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Effect of Stratospheric Aerosol Injection on Climate Change and Air Temperature Over West Africa

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Abstract

This study examines the application of stratospheric aerosol injection (SAI) as a climate intervention strategy to mitigate climate-change-induced warming of air temperature (TAS) over West Africa. Present-day TAS from ERA5 is first evaluated against CMIP6 (HIST) simulations, showing strong agreement in both magnitude and spatial structure, with bias-corrected results indicating only slight underestimation and minimal deviation and CMIP6 (HIST) dataset is reliable and appropriate for future climate projections. Future climate projections reveal widespread warming across West Africa, with slight warming in coastal regions, moderate warming over the savanna, and significant warming in the arid and semi-arid zones. The implementation of SAI under future scenarios substantially reduces TAS across all climatic regions of West Africa, effectively offsetting greenhouse-gas-driven warming and lowering temperatures toward minimum values. The reduced TAS alleviates heat stress on crops, improves growing conditions, enhances crop yield, and consequently boosts food security in climate-vulnerable regions such as West Africa. The study recommends that SAI be further explored as a complementary climate mitigation option alongside climate-smart agricultural practices and adaptation strategies, while emphasizing the need for continued assessment of its long-term regional impacts and sustainability.

Keywords: Air Temperature, ERA5, SAI, SSP2-4.5, SSP5-8.5

Introduction

Climate change refers to long-term changes in average weather patterns (temperature, rainfall, winds) driven primarily by increases in greenhouse gases (like CO_2) from human activities such as burning fossil fuels, deforestation, and agriculture. These changes alter global and regional climates, increasing the frequency and intensity of extreme events (heatwaves, droughts, floods) and shifting ecosystems and weather systems worldwide. West Africa is among the regions most vulnerable to climate change because the majority of its economies and livelihoods depend on climate-sensitive sectors like rain-fed agriculture, water resources, and pastoralism. Given that climate change threatens economic stability and raises death rates from climate-related illnesses throughout West Africa, its effects on public health and sustainable development highlight how urgent it is to address this issue. The term also describes the effects on the global climate of changes in the composition and interactions of natural materials, including rocks, ice, plants, animals, air, and oceans. West Africa, meanwhile, is at risk from climate change. For example, in 1972–1974, severe droughts annihilated the economies of numerous West African nations and in 1984–1985, a megadrought in Ethiopia killed roughly 450,000 people [1]. West Africa especially has been dubbed a hotspot for climate change because of human activities like the careless burning of fossil fuels from industrial sites and transportation, which have greatly increased greenhouse gas and aerosol emissions due to the region's high population growth and rapid urbanization. As a result of climate change, there are now more warm nights and days worldwide and fewer cold nights and days. Climate extreme events, including as temperature extremes that cause heatwaves and precipitation extremes that cause floods, are already having a negative impact on the African continent. They have a devastating effect on African infrastructure and communities leading to economic loss and health problems. Droughts are now common in South Africa the Greater Horn of Eastern Africa (Somalia, Ethiopia, Kenya, Sudan, and Tanzania), and the Guinea coast of West

