IMPACTS OF SOLAR RADIATION MANAGEMENT ON EVAPORATIVE HEAT FLUX OVER WEST AFRICA

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ABSTRACT

This study investigates the impacts of solar radiation management through stratospheric aerosol injection (SAI) on the spatial variability of evaporative heat flux across West Africa. Evaporative heat flux represents a key component of land and atmosphere energy exchange and plays a critical role in regulating regional hydrological processes and surface temperature. Monthly evaporative heat flux data from the ERA5 reanalysis dataset were used as an observational reference for the historical period 1980–2014. Climate projections were obtained from an ensemble of fifteen global climate models participating in the Coupled Model Intercomparison Project Phase 6 (CMIP6). Future climate conditions were analysed under two greenhouse-gas emission scenarios, SSP2-4.5 and SSP5-8.5, for the period 2035–2069. To evaluate the potential effects of solar geoengineering, the ARISE-SAI-1.5 experiment was incorporated. All datasets were re-gridded to a common spatial resolution of $0.25^\circ \times 0.25^\circ$ using bilinear interpolation implemented through Climate Data Operators. Model performance was evaluated through grid-based bias analysis using ERA5 observations. Results reveal strong spatial gradients in evaporative heat flux across West Africa, with values exceeding 80 W m^{-2} in humid coastal regions and falling below 40 W m^{-2} across the Sahel. The CMIP6 historical simulations reproduce these spatial patterns reasonably well, with bias values generally ranging between -10 and $+10$ W m^{-2}. Under future emission scenarios, moderate increases in evaporative heat flux are projected across several parts of the region. However, the introduction of SAI results in a reduction of evaporative heat flux across large portions of West Africa, with changes typically ranging between -25 and 10 W m^{-2}. These results suggest that solar radiation management could influence land and atmosphere energy exchanges and potentially moderate extreme climate conditions in climate-sensitive regions. The study provides new insights into the regional implications of solar geoengineering and highlights the need for further evaluation of SAI alongside conventional mitigation and adaptation strategies in West Africa.

Keywords: Evaporative heat flux; Stratospheric aerosol injection; CMIP6 climate models; ERA5 reanalysis; Solar radiation management

1. | Introduction

Latent heat flux also known as evaporative heat flux is the energy transfer between the earth surface and the atmosphere by the process of evaporation and transpiration by plants (*Oke, 1987*; *Allen et al., 1998*). The process is a significant part of the surface energy balance and it is a direct connection between atmospheric circulation and hydrological cycle (*Trenberth et al., 2009*). In areas where moisture is rather rich, energy is passed on to the atmosphere through evapotranspiration causing changes in atmospheric stability, cloud cover and precipitation distribution (*Betts et al., 1996; Seneviratne et al., 2010*). Therefore, the differences in evaporative heat flux may have a substantial influence on water-energy relations as well as climatic conditions in the region (*Jung et al., 2010*). In West Africa where the agricultural productivity is greatly reliant on the variability and the spatial distribution of the rainfall and land-atmosphere interactions, it is especially crucial to understand the variability and the spatial distribution of the evaporative heat flux as a measure of climate dynamics and environmental sustainability (*Sultan & Gaetani, 2016*; *Nicholson, 2013*). The concept of solar radiation management has surfaced as a possible solution in recent decades to the global warming of the planet occurring in a short-term perspective, and thus addressing the impact of global warming caused by anthropogenic climate change (*Crutzen, 2006*; *Shepherd et al., 2009*). Solar radiation management entails the reflection of a small percentage of the radiated solar energy back to space so as to minimize the energy reaching the surface of the earth (*IPCC, 2021*). There is a variety of methods that are suggested such as marine cloud brightening, high-albedo surfaces, space-based reflectors, and stratospheric aerosol injection (*Shepherd et al., 2009; National Research Council, 2015*). Stratospheric aerosol injection is one such technique to which scientists have given considerable attention due to its relatively high cooling capacity, relative costs are low and the technology is feasible compared to other geoengineering methods (*Crutzen, 2006; Tilmes et al., 2018*). This idea is founded on the findings that large-scale volcanic eruptions release sulphate aerosols into stratosphere, raising planetary albedo, and causing short-term global cooling processes (*Robock, 2000*). Climate models that are involved in the Coupled Model Intercomparison Project Phase 6 are commonly used as climate projections to assess the possible future climate conditions (*Eyring et al., 2016*). These models model climate reactions on varied socioeconomic pathways depicting other greenhouse gas emission pathways (*Neill et al., 2016*). The SSP2-4.5 pathway will be a moderate scenario of mitigation that has stabilized emissions, and SSP5-8.5 will be a high emission scenario that can be characterized by the fact that it will rely on fossil fuels (*Neill et al., 2016*). A measurement of how evaporative heat flux reacts to such scenarios, and to such possible solar radiation management interventions, is critical to the understanding of future land-atmosphere energy interactions in West Africa (*Seneviratne et al., 2010*). Although solar geoengineering is sparking the interest of more researchers all over the world, comparatively little research has been conducted to describe its potential in regards to surface energy fluxes of the West African region (*Tilmes et al., 2020*). This paper hence examines the spatial variability of evaporative heat flux in West Africa based on CMIP6 climate models and how solar radiation management by injection of stratospheric aerosols can alter surface exchanges at the regions.

