarios, relatively few have analyzed the annual cycles of these variables (e.g., Da-Allada et al., 2020). Potential changes in the annual cycle of precipitation are important, as concerns have been expressed that SAI-induced changes in the onset and termination dates of regional monsoons, as well as their intensity, could have profound impacts (e.g., Robock et al., 2008; Simpson et al., 2019).

The annual cycles of precipitation and temperature are critical for food security in the regions examined here (Gbode et al., 2021; He et al., 2022; Stewart et al., 2022; Amale et al., 2023). Several studies (e.g., Zhang and Wang, 2008; Gadgil, 2018; Bombardi et al., 2019) have pointed out that the monsoon's traditional wind-based definition (Ramage, 1971) can exclude regions, such as the Americas (Zhou and Lau, 1998). The monsoon can also be defined as seasonal changes in precipitation due to a meridional shift in the Intertropical Convergence Zone (ITCZ) (Geen et al., 2020); however, this definition can also exclude regions such as northwest India (Bombardi et al., 2019). Thus, we join others (e.g., Wang and LinHo, 2002; Liebmann et al., 2012; Zhang and Wang, 2008) in referring to a wet season rather than a monsoon season. For each simulation and region, we computed a cosine-weighted regional average of daily temperature and precipitation, using only land grid points, and we use a five-day centered moving average to smooth the daily data. Even though the SAI scenarios do not explicitly target the preservation of the seasonal cycle, the overall shapes of the temperature and precipitation cycles are well-preserved in all scenarios (see Supplemental Figs. 1 and 2). Differences by day

from the base-period annual cycle are shown for both precipitation (Fig. 3) and surface temperature (Fig. 4).

As precipitation (Fig. 3) is a relatively noisy variable (IPCC, 2021), the ensemble ranges for the different scenarios largely overlap; the extent and nature of this overlap, however, differ regionally. In EAS (Fig. 3b), days of significantly different precipitation under the climate change scenario tend to have greater precipitation than the base period, but they are not concentrated in one season. In contrast, in SCA and WAF, and to a lesser extent SAS (Fig. 3a, c, and d), precipitation tends to be significantly less during the wet season (May-October) in the climate change scenario, as is also evident in Fig. 2a. As will be shown later, these precipitation decreases are associated with deficits in simulated soil moisture and declines crop yields, especially in SCA and WAF. It is noteworthy, however, that even in these regions, the number of days with significantly less precipitation is a relatively small fraction of the year due to the presence of large internal variability.

(2050-2069) - SSP2-4.5 (2020-2039)

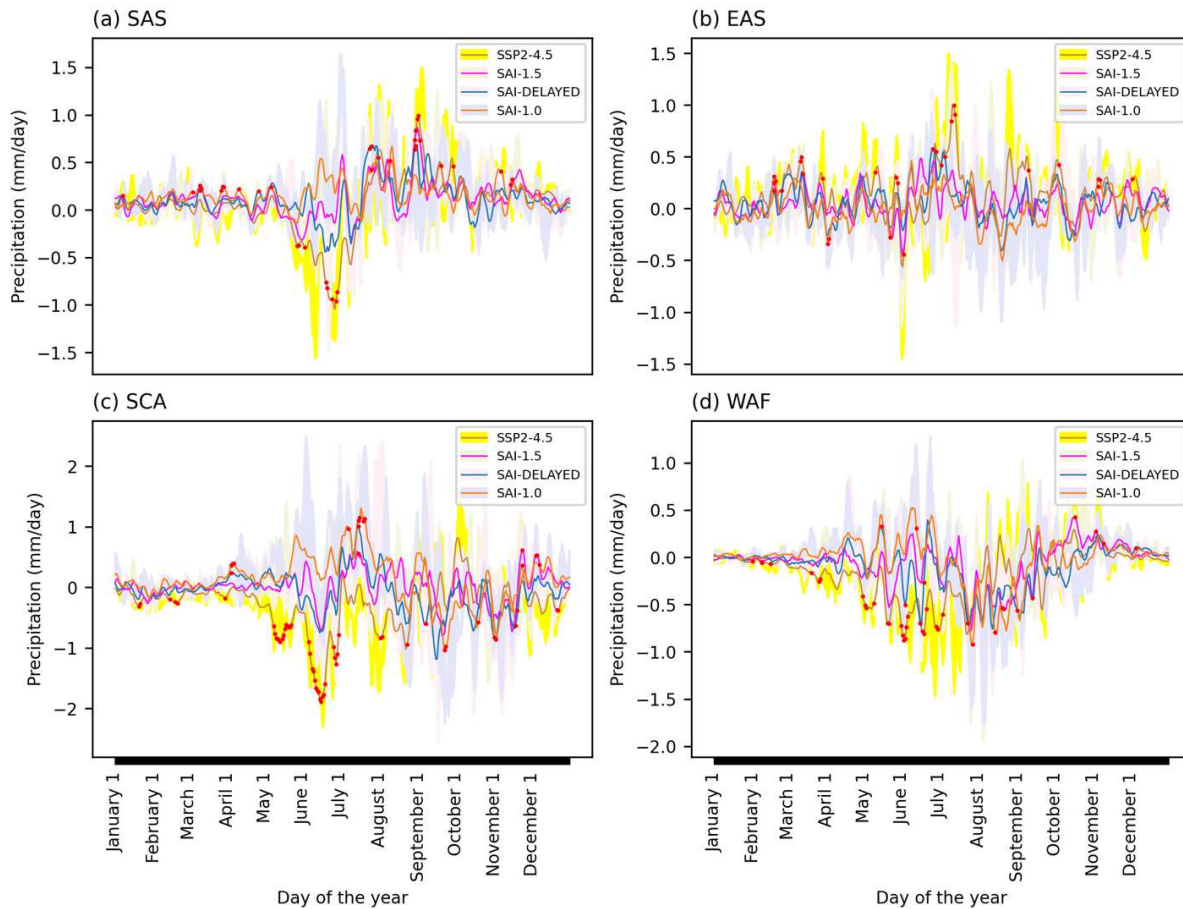


Figure 3. Changes in 2050-2069 average precipitation relative to SSP2-4.5 (2020-2039) by region and day of the year for SSP2-4.5 (brown), SAI-1.5 (pink), SAI-DELATED (blue), and SAI-1.0 (orange). Red dots indicate days of the year in which differences are statistically significant at the 99% confidence level using a Welch t-test.

Consistent changes in surface temperature relative to the base period are much clearer (Fig. 4). Under the climate change scenario, temperatures are significantly greater than those in the base period for nearly every day of the year in all regions. However, the number of days per year with significant changes from the base period is relatively few under SAI-1.5 and SAI-DELATED, and the magnitude of these changes is also less than those of the climate change scenario. In SAI-1.5, changes in surface temperature tend to be positive (i.e., temperature increases). In SAI-DELATED, the changes are mostly negative (i.e., temperature decreases).

Finally, under SAI-1.0, surface temperatures decrease significantly in all four regions for most of the year, with fewer days with statistically significant decreases in EAS. Thus, the SAI simulations fulfill their objective of stabilizing or lowering surface temperatures relative to the base period even regionally.