Africa [2]. All sectors of the economy that rely on energy and water have been negatively impacted by these dry spells, which have also resulted in crop failure because agriculture is mostly rainfed, which makes food security more of a problem. Similarly, flooding has become a common occurrence in the Central Sahel region of West Africa and is linked to health problems that can result in fatalities. The increase in global temperature brought on by an increase in the concentration of greenhouse gas emissions in the atmosphere is known as global warming. Unprecedented extremes may arise as a result of climate change, which also affects the frequency, intensity, amplitude, duration, and timing of extreme weather and climate events. Infrared (longwave) radiation emitted from the Earth's surface can be absorbed by greenhouse gases and reradiated back to the Earth's surface, contributing to the greenhouse effect. To keep the Earth's surface warm, greenhouse gases trap outgoing longwave radiation while allowing shortwave radiation to flow through the atmosphere. For example, the most powerful greenhouse gases are carbon dioxide (CO2), methane (CH4), and water vapour. A few steps have been taken by African countries to mitigate these climatic impacts. The 2015 Paris Climate Agreement, which all African countries ratified, aims to keep global warming "well below 20C and to pursue efforts to limit warming to 1.5^{0}C above preindustrial level". Air temperature (TAS) also known as near surface air temperature is a measure of how hot or cold the air is, usually expressed in degrees Celsius (°C) or Fahrenheit (°F). It reflects the average kinetic energy of air molecules—higher values mean the molecules are moving faster and the air feels warmer; lower values mean slower movement and cooler air. Meteorologists typically measure air temperature at about 1.25–2 m above the ground in shaded, ventilated shelters to get consistent, comparable readings. Air temperature (TAS) is a fundamental climate and weather variable that influences humidity, precipitation, evaporation, and human comfort. High air temperature has emerged as a major climate stressor in West Africa, driven by both natural tropical conditions and anthropogenic climate change, with clear evidence of increasing mean temperatures and more frequent and intense heat waves across the region [3,4]. Rising temperatures have significantly increased human exposure to heat stress, overwhelming the body's thermoregulatory capacity and leading to higher incidences of heat exhaustion, heat stroke, cardiovascular complications, and heat-related mortality, particularly among vulnerable populations such as the elderly, children, outdoor workers, and individuals with pre-existing health conditions [5,3]. These health risks are further intensified in rapidly expanding West African cities due to the urban heat island effect, which elevates both daytime and night-time air temperatures and reduces opportunities for thermal recovery [6,4]. In the agricultural sector, high air temperature has adversely affected productivity and livelihoods across West Africa, where farming systems are predominantly rain-fed and highly climate-sensitive [7,8]. Elevated temperatures increase evapotranspiration rates, reduce soil moisture availability, and intensify crop water stress, thereby suppressing photosynthesis, shortening crop growing periods, and lowering yields of staple crops such as maize, millet, sorghum, and rice [8,3]. Livestock production is also negatively impacted, as prolonged exposure to high temperatures reduces feed intake, milk and meat production, reproductive efficiency, and increases mortality rates, further undermining food security and rural incomes [7,9]. High air temperature additionally exacerbates water scarcity in West Africa by accelerating evaporation from rivers, reservoirs, and soils, leading to reduced surface and groundwater availability for domestic use, agriculture, and ecosystem functioning [4,3]. When combined with increasing rainfall variability and recurrent droughts, rising temperatures intensify hydrological stress and compound water insecurity across the region [9,4]. In coastal and southern parts of West Africa, high air temperatures frequently coincide with elevated humidity levels, producing dangerous humid heat conditions in which the heat index reaches thresholds hazardous to human health, even during short exposure periods [10,11]. Overall, the combined impacts of high air temperature on human health, agriculture, water resources, and economic activities underscore its role as a key driver of climate vulnerability in West Africa, with projected future warming expected to further amplify heat-related risks, food and water insecurity, and socio-economic pressures if effective adaptation and mitigation measures are not implemented [3,9]. Periods of low air temperature in West Africa occur mainly during the boreal winter months (December–February), when the region is influenced by the Harmattan season, characterized by the southward penetration of cold, dry continental air masses from the Sahara associated with the northeast trade winds (Harmattan winds) [12,4]. During this period, night-time and early-morning temperatures can drop significantly, particularly in the Sahelian and Sudano–Sahelian zones, affecting countries such as Mali, Niger, northern Nigeria, Burkina Faso, and northern Senegal, where minimum temperatures may fall below 15°C and, in some locations, approach 10°C [6,4]. These low temperatures are most pronounced at night due to strong radiative cooling under clear skies and low humidity conditions associated with Harmattan flow [12,3]. Low air temperature during the Harmattan season has notable impacts on human health, particularly in vulnerable populations, as cooler nights combined with dry, dusty conditions increase the incidence of respiratory illnesses, asthma, and cardiovascular stress, especially among children and the elderly [5,6]. In agricultural systems, reduced night-time temperatures can slow crop physiological processes, delay early growth stages, and in some cases increase cold stress for temperature-sensitive crops, particularly in northern West Africa where farming calendars are tightly linked to seasonal climate conditions [7,8]. Livestock may also experience stress due to cold nights and reduced forage quality during the dry season, leading to lower productivity and increased vulnerability to disease [7]. In addition, low temperatures during the Harmattan season influence surface–atmosphere energy exchanges by reducing sensible heat flux and modifying near-surface thermal gradients, which can affect boundary-layer dynamics and local circulation patterns across West Africa [3,4]. Overall, although low air temperature events in West Africa are less extreme than cold conditions in mid-latitude regions, their seasonal occurrence during the Harmattan period plays an important role in shaping human health outcomes, agricultural productivity, and land–atmosphere interactions, particularly in the Sahel and northern parts of the region [6,3].