2 | Materials and Methods

2.1 | Study domain

The region between 15°W and 16°E and 4°N and 28°N is an approximation of the West Africa. The area is typified by the presence of steep climatic gradients between the wet coastal conditions near the Gulf of Guinea and semi-arid and desert like conditions in Sahel and southern Sahara as illustrated in Figure 1. The Intertropical Discontinuity and the West African monsoon circulation are the main factors that govern climatic variability over the region due to their seasonal movement. The process of interaction of moist south-west marine air masses and dry north-eastern continental air masses results in the strong seasonal differences in precipitation, vegetation distribution, and surface energy flux. (*Nicholson, 2013*; *Barry and Chorley, 2010*).

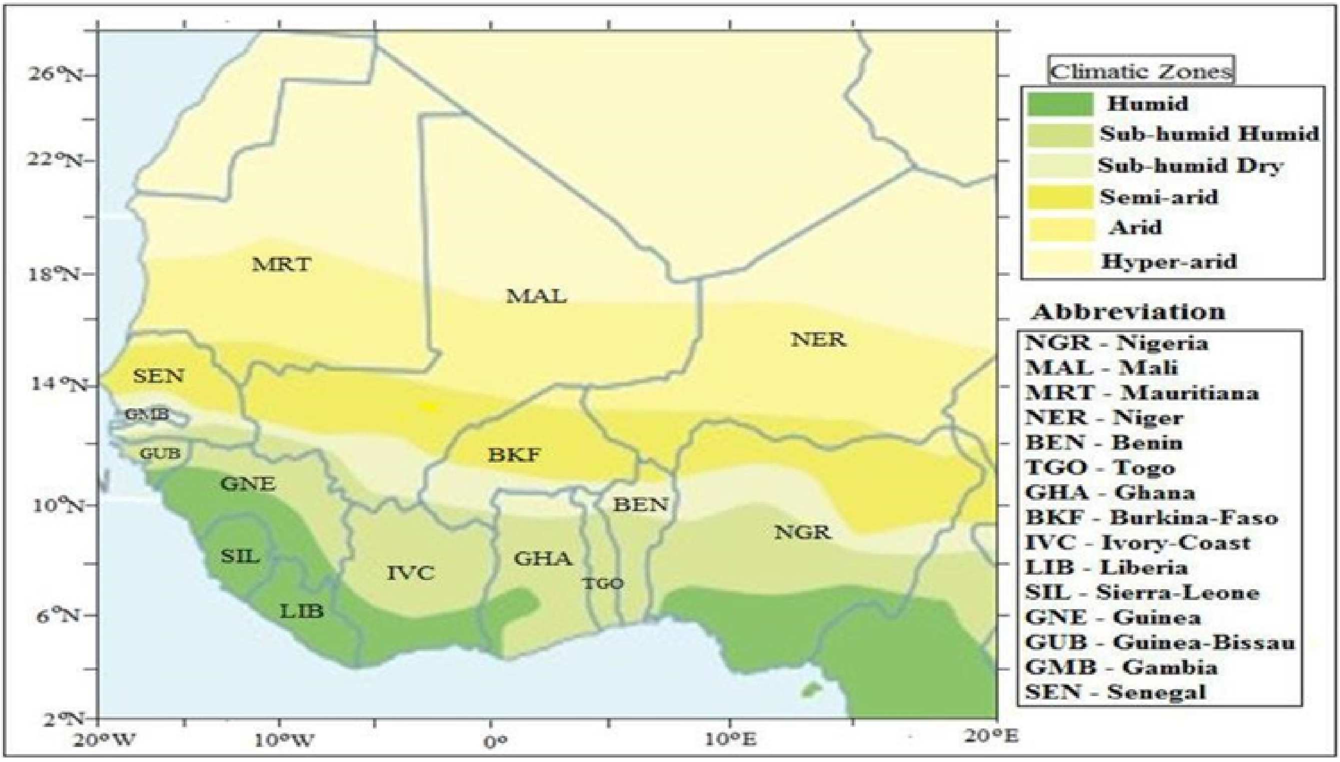


Figure 1 | A map of West Africa showing the investigated climate zones and their respective countries (source: OECD, 2007, 2008a; Ojo *et al.*, 2021)

2.2 | Data source

This paper combines the observational reanalysis data with climate model simulations in the investigation of the variability of evaporative heat flux across West Africa. The observational data was acquired through the ERA5 reanalysis generated by European Centre of Medium-range Weather Forecasts which offers a consistent world-wide atmospheric sampling having a spatial resolution of 0.25° × 0.25° concentrating on energy interchanges between the land and atmosphere. The simulations of climate projections were obtained through the coupling model intercomparison Project Phase 6 (*Eyring et al., 2016*). A collection of global climatic models was examined over the past time (1980-2014) and projected to the future under moderate and high emission pathways of greenhouse gases using SSP2-4.5 and SSP5-8.5 scenarios. These were analyzed together