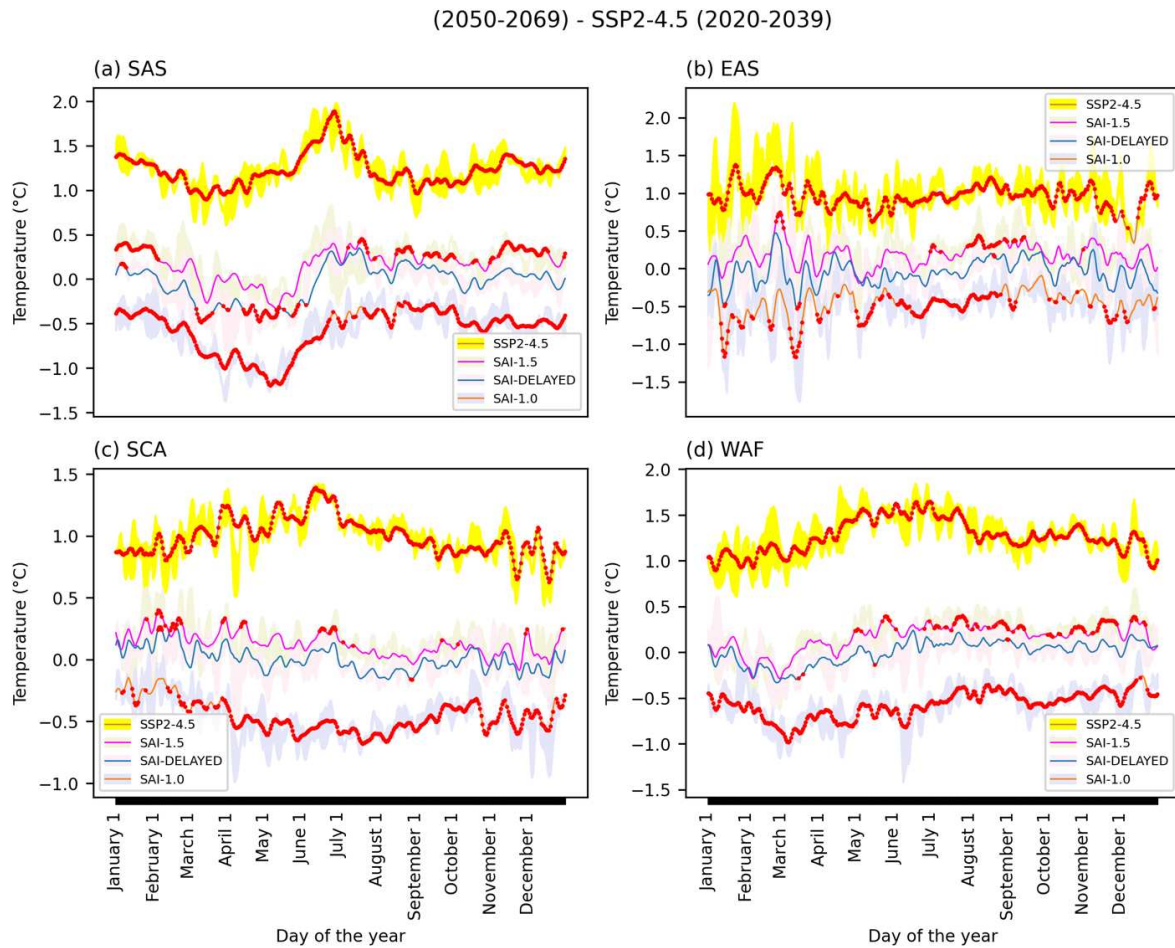


Figure 4. As for Figure 3, but for surface temperature.

The regional precipitation changes under the different climate futures (Fig. 3) are further highlighted in Figure 5, which – unlike Figure 2 – shows changes for only the wet season (May-October). Under climate change, large parts of SAS and EAS experience no significant change in wet season precipitation, while isolated regions exhibit precipitation

increases (Fig. 5a). In contrast, SCA and WAF, due to their location in the lower latitudes, are affected by increased subsidence and drying under the SSP2-4.5 climate change scenario (Fig. 2; see also Held and Soden, 2006; IPCC, 2021; Zaitchik et al., 2023). This drying is lessened or even reversed in SAI-1.5, SAI-DELAYED, and (especially) SAI-1.0 (Figs. 5b-d). Note that the spatial distribution of SAI-1.0 changes for WAF is nearly a mirror image of the climate change signal. Several areas of SAS and SCA also experience significant wetting in SAI-1.0. As discussed above, less vigorous tropical convection under SAI leads to tropical drying and, thus, reduced subsidence and wetting of the adjacent subtropics (Fig. 2; see also Simpson et al., 2019).

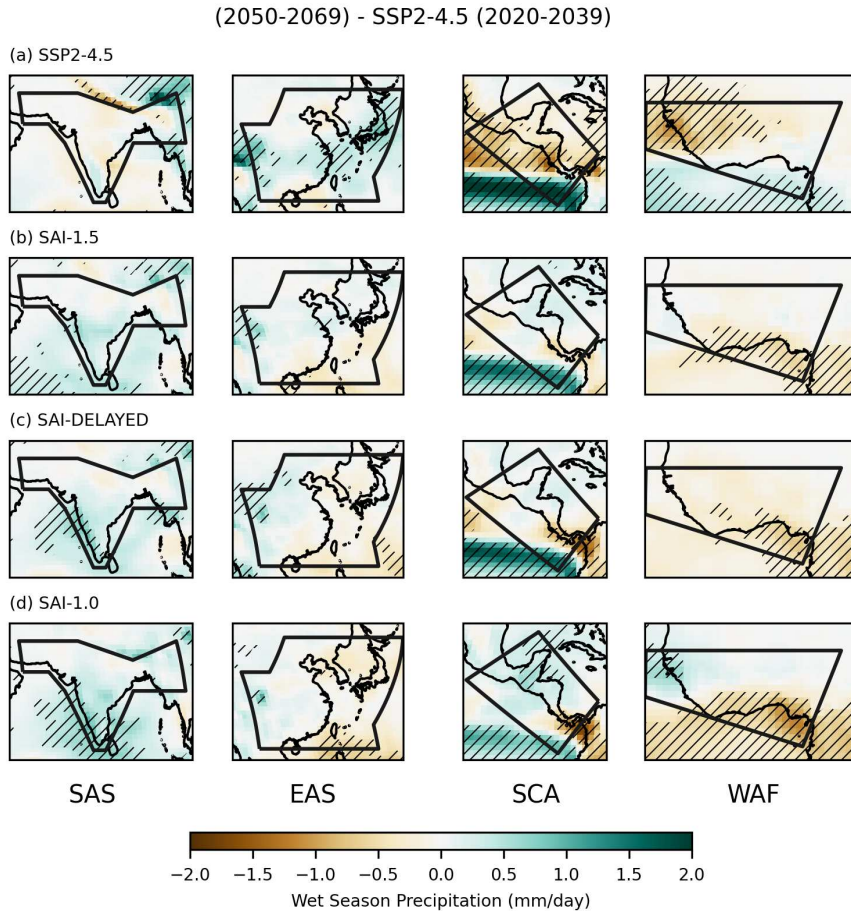


Figure 5. Changes in wet season (May-October) average precipitation for each region and scenario relative to the base period. Hatching indicates significant differences at the 99% significance level using a Welch t-test.

2.3.2.2 EXTREMES

Global increases in the frequency, intensity, and duration of high temperature extremes since 1950 are virtually certain ($\geq 99\%$ probability) (IPCC, 2021), and an increasing number of studies have attributed these changes to GHG gas forcing using indices such as the WSDI (Christidis and Stott, 2016; Hu et al., 2020) and TXx (Kim et al., 2016; Dong et al., 2018). In both CMIP5 and CMIP6 models, there are much more frequent, persistent, and severe high temperature extremes on land with 2°C of warming (relative to 1850-1900) compared to 1.5°C of warming (Fischer et al., 2014; IPCC, 2021; Li et al., 2021). In SSP2-4.5, global temperatures are projected to reach $\sim 2^{\circ}\text{C}$ above pre-industrial levels by 2050 (IPCC, 2021). Regarding changes in high temperature extremes under SAI scenarios, geographically widespread decreases relative to climate change scenarios have been documented in several temperature indices, such as TXx (Ji et al., 2018) and WSDI (Ji et al., 2018; Alamou et al., 2022; Jiang et al., 2024), as well as the percentage of days with maximum temperatures above the 90th percentile (Barnes et al., 2022).

Here, we show future regional changes in surface temperature extremes that are broadly consistent with the existing literature (Figs. 6-7). Under the climate change scenario, TXx increases significantly over nearly all of the regions relative to the base period (Fig. 6a). In parts of EAS, such as in Southern China, these increases are relatively small compared to other areas, consistent with relatively small increases in annual-mean annual temperatures in this area with climate change (Fig. 1a). In the SAI-1.5 and SAI-DELAYED scenarios, TXx shows relatively few significant changes compared to the base period, with considerable spatial heterogeneity in the sign of the changes (Figs. 6b and c). In the SAI-1.0 scenario, TXx is projected to decrease significantly over most of the four regions (Fig. 6d).

The implications of TXx reductions in the SAI scenarios relative to the climate change scenario are significant. Vicedo-Cabrera et al. (2021) find that, in studied locations in Panama, Costa Rica, and Guatemala, ~40-60% of heat-related human deaths in 1991-2018 could be ascribed to climate change. In China, South Korea, Japan, and Taiwan, the percentages were ~20-40%. In India, as heat waves have become more frequent, intense, and persistent (e.g., Rohini et al., 2016; Singh et al., 2021), so has heat-related mortality. Mazdiyasi et al. (2017) find that, as summer mean temperatures and heat wave frequency in India increased from 1960-2009, the probability of more than 100 deaths from a given heat wave rose by 146%. In West Africa, although heat-related mortality has been much less extensively documented (Barry et al., 2018; Fotso-Nguemo et al., 2023), the risks are high. According to records from 13 West African countries over 1960-2010, mean annual maximum and minimum temperatures as well as the frequency of warm days and nights have all significantly increased (Barry et al., 2018). Thus, in the coming decades, even a small increase in TXx could have serious or even lethal impacts, which SAI (under the scenarios examined here) may lessen or even prevent.