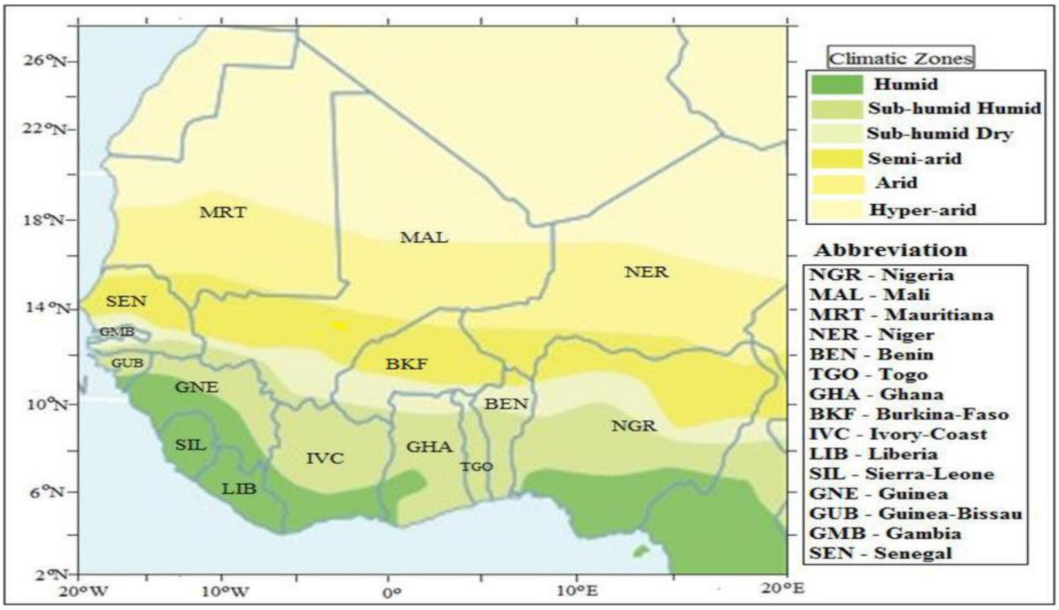

Figure 1: A map of West Africa showing the investigated climate zones and their respective countries (source: OECD, 2007, 2008a; Ojo et al. 2021