with the simulation of the ARISE-SAI-1.5 experiment, which depicts the stratospheric aerosol injection as a climate intervention practice. The significance of involving SAI is justified by the results of *Abiodun et al., 2023* that highlight the necessity to assess its implications to the region, especially its impact on the variability of rainfall, and patterns of drought and surface energy balance. All future projections, including SSP2-4.5, SSP5-8.5, and SAI experiments, were analysed over a 35-year period spanning 2035–2069 to provide a consistent basis for assessing long-term climate responses and potential mitigation effects. Given the differences in spatial resolution between ERA5, CMIP6, and SAI datasets, all outputs were re-gridded to a common resolution of 0.25° × 0.25°. This was achieved using bilinear interpolation through the Climate Data Operators remapbil function, implemented within Ferret version 7.6, ensuring spatial consistency and enabling reliable grid-by grid comparison across West Africa. The evaporative heat flux (LE) represents the energy transferred from the surface to the atmosphere through evaporation and transpiration processes. It can be expressed as

$$\mathrm{LE} = \rho L_V \frac{(q_s - q_a)}{r_a} \qquad (1)$$

where LE is the Evaporative heat flux (Wm^{-2}), ρ is the air density (kg m^{-3}), L_V is the latent heat of vaporization (J kg^{-1}), q_S is the specific humidity at the surface (kg kg^{-1}), q_a is the specific humidity at reference height (kg kg^{-1}) and r_a is the aerodynamic resistance (s m^{-1}).

In order to estimate the monthly evaporative heat flux (LE), the evaporative heat flux at surface was averaged over a 35-year period

3. | Results and Discussion

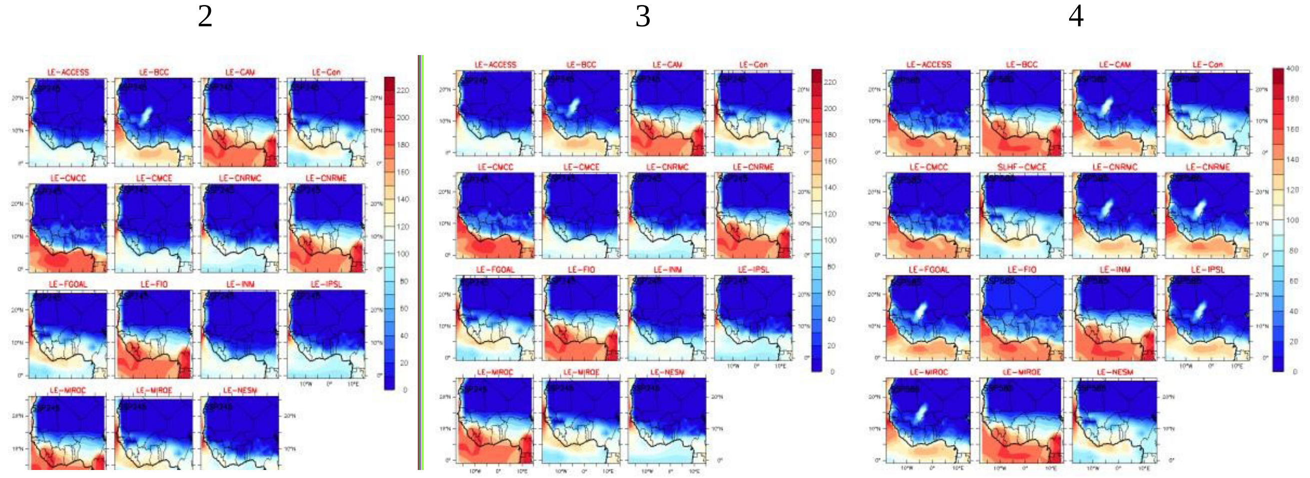
3.1 | Ensemble Climate Model Approach for Analyzing Evaporative Heat Flux Variability