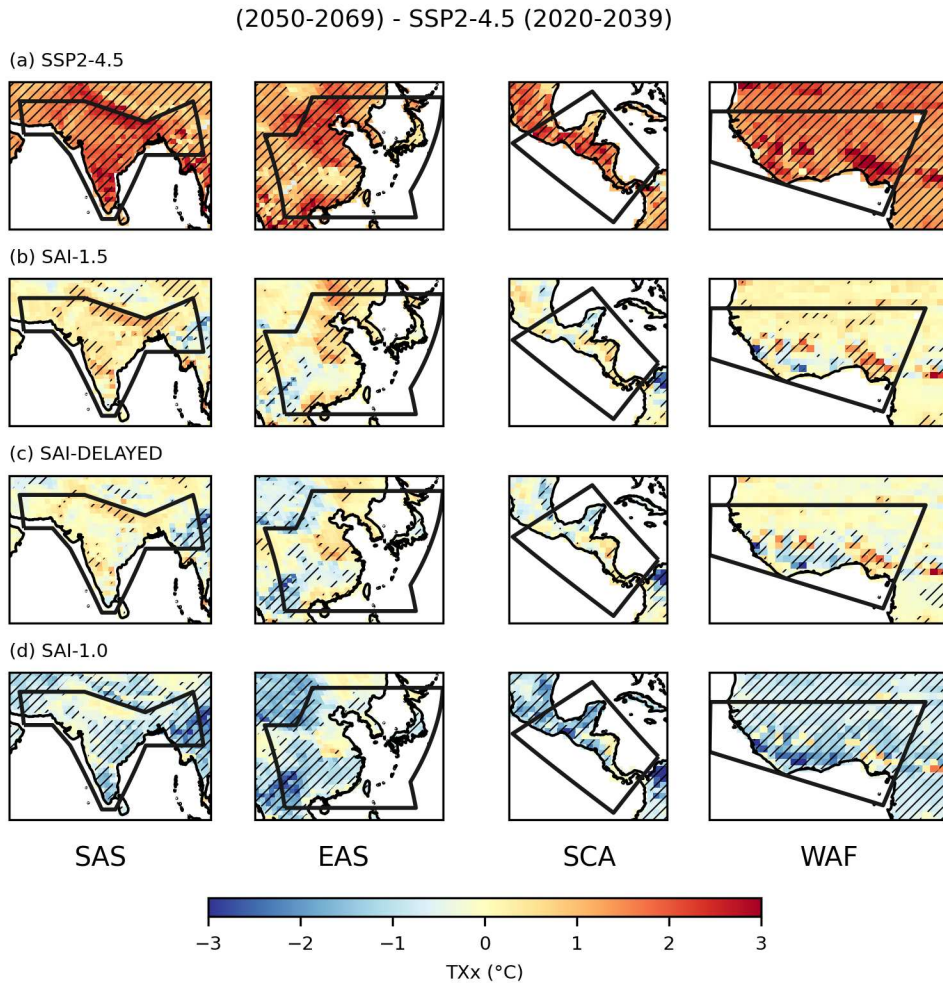


Figure 6. Changes in the maximum annual surface temperature (TXx) for each region and scenario relative to the base period. Hatching indicates significant differences at the 99% significance level using a Welch t-test.

Another extreme temperature index is WSDI, which measures the total number of days per year that are characterized as warm spells. A warm spell is a period of at least six consecutive days in which daily maximum temperatures exceed those of the 90th percentile for SSP2-4.5 (2020-2039) (ETCCDI, n.d.). Using all 10 ensemble members of SSP2-4.5 (2020-2039), we calculated, for each day of the year and grid point, the 90th percentile of maximum surface temperatures, using a centered, five-day moving average of daily data, as stipulated by ETCCDI (n.d.). WSDI is relevant to not only human well-

being (e.g., Christidis and Stott, 2016; Hu et al., 2020), but also to the productivity of crops, which are vulnerable to heat stress (Luo, 2011; Kaushal et al., 2016; Hassan et al., 2020).

WSDI increases significantly relative to the base period under the climate change scenario for nearly all areas of the four regions (Fig 7a), consistent with projected changes in annual mean surface temperatures. Indeed, SAS experiences relatively large increases in both WSDI and annual mean surface temperatures (Fig. 1a) relative to other regions of approximately the same latitude; in EAS, the increases in both these variables are smaller. Under SAI-1.5 and SAI-DELAYED, there are relatively few significant changes in WSDI in the four regions (Figs. 7b and c), while under the SAI-1.0 scenario, WSDI decreases significantly across the four regions, particularly in SAS and WAF (Fig 7d).

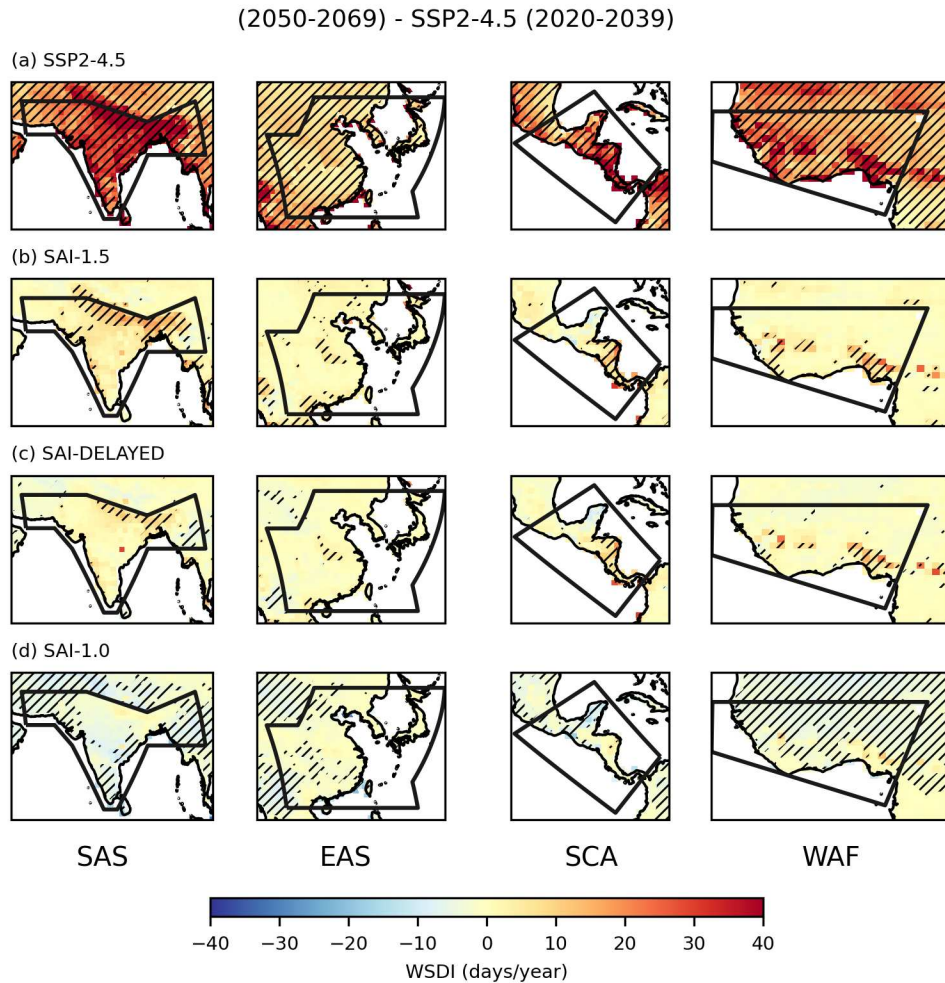


Figure 7. Changes in the Warm Spell Duration Index (WSDI) for each region and scenario relative to the base period. The WSDI is the number of days per year that are part of heat spells (at least six consecutive days with temperatures above the 90th percentile relative to the SSP2-4.5 (2020-2039) base period. Hatching indicates significant differences at the 99% significance level using a Welch t-test.