Materials and Method

West Africa locates between latitudes 4°N-28°N and longitudes 15°E-16°W. The climate of West Africa is controlled by the interaction of two air masses which varies throughout the year with influence of the north-south movement of the Intertropical Convergence Zone (ITCZ), it migrates from a humid tropical zone in the southern part of the region to arid zones in the northern areas bordering the "Sahara Desert as shown in Fig.1. Arid zones (hyper-arid, arid and semi-arid) cover latitudes (13.95°N – 27.17°N) and longitudes (17.07°W – 14.97°E). Dryland, sparse vegetation, and seasonal rainfall extremes are their defining characteristics. The plants that grow in these zones are mostly drought-tolerant, including groundnuts, cowpeas, sorghum, millet, bushes, grasses, and sporadic thorny trees (like acacia). The yearly rainfall in these regions varies from 100 mm to 600 mm ,and is unevenly distributed, decreasing gradually from south to north, which restricts the amount of water available for human activity and agriculture. These zones have a short wet season, lasting for 4 months (June-September) and the rain tends to come with intense thunderstorm, leading to quick flooding and minimal soil absorption. The dry season of these zones lasts for 8 months (October to May) with intense heat and desiccating winds, such as harmattan (a dry, dust-laden wind from the Sahara). The population density of these area is relatively low compared to wetter zones owing to the challenging living conditions. Humid zone ((sub-humid dry, sub-humid humid, and humid) are typically located between latitudes 4.56°N-12.47°N and longitudes 16.85°W-13.25°E with abundant annual rainfall ranges between 1200mm to over 4000mm annually [3]. The rainfall is more evenly distributed in humid zones compared to arid zones. Humid zone's climate is characterized by two main rainy seasons, April-July and September-October, while the dry season of these zones lasts for 5 months (November to March), coinciding with the harmattan winds, which bring dry and dusty condition. These zones are densely tropical rainforests, with layers of vegetation, including tall evergreen trees, understory, shrubs and climbing plants. These area are vulnerable to climate extremes, such as flooding and crop loss, due to the dense population Monthly data of 2m air temperature was obtained from the archive of ERA5 database of European Center for Medium-Range Weather Forecast (ECMF) at a resolution of 0.25o ×0.25o grid system for the period of 35 years (1980-2014) over West Africa as the control baseline simulation dataset that was used to study the characteristics of the present-day climate. Three different simulation control dataset scenarios—historical, SSP245 and SSP585—at different resolutions were obtained from Coupled Model Intercomparison Project Phase 6 (CMIP6). The simulations span 86 years, from 2015 to 2100, while the historical dataset spans 35 years, from 1980 to 2014.The control SSP245 and SSP585 simulation datasets were used to study the characteristics of future climate. The control historical dataset was used to study the characteristics of preindustrial climate. Finally, Assessing Responses and Impacts of Solar climate intervention on the Earth system with Stratospheric Aerosol Injection (ARISE-SAI-1.5) model for the period of 56 years (2015-2070) were obtained from https:/www.earthsystemgrid.org/dataset/ucar.cgd.ccsm4.ARISE-SAI-1.5.html/. at a resolution of 0.9o latitude x 1.25o longitude (Tilmes et al. 2018) and used in this study as solar geoengineering [1]. The feedback simulation dataset (SAI) was used to examine the characteristics of the future climate under the SSP245 scenario with the SAI intervention (2035-2069; hereafter, SAI). The control experiment has four datasets: reference simulation dataset (1980-2014), SSP245 and SSP585 scenarios simulation datasets (2015-2100), and historical scenario simulation dataset (1980-2014), but feedback experiment has one dataset, known as feedback simulation dataset (2015-2070).

The 2m air temperature was analyzed and averaged on a monthly basis over a period of 35 years. The same dataset obtained from ERA5, CMIP6 and ARISE-SAI was used to plot spatial distribution for impact of climate change and impact of stratospheric aerosol injection on air temperature.