In order to obtain a robust assessment of evaporative heat flux variability across West Africa, this study adopted a multi-model ensemble approach based on selected Global Climate Models from the CMIP6 archive. There are also usually differences in how individual climate models describe atmospheric circulation, land surface interactions, and surface energy fluxes as a result of differences in model structure, parameterization schemes and spatial resolution. Therefore, the use of one model may create a high degree of uncertainty in climate analysis. Ensemble approach minimises these uncertainties through a combination of results of several models, which helps to make the plots of climate behaviour more reliable and representative of the region. The choice of the CMIP6 models was informed by the fact that the historical experiment has full simulations, and the future scenarios of emissions needed in this study. Moreover, CMIP6 is a global modelling project aimed at enhancing the comprehension of the nature of climate processes and enhancing the similarity between climate predictions of various modelling facilities (*Eyring et al., 2016*). Table 1 lists the models that were chosen, their spatial resolutions and the institution they were produced in. Seeing that the selected models had a different level of spatial resolution, the results were reconciled to make them comparable. Bilinear interpolation with the Climate Data Operators (CDO) software of Ferret version 7.6 was used to re-grid all datasets to the common spatial resolution of 0.25° × 0.25°, which corresponds to ERA5 dataset. This was

Table 1 | Global climate models (GCMs) with Resolutions, Countries and References

GCMs	Resolutions	Countries	References
ACCESS-CM2	1° × 1°	Australia	*Bi et al., 2020*
BCC-CSM2-MR	1.125° × 1.125°	China	*Wu et al., 2019*
CAMS-CSM1-0	2.8° × 2.8°	China	*Rong et al., 2018*
CanESM5-canOE	2.8° × 2.8°	Canada	*Swart et al., 2019*
CMCC-ESM2	1° × 1°	Italy	*Cherchi et al., 2019*
CNRM-CM6-1	1.4° × 1.4°	France	*oire et al., 2019*
CNRM-ESM2-1	1.4° × 1.4°	France	*Séférian et al., 2019*
FGOALS-f3-1	1° × 1°	China	*Li et al., 2020*
FIO-ESM-2-0	1° × 1°	China	*Shi et al., 2020*
INM-CM4-8	1.5° × 2°	Russia	*din et al., 2019*
IPSL-CM6A-LR	2.5° × 1.25°	France	*Boucher et al., 2020*
MIROC6	1.4° × 1.4°	Japan	*Tatebe et al., 2019*
MIROC-ES2L	1.4° × 1.4°	Japan	*Hajima et al., 2020*
NESM3	1.875° × 2.5°	China	*Cao et al., 2018*

followed by the calculation of ensemble mean values by averaging the results of all the models that were chosen at every grid point. This process causes less bias in models, and the strength of the simulated patterns in space is improved. The ensemble data was then used to study the spatial distribution of the evaporative heat flux at historical and future climate conditions as illustrated in Figures 2-4. These results of ensembles are useful in both the assessment of model performance, as well as in the analysis of projected variability of evaporative heat flux in West Africa.



Figures 2-4 | Spatial distribution of ensemble-mean evaporative heat flux derived from fifteen CMIP6 global climate models under the historical simulation (HIST) and future emission scenarios SSP2-4.5 and SSP5-8.5 across West Africa.