2.3.2.3_SOIL MOISTURE

Quantifying observed changes in soil moisture over the past few decades is hampered by a lack of geographically and temporally extensive observations (Dorigo et al., 2012; IPCC, 2021). Recent decreases in soil moisture have been documented in parts of EAS and WAF, while in many other regions, including SAS and SCA, recent soil moisture changes are unclear (Dai and Zhao, 2017; Jia et al., 2018; Spinoni et al., 2019;

Padrón et al., 2020). Model projections of soil moisture involve uncertainty not only with precipitation processes but also with soil processes (IPCC, 2021; Quintana-Seguí et al., 2020). A further problem is a lack of observations against which to test the models (Dorigo et al., 2012; IPCC, 2021). Overall, the CMIP6 models find a positive correlation between reduced precipitation and reduced soil moisture (Qiao et al., 2022). Decreases in soil moisture in the topmost layers of the soil tend to be relatively greater than decreases in precipitation due to anthropogenic changes in evaporative demand (Dai et al., 2018; Lu et al., 2019). However, the importance of internal variability relative to that of external forcing is high, rendering it difficult to make confident projections of future changes due to GHG forcing (IPCC, 2021).

One region expected to experience soil moisture decreases with relatively high confidence is SCA, and the decreases become even more pronounced with higher levels of global warming (Cook et al., 2014; Lu et al., 2019). Figure 8a shows that almost all land areas in SCA experience soil moisture decreases under climate change relative to the base period. Large portions of WAF also experience significant decreases in soil moisture. The SCA and WAF soil moisture decreases are consistent with projected future decreases in annual mean (Fig. 2a) and wet season (Fig. 5a) precipitation. In contrast, SAS experiences soil moisture decreases in only a few areas under climate change, while no clear drying signal emerges in EAS. In the SAI scenarios, due to both increased precipitation and decreased temperatures, soil moisture generally increases (Figs. 8b-d), and these increases are most widely significant in SAI-1.0.

Previous SAI studies have found fairly similar results in soil moisture changes. For instance, Cheng et al. (2019) found that soil moisture in the top 3.8 m of the soil under an SAI scenario (GLENS, Tilmes et al. 2018) increases in many world regions by the end of the century compared to the RCP 8.5 scenario (Riahi et al., 2011). Cheng et al. (2019) also show that soil

moisture is greater under SAI relative to climate change in parts of EAS and SCA, but, unlike our study, it is less in parts of WAF and SAS. Such differences in results are likely due to differences in soil moisture definitions, models, and future scenarios. Liu et al. (2024) compare an SAI scenario (G6sulfur, Kravitz et al., 2015) to SSP2-4.5, both averaged over 2081-2100. They find that, under the SAI scenario, soil moisture significantly increases in most land regions, including most areas of EAS, SAS, and WAF and a few areas of SCA.

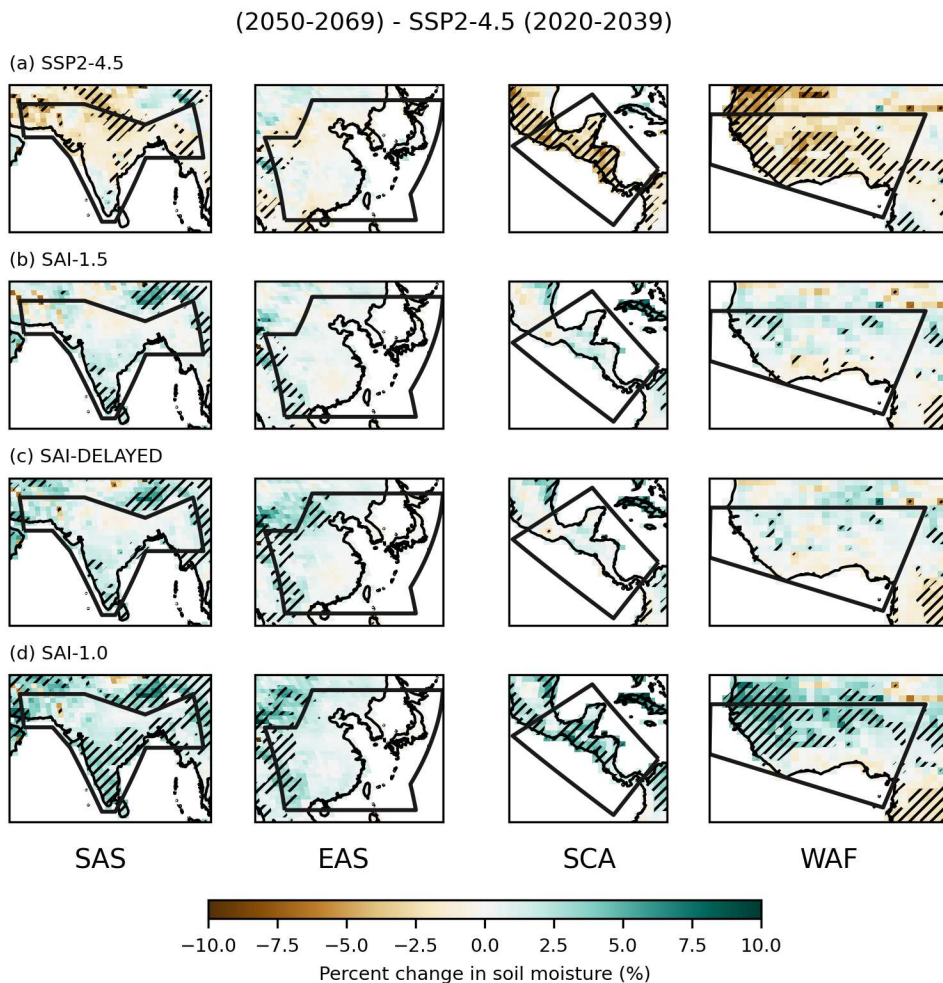


Figure 8. Percent changes in soil moisture in the top ten centimeters of the soil for each region and scenario relative to the base period. Hatching indicates significant differences at the 99% significance level using a Welch t-test.

2.3.2.4_CROP PRODUCTIVITY

Under many climate change scenarios, the detrimental effect of heat stress has been found to override the “CO₂ fertilization effect”, by which greater atmospheric CO₂ stimulates photosynthesis and crop growth (Deryng et al., 2014; Fan et al., 2021; Rezaei et al., 2023). Other factors influencing crop productivity include changes in precipitation, soil moisture, and the extent to which plants open their stomata to receive CO₂ for photosynthesis. The greater the amount of CO₂, the less the stomata open and the less water leaves the plant, which is crucial in hot and arid conditions (Liang et al., 2023).

Under SAI, one might expect that plant productivity increases from CO₂ fertilization and decreased heat stress (Pongratz et al., 2012; Irvine et al., 2017; Zhan et al., 2019). However, sunlight is critical for photosynthesis, and SAI scatters a small percentage of total sunlight away from Earth (Proctor et al., 2018). The abundance of diffuse sunlight, however, would increase under SAI. Some studies (e.g., Cheng et al., 2015) have indicated that plant productivity increases under diffuse sunlight, while others (e.g., Proctor et al., 2018, Xia et al., 2016) find that this tendency is not universal. Overall, there have been relatively few studies examining crop productivity under SAI. One exception is Grant et al. (2025). They found that, due to decreased heat stress combined with largely unchanged monsoon rainfall, rainfed rice and wheat yields tend to be greater in India in SAI-1.5 relative to SSP2-4.5 (both analyzed over 2050-2069).

Figure 9 analyzes percent changes in total crop yields relative to the base period. For a given crop, we combined rainfed and irrigated yields. We converted crop yields in a flux form (i.e., monthly-averaged values of grams of carbon per square meter per second) to average annual yields (grams of carbon per square meter). We then calculated percentage changes in yields. We note that, while CLM5 simulates important staples such as soy, rice, corn, and wheat,

many important crops (e.g., cassava, millet, etc.) are not actively simulated by CLM5 (Lombardozzi et al., 2020).

In Figure 9a, some areas of SAS, SCA, and WAF show significant increases in crop yields, but several areas experience overall yield decreases, particularly in WAF and SCA. In all three SAI scenarios (Figs. 9b-d), crop yields increase in most areas of SAS, SCA, and WAF, consistent with decreased heat stress, greater precipitation and soil moisture (Figs. 2, 5, 6, 7, and 8), as well as enhanced CO₂ fertilization. In contrast, EAS crop yields increase under all scenarios, consistent with the overall lack of statistically significant reductions in precipitation and soil moisture due to both climate change and SAI, as well as the effect of CO₂ fertilization (Figs. 2, 5, and 8).