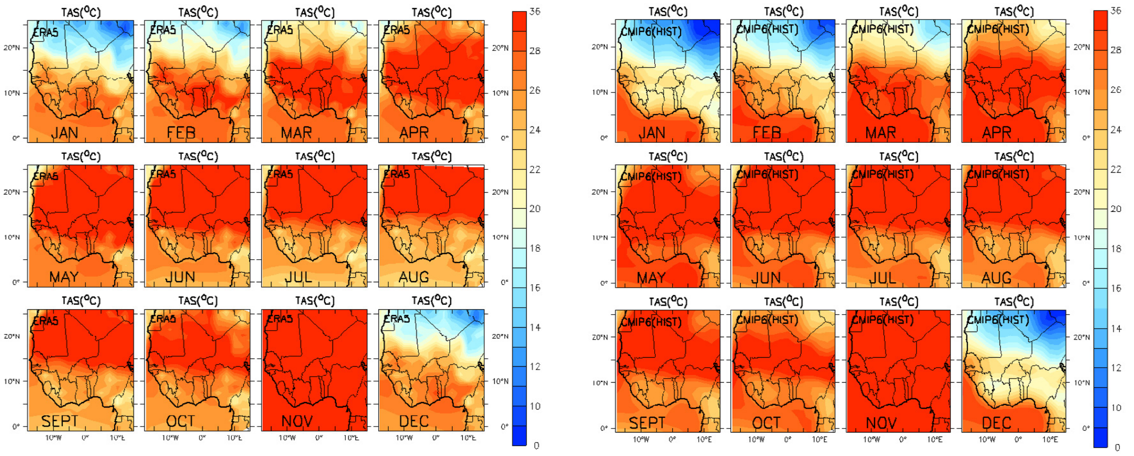

Figure:2: Monthly spatial distribution of TAS (OC) under (a) ERA5 and (b) CMIP6 (HIST) scenarios

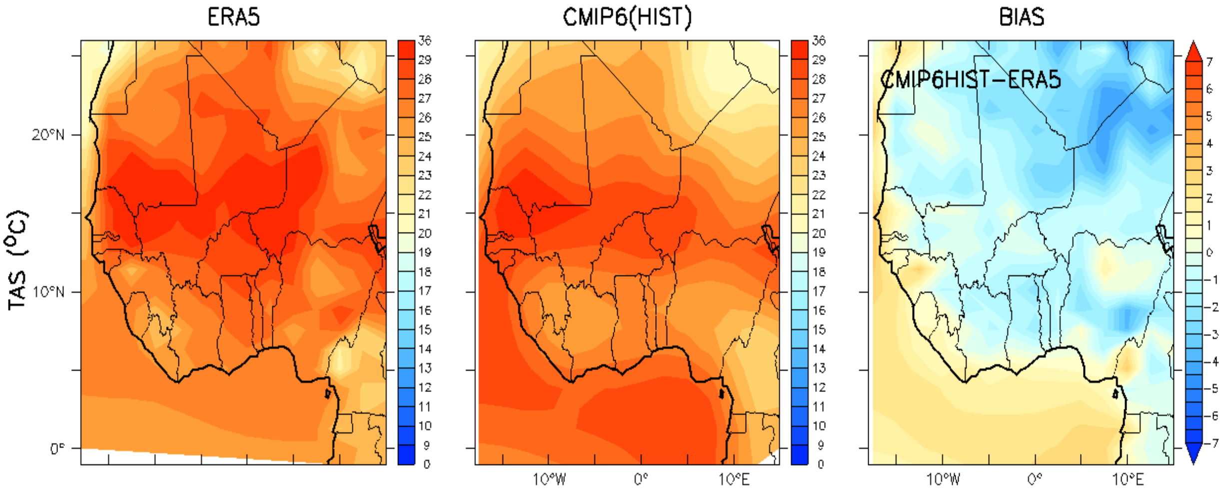

Figure:2c: Spatial distribution of bias of ERA5 dataset (observation dataset) using CMIP6 (HIST) for TAS (OC)