3.2 | Evaluation of CMIP6 Historical Simulations Using ERA5 Reanalysis

To evaluate the performance of the CMIP6 climate model ensemble, simulations in the past were compared against the ERA5 reanalysis dataset so as to know the extent to which the models were able to capture the spatial variability of evaporative heat flux over West Africa. Figure 5 shows the spatial distribution of evaporative heat flux of ERA5 observation and CMIP6 historical simulation. The findings show that there is a strong latitudinal gradient in the region. The higher values of evaporative heat flux are prevalent in the Sahel and the north of West Africa, whereby the amount of precipitation, the vegetation cover, and the soil moisture are scarce, limiting the processes of evapotranspiration. Conversely, the evaporative heat flux values are higher in the humid coastal areas of the Gulf of Guinea due to the presence of high values of rainfall, dense vegetation, and humidity of the atmosphere that promote evaporation and transpiration of plants (*Barry and Chorley, 2010; Nicholson, 2013; Monteith and Unsworth, 2013*).

The grid-by-grid grid bias analysis between CMIP6 and ERA5 output and observation was used to assess model performance. To compute the mean bias at each grid point as defined by *Willmott (1982)*, the following was used:

$$\text{Mean bias} = \frac{1}{n}\sum_{i=1}^{n}\left(M_i(x,y) - O_i(x,y)\right) \qquad (2)$$

Mi(x,y) is the model value of CMIP6 applicable at the month i and location (x,y), Oi(x,y) is the ERA5 value at the month i and location (x,y) and n is the amount of months in the analysis period. The values of the positive bias suggest that the model overestimates the observations and the value of the negative bias suggests underestimation. It is compared that the main spatial aspects of evaporative heat flux across West Africa are reproduced by the CMIP6 historical simulations with comparatively minor deviations. CMIP6 historical simulation exhibits a negative bias relative to ERA5 observation in the semi-arid Sahel region and positive bias in the Guinea costal region with bias values generally ranging between −10 and +10 W m^{-2}. Such findings prove that the multi-model ensemble is an effective way of capturing the pattern of surface energy fluxes at regional scale and can thus be applied to study the issue of future climate variability and future evaporative heat flux changes in various emission conditions (*Eyring et al., 2016; Hempel et al., 2013*).