Another important factor in analyzing future projected changes in crop yields is the crop type. C3 crops (e.g., rice, wheat, and soybeans) have higher stomatal conductance than C4 crops (e.g., sugarcane and corn) and therefore lose more water in warmer conditions. The higher water use during photosynthesis means that C3 crops are more susceptible to drought and extreme heat than C4 crops (Wang et al., 2008; Rezaei et al., 2023). C3 crops also benefit more from elevated CO₂ than C4 crops (Rezaei et al., 2023). Fan et al. (2021) doubled CO₂ concentrations from 380 to 760 ppm and found that corn yields increased by only 9%, while they increased by 20% and 31% for rice and wheat, respectively. They also concluded that wheat and rice were much less sensitive to temperature changes than the other crops. Lombardozzi et al. (2018) found that rice and wheat yields increased in all regions under RCP 8.5 in 2100 relative to 2000, whereas crop yields of soy and corn depended on the region.

In SAS and EAS, rice and wheat are major crops, which helps explain why these regions fare better in terms of crop yields than SCA and WAF, where corn is a major grain staple (Leff et al., 2004). In 2022, China was the world's largest producer of rice and wheat, whereas India was the second largest producer (FAO, n.d.). Although corn is a major commodity in these countries, especially in China, the relative importance of rice and wheat is greater; for instance, in 2022, the combined yields of rice and wheat in China and India were about 1.3 and 9.2 times greater than those of corn, respectively (FAO, n.d.). In contrast, in Nigeria and Guatemala, corn yields were about 1.5 and 74.3 times greater, respectively, than combined rice and wheat yields (FAO, n.d.).

Given the importance of rice to SAS and EAS and corn to SCA and WAF, Figure 10 illustrates how yields of these crops would change under the climate change and SAI scenarios. The changes in precipitation, changes in soil moisture, and the distributions of C3 and C4 plants all contribute to the different trajectories of SAS and EAS versus WAF and SCA. In EAS, rice yields increase significantly in all scenarios in most areas. In SAS, rice yields increase significantly in the three SAI scenarios (Fig. 10b-d) and to a lesser extent under the climate change scenario (Fig. 10a). The increase in SAS rice yields under SAI-1.5 compared to SSP2-4.5 is consistent, overall, with the findings of Grant et al. (2025). In SCA and WAF, by contrast, the climate change scenario leads to a statistically significant decrease in corn yields. Under the SAI scenarios, corn yields are the same or, in a few areas, statistically significantly greater than in the base period, but these increases are much smaller than those experienced in SAS and EAS.

(2050-2069) - SSP2-4.5 (2020-2039)

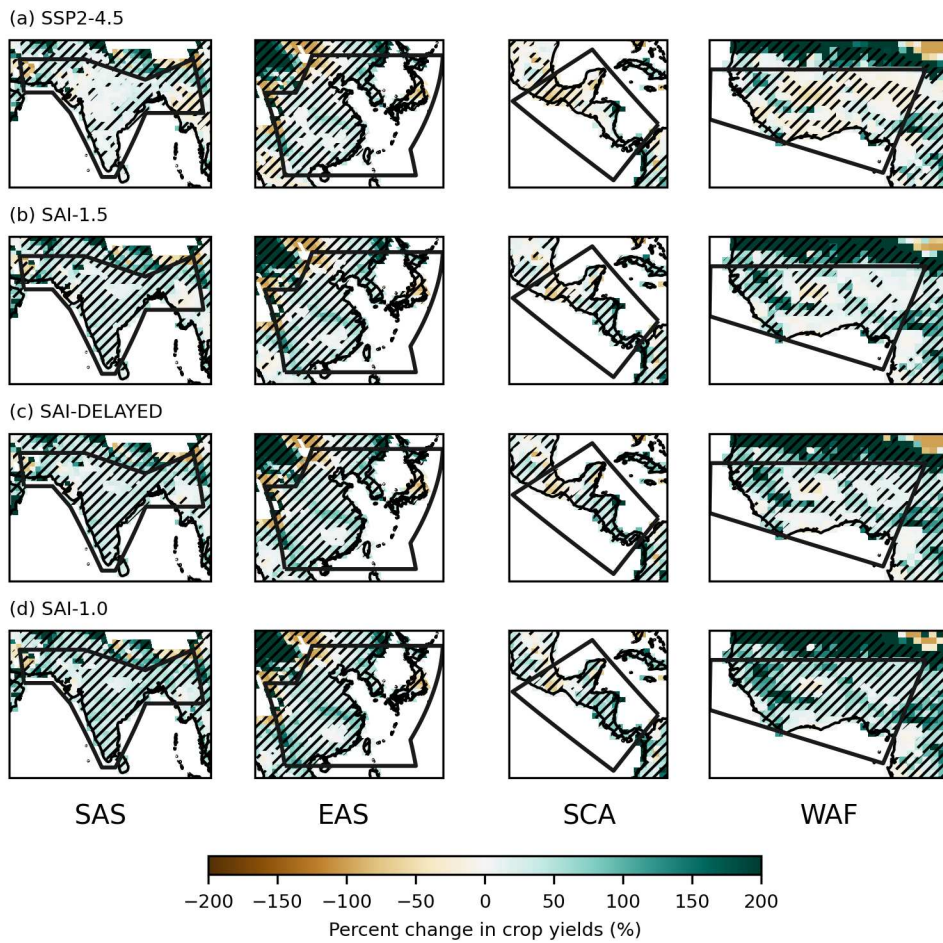


Figure 9. Percent changes in average annual total crop yields (measured in grams of carbon per square meter) for each region and scenario relative to the base period. Hatching indicates significant differences at the 99% significance level using a Welch t-test.

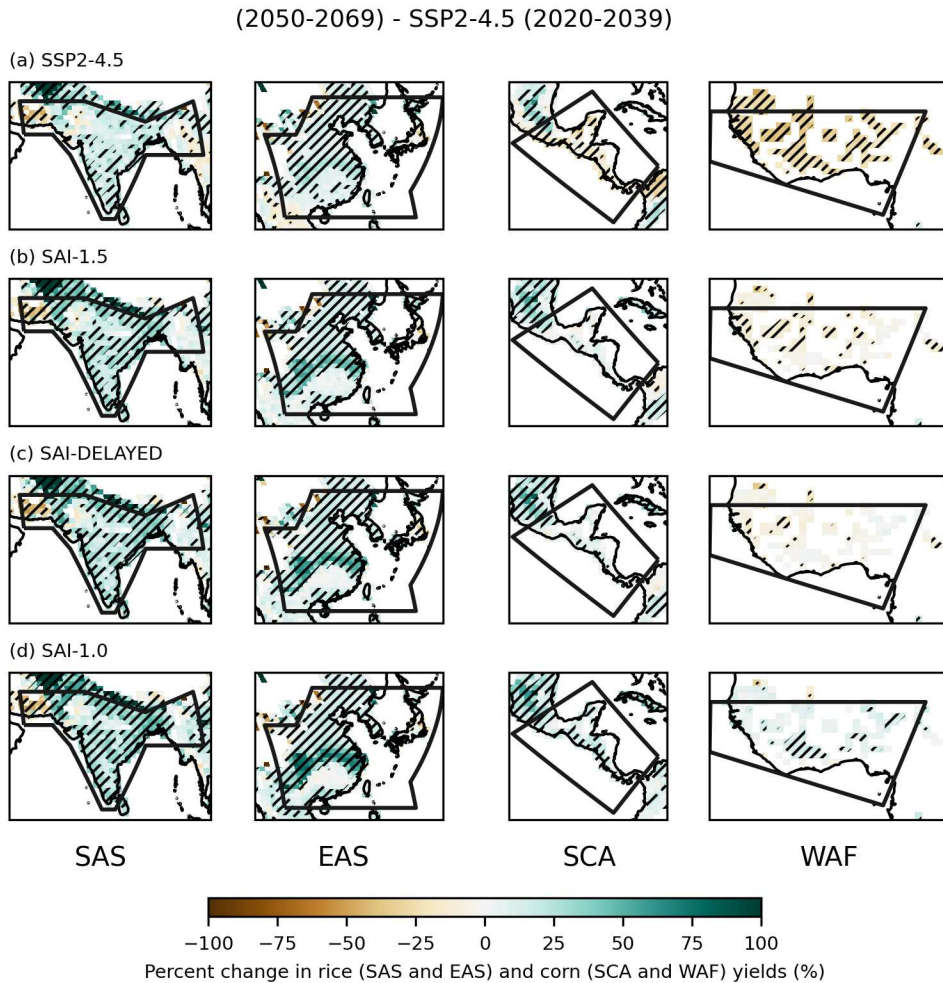


Figure 10. Percent changes in yields of major crops (rice for SAS and EAS, corn for WAF and SCA) for each region and scenario relative to the base period. Hatching indicates significant differences at the 99% significance level using a Welch t-test.