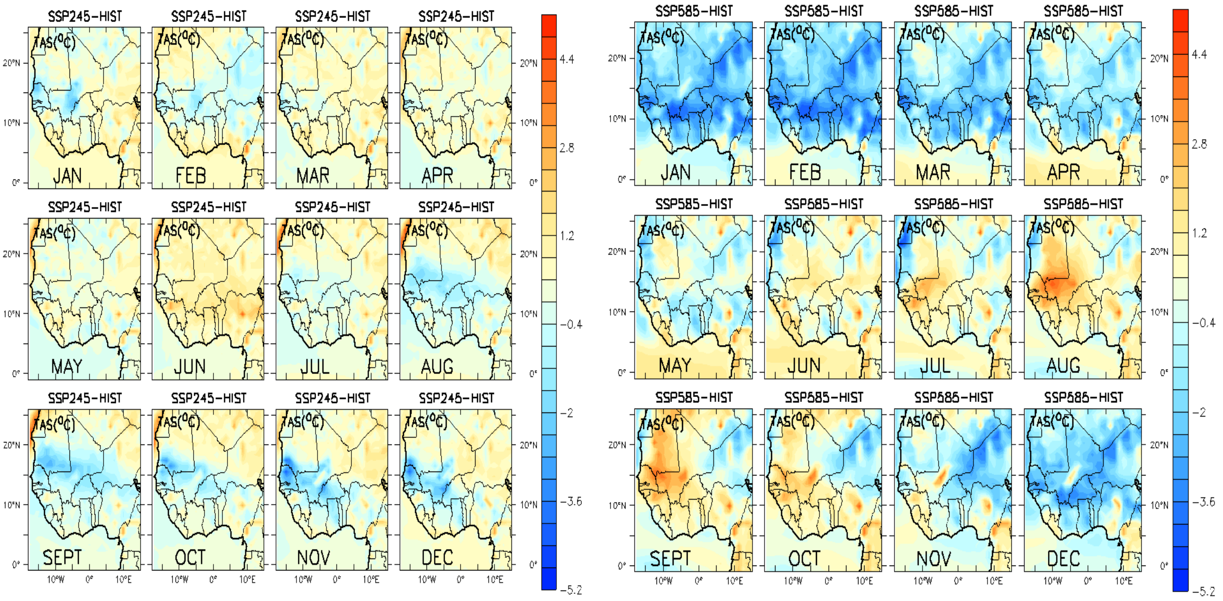

Figure:3: Monthly spatial distribution of impact of climate change (CC) on TAS (OC) under (a) SSP2-4.5 and (b) SSP5-8.5 scenarios

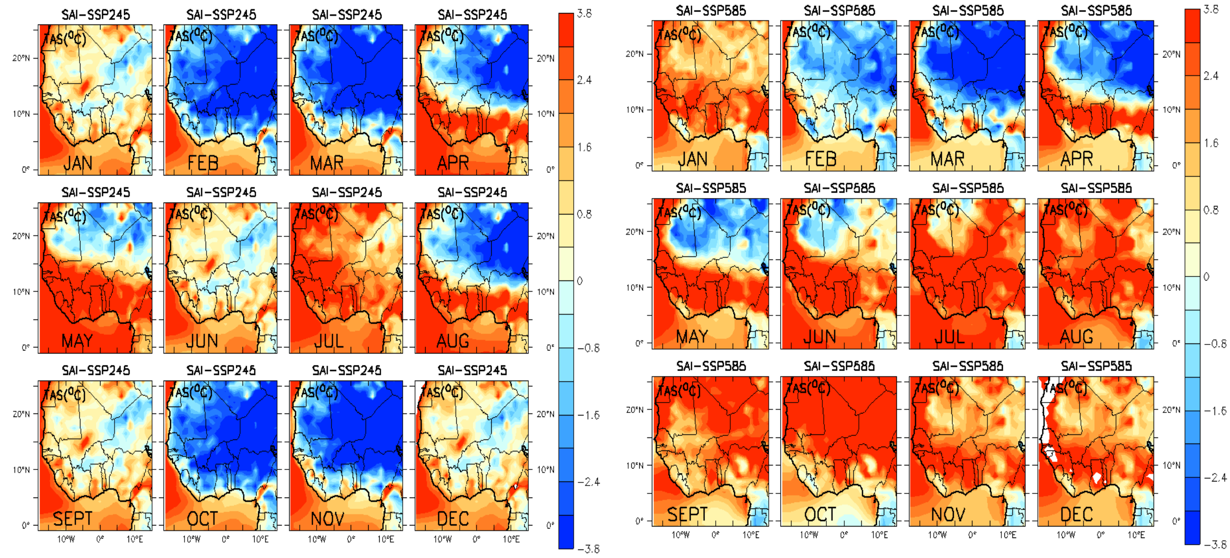

Fig.4: Monthly spatial distribution of impact of SAI on TAS (OC) under (a) SSP2-4.5 and (b) SSP5-8.5 scenarios