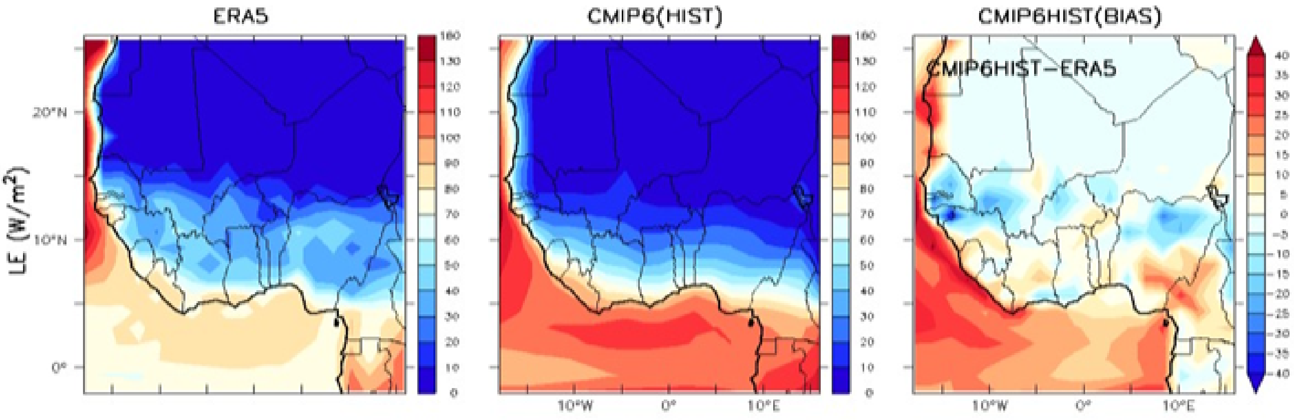
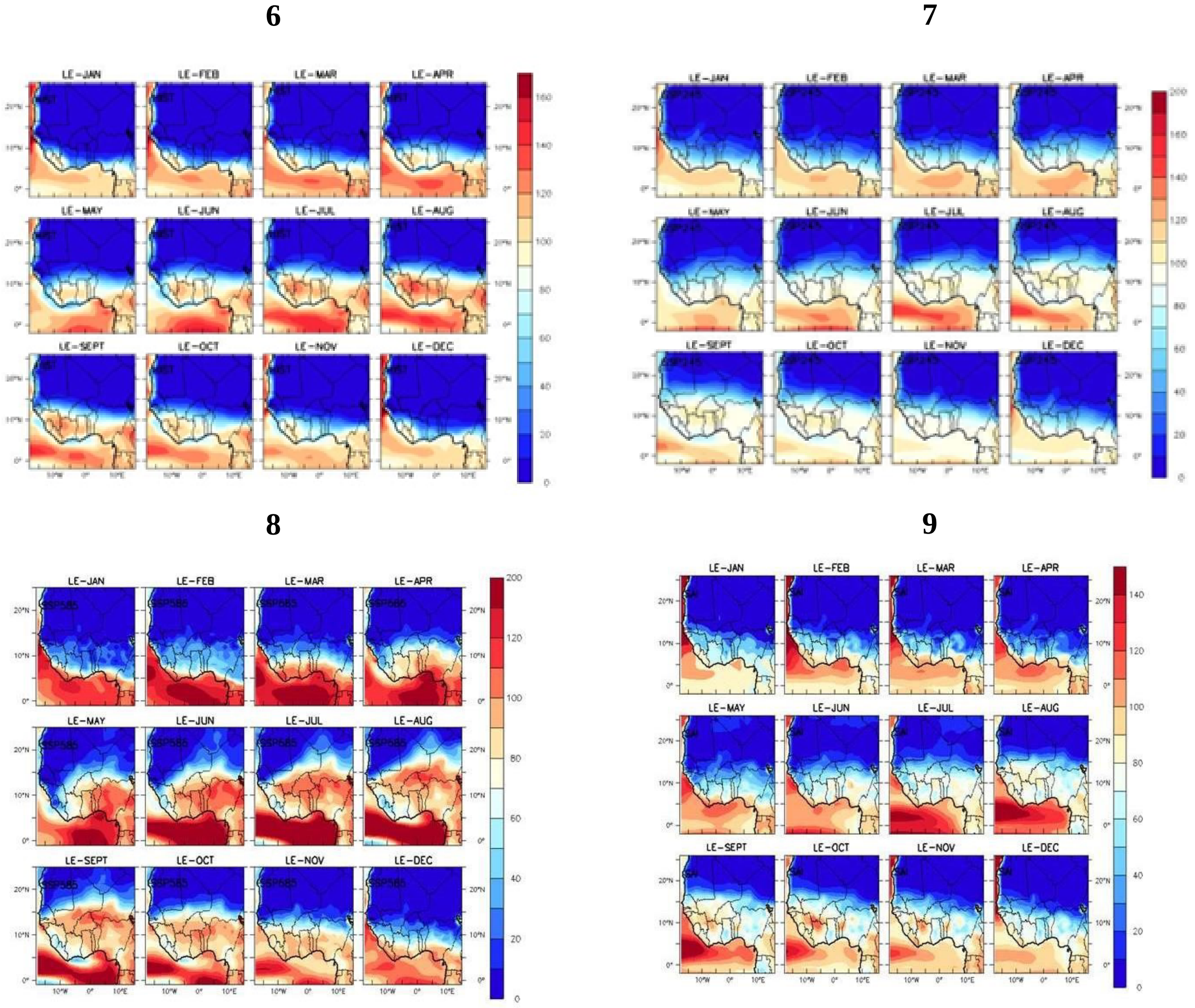


Figure 5 | Spatial comparison of evaporative heat flux across West Africa derived from ERA5 reanalysis observations and CMIP6 historical simulations, including the corresponding model bias distribution.

3.3 | Spatial Variability of Evaporative Heat Flux under Historical and Future Climate Scenarios