Finally, Figure 11 analyzes percentage changes of spring wheat, soybeans, corn, and rice in each region and under each scenario. CLM5 makes a distinction between tropical and temperate soybeans and corn based on latitude (Lombardozzi et al., 2020). EAS is the only region producing both temperate and tropical corn and soybeans. Thus, for a just comparison among regions, only the tropical varieties of corn and soybeans were considered.

For all regions, the yields of rice, wheat, corn and soy are generally greater under SAI-1.0 compared to climate change. One exception is wheat yield in WAF, which is slightly smaller

under SAI-1.0 than under climate change. Soybean yields, which tend to be overestimated in CLM5 (Fan et al., 2021), increased substantially in all regions and all scenarios relative to the base period. Corn yields experience significant decreases under the climate change scenario in all four regions.

In EAS and SAS, rice and wheat show large increases in crop growth compared to the base period under all scenarios. In contrast, in SCA, the yields of rice and wheat increase slightly or decrease. In WAF, wheat yields significantly decrease under all four scenarios and corn yields significantly decrease under all scenarios except SAI-1.0. The reduced precipitation and soil moisture in SCA and WAF help explain the differences in the results relative to EAS and SAS. We computed the correlation coefficient between regionally averaged, annual-mean time series of total crop yields and soil moisture for SSP2-4.5 (2020-2069), with all 10 ensemble members combined as one 500-year time series. The coefficients were 0.14, -0.03 (not significantly different from zero), 0.40, and 0.61 for SAS, EAS, SCA, and WAF, respectively. Thus, in SCA and WAF, the relationship between soil moisture and crop yields is much stronger than in SAS and EAS. Since soil moisture decreases overall under climate change in SCA and WAF, crop yields also dwindle in these regions.

(2050-2069) - SSP2-4.5 (2020-2039)

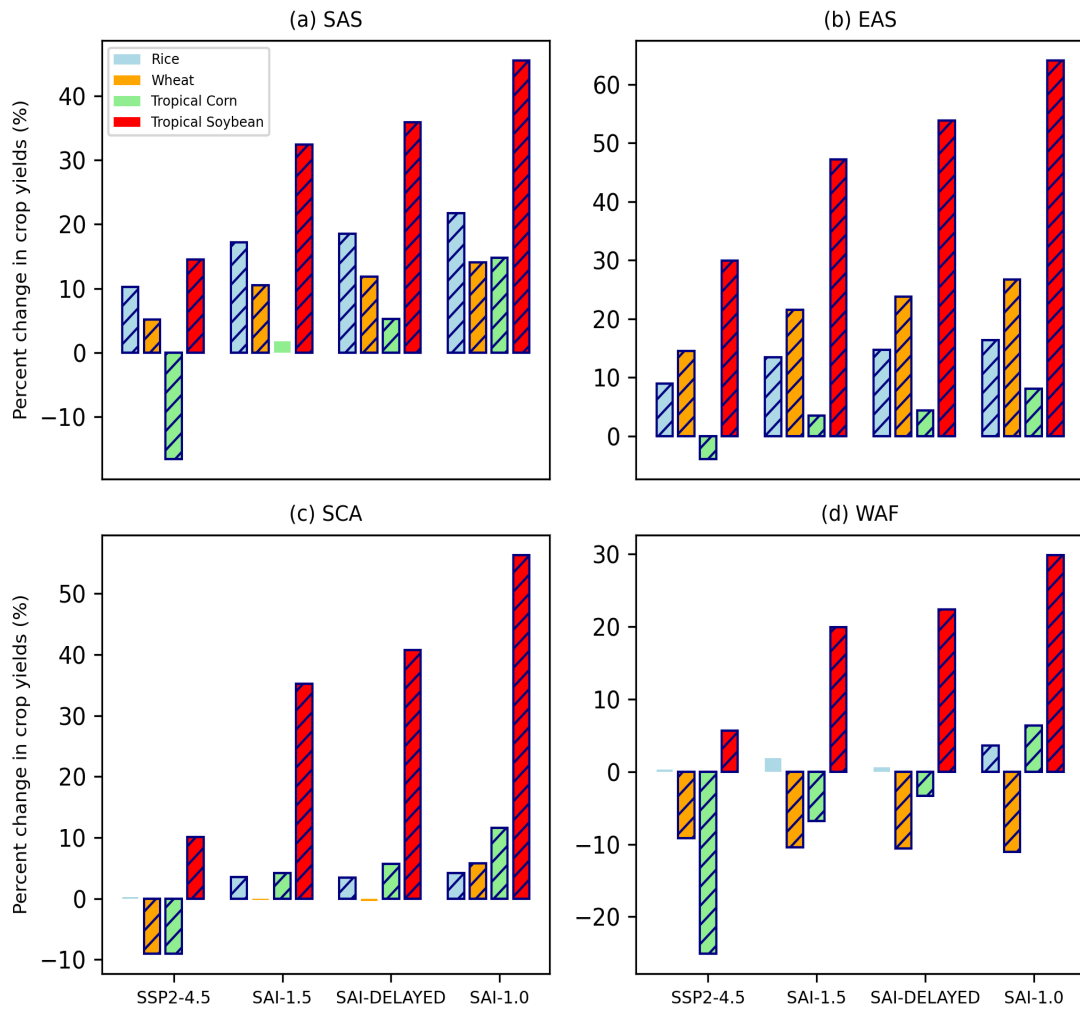


Figure 11. A comparison of percent changes in corn, rice, wheat, and soy yields for the four regions with respect to the base period. The climate change and SAI scenarios are analyzed from 2050-2069. Hatched bars indicate statistically significant changes at the 99% confidence level using a Welch t-test.

2.4 DISCUSSION

In recent years, as the effects of anthropogenic climate change have become more widespread and severe, scientific investigation into the potential benefits and risks of SAI has also increased. Many studies (e.g., Mamalakis et al., 2023, Simpson et al., 2019; Richter et al., 2022; Haywood et al., 2022; Zhang et al., 2024) have analyzed the global impacts of SAI on

fundamental variables such as temperature and precipitation. Other studies have globally analyzed the impact of SAI on other Earth-system variables, such as temperature extremes (e.g., Ji et al., 2018; Alamou et al., 2022; Jiang et al., 2024) and soil moisture (e.g., Cheng et al., 2019; Liu et al., 2024). Relatively few studies (e.g., Da-Allada et al., 2020; Grant et al., 2025) have examined various SAI-induced impacts in specific regions.

Our study is a somewhat unique contribution to this ever-growing body of scholarship. While the relationship between socioeconomic conditions and climate change severity has been extensively studied (World Bank, 2013; Bathiany et al, 2018; Jafino et al., 2020), the socioeconomic aspect of SAI has received relatively little attention. We analyze regions (SAS, EAS, SCA, and WAF) whose populations may be particularly vulnerable to climate change. We analyze several variables pertinent to human well-being, such as wet season precipitation, temperature extremes, and crop productivity. We also examined three different SAI scenarios; to our knowledge, no other study has done so.

We found that the SAI scenarios mitigate some of the adverse impacts of climate change in our four regions. Specifically, under the SAI scenarios, precipitation, soil moisture and crop productivity tend to be greater relative to climate change, and average temperatures and temperature extremes (TXx and WSDI) are reduced. The overall shapes of the regions' annual temperature and precipitation cycles are also maintained under the SAI scenarios. In general, larger changes relative to the climate change scenario are observed in SAI-1.0 relative to SAI-1.5 and SAI-DELAYED due to the targeting of lower global surface temperatures in the former.

In contrast to the SAI impacts, which are similar in the four regions, the impacts of climate change differ substantially from one region to the next. For instance, under the climate change scenario, there are few significant changes (relative to the base period) in SAS and EAS in wet season precipitation; in SCA and WAF, however, wet season precipitation decreases significantly. These regional differences help explain projected changes in soil moisture. Under the climate change scenario, soil moisture experiences few significant changes in EAS and decreases in relatively small areas of SAS and large areas of SCA and WAF. Under the SAI scenarios, particularly SAI-1.0, soil moisture generally increases in all regions.