Results and discussion

Comparing spatial distribution of TAS obtained from present day observation dataset (ERA5) with simulated CMIP6 (HIST) dataset Figure 2a–b show that the spatial distribution and magnitude of air temperature (TAS) from ERA5 and CMIP6 (HIST) are nearly identical across West Africa, indicating a strong agreement in both large-scale patterns and regional gradients. This close correspondence suggests that the CMIP6 (HIST) simulation reliably reproduces the observed present-day TAS, such that Figure 2b effectively captures the same spatial characteristics as Figure 2a. In Figure 2c, CMIP6 (HIST) was used to bias ERA5 for TAS, and the result reveals a slight underestimation of ERA5 temperatures, with minimal spatial deviation. Overall, the small bias magnitude confirms the robustness of the bias-correction approach and supports the use of CMIP6 (HIST) outputs for further climate impact assessments over the region. This minimal bias implies that the CMIP6 (HIST) dataset is reliable and suitable for future climate projection studies of TAS over West Africa.

Spatial distribution of the impact of climate change (CC) on TAS under future scenarios

Figure 3a–b illustrate the projected spatial distribution of TAS changes under future climate scenarios across different climatic zones of West Africa. Slight warming is evident over coastal and humid regions, while moderate warming dominates the savanna and transition zones. Significant warming is projected over the arid and semi-arid regions, particularly in the Sahel, reflecting enhanced land–atmosphere feedbacks and reduced soil moisture. In contrast, localized areas exhibit slight to moderate cooling, mainly over regions influenced by increased cloud cover or precipitation feedbacks. These spatial contrasts highlight the heterogeneous response of TAS to climate change, with warming intensity generally increasing from the coastal belt toward the northern arid zones.

Spatial distribution of the impact of stratospheric aerosol injection (SAI) on TAS under future scenarios (Figure 4a–b)

Figure 4a–b present the spatial distribution of the impact of SAI on TAS under future climate scenarios. The results show that SAI intervention consistently reduces air temperature across all climatic regions of West Africa. The cooling effect is evident in coastal, savanna, and Sahelian zones, where TAS is reduced toward minimum values relative to the corresponding non-SAI scenarios. This widespread temperature reduction demonstrates the effectiveness of SAI in counteracting greenhouse-gas-induced warming and moderating extreme temperature conditions across diverse climate regimes.

Conclusion

This study compared the spatial distribution of air temperature (TAS) from ERA5 observations with CMIP6 (HIST) simulations and assessed the impacts of climate change and stratospheric aerosol injection (SAI) on TAS over West Africa. The results show a strong agreement between ERA5 and CMIP6 (HIST), with minimal bias after correction, confirming the reliability of the simulated dataset. Future climate scenarios project widespread warming, ranging from slight to significant increases depending on the climatic zone, with the strongest warming over arid and semi-arid regions. In contrast, SAI substantially reduces TAS across all regions, lowering temperatures toward minimum values. Reduced TAS is beneficial for agriculture, as lower temperature stress enhances crop growth, improves yield stability, and ultimately boosts food security in climate-vulnerable regions such as West Africa. It is therefore recommended that future climate adaptation strategies integrate temperature-mitigation options, alongside sustainable agricultural practices, while further research evaluates the long-term regional impacts and potential risks of SAI deployment.

Declaration of Competing Interest

There is no conflict of interest in the preparation and execution of the research.

Acknowledgment

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