The evaporative heat flux in space of West Africa has great regional differences that symbolize the differences in climatic conditions, vegetation cover, and the availability of surface moisture. The ensemble simulations indicate the existence of higher values of evaporative heat flux in the humid coastal belt and forest regions close to the gulf of guinea under the historical climate conditions. These regions are marked with high rainfall, thick vegetation, and high soil moisture that favor the increased process of evapotranspiration. Contrarily, the Sahel and northern regions of West Africa are inhabited by lower values because of the low levels of precipitation, low vegetation cover, and low soil moisture that limit evaporation and plant transpiration. This noticeable latitudinal gradient in the exchange of surface energy in the region is pointed out by the spatial pattern in Figure 6. The projections at the SSP2-4.5 scenario in Figure 7 show that evaporative heat flux would reduce in several regions of the humid and sub-humid areas on the moderate level. Increase in temperatures increases the rate of evaporation and the demand in the atmosphere of moisture, which in turn intensifies the extraction of latent heat between the surface and the atmosphere. Nevertheless, the scale of change is not very drastic since such a situation presupposes moderate greenhouse gas emissions and slow mitigation processes. In the high emission scenario SSP5-8.5 scenario case, as in Figure 8, greater variation in evaporative heat flux can be seen in West Africa. The increase of warmer conditions on the surface is expected to enhance the rate of evapotranspiration in most regions, especially in the coastal and forest regions. However, some regions of the Sahel can experience lesser growth or focalized decreases because of the continued soil moisture shortage. The two future situations show that the surface energy fluxes are sensitive to increases in temperature as well as the changes in the regional hydrology. The geometrical variations between the past and the future scenarios can be summed up in Figure 9 that shows the estimated variations in the evaporative heat flux across the region. These changes indicate complexity of interaction among land surface conditions, atmospheric warming and availability of water. Evaporative heat flux contributes to the control of the surface energy



Figures 6-9 | Spatial distribution of evaporative heat flux across West Africa under different climate scenarios: (6) CMIP6 historical simulation, (7) SSP2-4.5 scenario, (8) SSP5-8.5 scenario, and (9) ARISE-SAI-1.5 solar geoengineering experiment.

balance and the hydrological cycle, and alteration of this flux may impact the regional climate processes such as precipitation variability, land atmosphere feedback processes (*Ma et al., 2014; Monteith* and *Unsworth, 2013*).

3.4 | Impact of stratospheric aerosol Injection on evaporative heat flux

The geographical distribution of evaporative heat flux in West Africa during both historical climatic and future emission scenario (SSP2-4.5 and SSP5-8.5) with SAI intervention is shown in Figure 10, which is the geographical response of evaporative heat flux to the stratospheric aerosol injection (SAI). The results indicate that the spatial distribution of the heat flux through evaporation over the region is significantly disturbed with the introduction of SAI. Evaporation heat flux rates in most parts of West Africa tend to decrease in both past and present climatic conditions, representing the cooling effect caused by the reduction of the incoming solar radiation due to the stratospheric aerosol particles (*Robock, 2015*; *Kravitz et al., 2016*). In the humid coastal zones and parts of the southern West Africa, application of SAI has led to reduced values of evaporative heat flux, which is usually between -25 and10 W m^{-2}. This decrease poses a decrease in the volume of energy availed between the land surface and the air by the procedure of evaporation, which means it is stronger cooling impacts in these humid areas. The same cuts have been recorded in major regions of West Africa under the conditions of the future climatic scenario SSP2-4.5 and the SSP5-8.5, where the evaporative heat flux values are very low, usually between about 10 and 20 W m^{-2}. These patterns exhibit a certain cooling effect in a vast percentage of the region. Some areas however have localized variances. In the Nigeria case, the SSP2-4.5 scenario reveals that some areas of the country record a little more evaporative heat flux of approximately 15 W m^{-2} relative to the CMIP6 historical simulation which depicts moderate cooling in comparison with the adjoining areas. Conversely, isolated increases in evaporative heat flux are observed in several semi-arid areas, especially in the Guinea savannah zone. Values may approach 75 W m^{-2} in some regions, suggesting relatively weaker cooling effects. Regional variations in surface temperature, vegetation cover, soil moisture availability, and atmospheric moisture transport, all of which affect land-atmosphere energy exchanges, may be connected to these deviations. In generally, evaporative heat flux values tend to move toward ranges that are similar to those associated with previous climate conditions when SAI is introduced. The SAI adjusted values for the historical and future scenarios, such as SAI-CMIP6 (HIST), SAI-SSP245, and SAISSP585, fall between −25 and 10 W m^{-2} in many portions of West Africa. As shown in Figure 10, this trend indicates that solar geoengineering may be able to partially mitigate the effects of greenhouse-gas-induced warming by returning some parts of the regional surface energy balance toward preindustrial or historical climate state conditions.