Total crop yield changes further mirror the tendencies in soil moisture: SCA, WAF, and to a lesser extent, SAS experience lower yields under climate change (relative to the base period) and higher yields under SAI, while EAS yields increase under all scenarios. Besides reduced heat stress, CO₂ fertilization, and increased precipitation, the type of crop also helps explain these regional differences. In SAS and EAS, major crops include rice and wheat, while, in SCA and WAF, corn is a major staple (Leff et al., 2004; FAO, n.d.). Higher CO₂ concentrations tend to increase the productivity of rice and wheat (C3 crops) but not corn (a C4 crop) due to their greater stomatal conductance (Rezaei et al., 2023). The percent changes in yields of major crops (rice, wheat, corn, and soy) compared to the base period are mostly positive in all scenarios in SAS and EAS, but this is not the case for SCA and WAF (Fig. 11).

We emphasize that our findings are dependent on the model and emissions scenario used. Many different SAI scenarios exist (e.g., Kravitz et al., 2011; Tilmes et al., 2017; Lee et al., 2021; Lee et al., 2023; Goddard et al., 2023). Some scenarios are more unrealistic than others, such as those using the RCP 8.5 emissions scenario with SAI deployment starting in 2020, further hindering effective comparison among scenarios (MacMartin et al., 2022). One such

scenario the Geoengineering Large Ensemble (GLENS) (Tilmes et al., 2018). Simpson et al. (2019) compare precipitation in GLENS (2075-2095) to RCP 8.5 (2010-2030). They found a failure of the Indian monsoon (represented by JJA precipitation), which would be a disaster for millions of people. In contrast, we found that Indian subcontinent wet season (and annual-mean) precipitation under ARISE-SAI overall shows no significant change from the base period, with some significant increases in southern regions of India in SAI-DELAYED and SAI-1.0 (Figs. 2 and 5). Similarly, Grant et al. (2025) found that Indian monsoon rainfall in ARISE-SAI-1.5 (2050-2069) is maintained relative to 2015-2034. GLENS and ARISE, however, differ in important aspects. For instance, GLENS and ARISE were simulated with CESM1 and CESM2, use the RCP 8.5 and SSP2-4.5 emissions scenarios, and SAI deployment begins in 2020 and 2035, respectively (Tilmes et al, 2018; Richter et al., 2022). MacMartin et al. (2022) have created new SAI simulations with a range of realistic circumstances to facilitate inter-scenario comparison, which will likely prove valuable in future SAI research.

In addition, while Earth-system models are an incredibly powerful tool, they also possess limitations, including biases in the simulated mean climate (Danabasoglu et al., 2020), shortcomings in the representations of aerosol processes (Haywood et al., 2025), and problems in their simulation of crops, including over our regions of study. The crop biases are due to such factors as recent technological agricultural advances and the impacts of plant pathogens and extreme weather, none of which are incorporated in CLM5 (Lawrence et al., 2019; Lombardozzi et al., 2020). While the total yields found in our study are affected by these biases, our analysis only focuses on the net changes over time under various future climate scenarios. We also note that crop yields do not indicate

the crops' nutritional value. High temperature and enhanced CO₂ growing conditions, for instance, decrease the nutritional value of cereals and legumes, compounding the problem of decreased yields (Scheelbeek et al., 2018; Soares et al., 2019).

Overall, the detrimental impacts of climate change, particularly from a crop productivity perspective, are projected to be more severe in world regions already quite susceptible socioeconomically to climate change, such as WAF and SCA. If SAI were deployed under the scenarios examined here, some of climate change's deleterious impacts might be alleviated in these regions. We recommend further research to examine SAI's possible impacts on human welfare in other regions, especially those most vulnerable to climate change (Hurrell et al., 2024; Haywood et al., 2025).

CHAPTER 3

SUMMARY AND FUTURE RESEARCH AVENUES

3.1. THESIS SUMMARY

In this work, we analyze the projected impacts of one climate change and three SAI scenarios on several Earth-system variables in four Global South regions particularly vulnerable to climate change (SAS, EAS, SCA, and WAF). In all four regions, the SAI scenarios reduce temperature extremes and increase wet season precipitation, soil moisture, and crop productivity relative to the climate change scenario. The impacts of the climate change scenario, in contrast, vary regionally. Wet season precipitation remains roughly constant relative to the base period in EAS and SAS, while it significantly decreases in SCA and WAF. Similarly, soil moisture in the climate change scenario remains overall constant relative to the base period in nearly all regions of EAS and most regions of SAS, while it significantly decreases in large parts of SCA and WAF. Consequently, crop productivity tends to increase in the climate change scenario in EAS, stay roughly constant in SAS, and decrease significantly in SCA and WAF. Besides changes in precipitation and soil moisture, another factor is the prevalence of rice and wheat in EAS and SAS and corn in SCA and WAF; the former crops are generally more resistant to climate change than the latter (Rezaei et al., 2023). Thus, these SAI scenarios may more greatly alleviate climate change's effects on crop productivity in SCA and WAF than in SAS and EAS.

Our results are intimately tied to the model and emissions scenario; indeed, scientific analysis of different SAI and climate change scenarios has produced varying results (MacMartin et al., 2022). We also recognize model biases on the climate system (Danabasoglu et al., 2020)

and in crop yields (Lawrence et al., 2019; Lombardozzi et al., 2020). In our work, however, we analyze overall changes rather than the numerical values themselves. Thus, we conclude that, in the scenarios analyzed, SAI may help ameliorate climate change's detrimental effects on the well-being of our four regions.

3.2. FUTURE RESEARCH AVENUES

Many possible future research avenues exist to enrich the findings of this work. For instance, the impact of SAI on crop productivity has been underexplored. To our knowledge, besides this present work, only a few studies have examined agriculture under SAI (e.g., Fan et al., 2021; Grant et al., 2025). Several studies project that climate change, due to heat stress, drought, plant pathogens, etc., will lead to crop productivity decreases in many world areas (e.g., Anderson et al., 2020; Kim and Mendelsohn, 2023; Rezaei et al., 2023). Thus, further research that explores to what extent SAI may ameliorate crop productivity losses is needed. Similarly, improvements of crop simulation in Earth system models would give greater confidence to future projections (Lawrence et al., 2019; Lombardozzi et al., 2020).

In this study, we indirectly examine the effects of climate futures on one aspect of human health by analyzing heat extremes. More direct and holistic analyses would greatly improve scientific understanding of the impact of climate change and SAI on human health. Heat-related human morbidity and illness could be more specifically analyzed by considering the medical community's findings on perilous temperature and relative humidity thresholds. The spread of vector-borne diseases due to temperature and precipitation changes under climate futures and its direct implications to human health and morbidity is also an important area of possible future research.

In this work, all three of the SAI scenarios we examined assume that SAI is implemented in an interrupted fashion, which is perhaps unlikely given international political tensions (Halstead, 2018; Hueholt et al., 2023). Further research could consider effects of climate change and SAI scenarios in alternate geopolitical circumstances. Some researchers (e.g., Bell and Keys, 2023; Keys, 2023) have already begun to consider the possibilities and effects of unilateral SAI deployment. Others (e.g., MacMartin et al., 2022) have used Earth-system modeling to numerically simulate the effects of geopolitical risks with SAI, such as sudden termination, interruption, and a gradual phase-out. Additional exploration of the effects of geopolitics on SAI will inform humanity of a wider possible range of outcomes.

Finally, the viewpoints and concerns of all people need to be taken into account when investigating SAI. Global North researchers have dominated the SAI field; it is critical to collaborate with Global South researchers to address the concerns and priorities of all world areas in the global challenge of climate change (Rahman et al., 2018; Hurrell et al., 2024; Haywood et al., 2025).