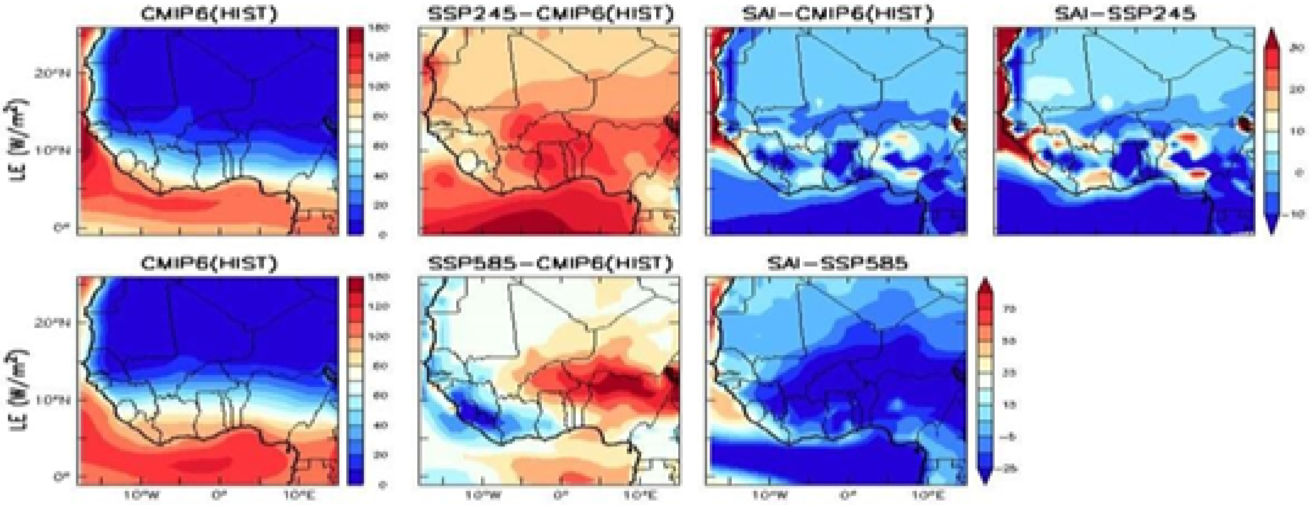


Figure 10 | Projected spatial response of evaporative heat flux to stratospheric aerosol injection (SAI) across West Africa under historical and future emission scenarios (HIST, SSP2-4.5, and SSP5-8.5).

4. | Conclusion

This study examined the spatial distribution and variability of evaporative heat flux across West Africa using ERA5 reanalysis data, CMIP6 climate model simulations, and the ARISE-SAI experiment to assess the potential influence of solar radiation management. Findings indicate a obvious, steady latitudinal gradient with the greater values of the evaporative heat flux in the wet coastal belt and lesser values in the semi-arid Sahel due to the variations in the soil moisture availability, the vegetation cover, and the environmental factors. Comparison of CMIP6 simulations of history with that of ERA5 indicates a high level of agreement in the reproduction of the observed spatial patterns of evaporative heat flux throughout the region. There are slight inconsistencies, but the scale of model bias is also rather small, ranging from -10 to +10 W m^{-2}, and so it can be concluded that the ensemble approach represents the current climate conditions quite well. Evaporation heat flux will also have some noticeable variations under future climate conditions (SSP2-4.5 and SSP5-8.5) due to variations in land-atmosphere interactions, moisture supply, and atmospheric circulation. Nevertheless, with the injection of stratospheric aerosol, there is an overall decrease in the evaporative heat flux in most of West Africa, especially in the humid and semi-humid areas, where ranges of values are normally within -25 and 10 W m^{-2}. There is a possibility of spatial heterogeneity in climate response with values reaching about 75 W m^{-2} especially in the Guinea savannah in certain localized regions. These results indicate solar radiation management can adjust the energy exchanges processes at the surface and help reduce excessive evaporative heat flux and partially recover regional climatic conditions to historical levels. This brings to attention the essence of looking at the positive aspects as well as the geographical nuances of geoengineering interventions. According to the overall findings, this paper advises the policymakers to focus on the stratospheric aerosol injection feasibility test and renewable energy implementation, planting more trees, and sustainable land use interventions. Through the regulation of evaporative heat flux, and suppression of extreme temperatures, SAI has the potential to stabilize variability in rainfall and surface energy balance, and these are paramount to rain fed agriculture in West Africa. When carefully integrated with long-term mitigation and adaptation strategies, solar radiation management could serve as a complementary approach for enhancing climate resilience, supporting food production systems, and improving water resource sustainability in the region.

Declaration of Competing Interest

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

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