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[0442\(1998\)011<1020:DAMCEO>2.0.CO;2](https://doi.org/10.1175/1520-0442(1998)011<1020:DAMCEO>2.0.CO;2)

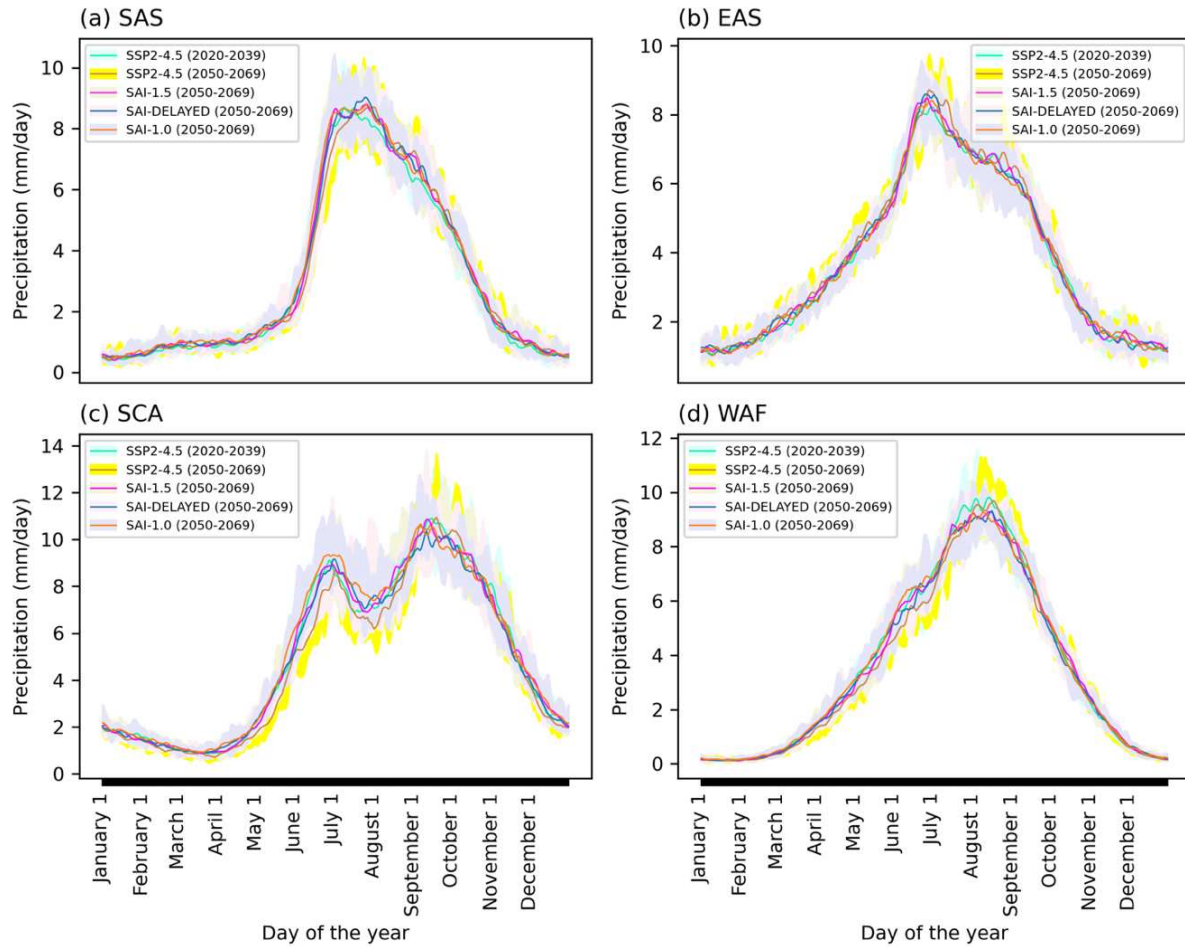
APPENDIX A

SUPPLEMENTAL FIGURES

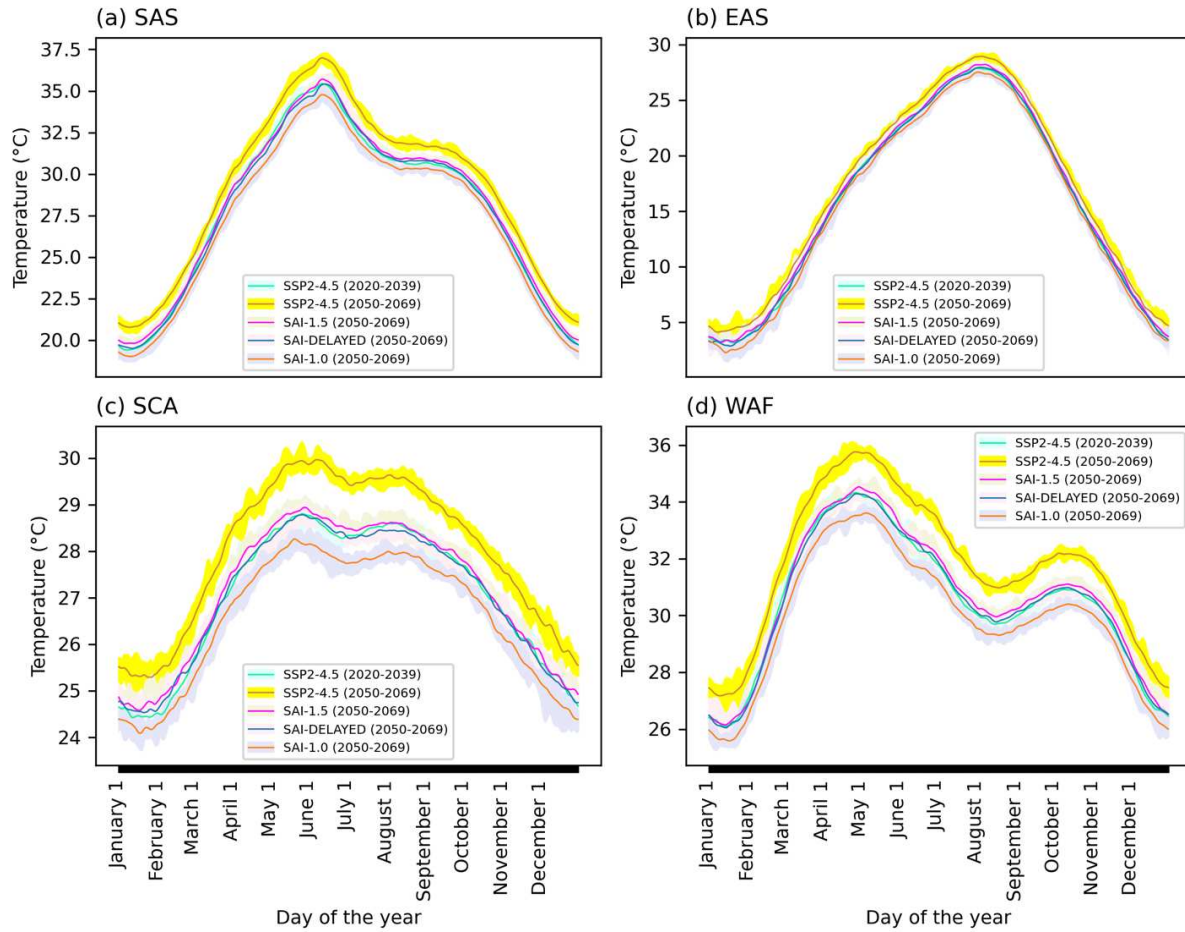
In this study (Chapter 2), we analyzed changes in average temperature and precipitation for our four regions by day of the year (Figs. 3 and 4). Here, we present the temperature and precipitation cycles themselves. The preservation of annual precipitation and temperature cycles is crucial for these regions' food security (Gbode et al., 2021; He et al., 2022; Stewart et al., 2022; Amale et al., 2023).

We first examine Supplemental Figure 1, which depicts the four regions' average precipitation by day of the year for the base period, climate change scenario, and three SAI scenarios. All four regions have distinct wet and dry seasons, though the nature of the wet seasons varies regionally in terms of onset and duration. Importantly, we see that the shape of the cycles in all SAI and climate change scenarios does not change relative to the base period. This preservation is particularly notable, given that ARISE-SAI does not specifically target the maintenance of annual cycles.

Supplemental Figure 2 depicts the regions' temperature cycles by scenario. The shape of the regions' temperature cycles differs regionally in terms of timing of peak temperatures and annual temperature range. However, as with precipitation, the overall shapes of the temperature cycles are preserved.



Supplemental Figure 1. Average precipitation by region and day of the year for SSP2-4.5 (2020-2039) (green), SSP2-4.5 (2050-2069) (brown), SAI-1.5 (2050-2069) (pink), SAI-DELAYED (2050-2069) (blue), and SAI-1.0 (2050-2069) (orange).



Supplemental Figure 2. As in Supplemental Figure 1, but for surface temperature.