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Seasonal precipitation changes in response to long-term aerosol anomalies: A case from West Africa

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ABSTRACT

In southern West Africa (SWA), highly absorbing aerosol types can significantly alter precipitation trends. Therefore, it is essential to investigate the changes in precipitation anomalies from the dry season to the monsoon season. This study examines the impact of aerosol anomalies on precipitation trends and anomalies during the pre-monsoon season in the SWA region. The study analyzed monthly datasets of aerosol optical depth (AOD_{550nm}), precipitation, and atmospheric parameters from 1981 to 2020. The results base on anomaly and MK trend tests shows a decline in precipitation trends and anomalies across most of SWA during the last two decades (2001–2020). High positive spatial AOD anomalies corresponded with negative precipitation anomaly patterns. The regression analysis indicates a strong negative spatial correlation and slope between AOD and precipitation, especially along the coasts, with statistical significance for both periods. However, precipitation did not show a statistically significant relationship with zonal wind speed, geopotential height, or relative humidity at 850 hPa, even though these parameters exhibited stronger negative correlations and slope patterns over major cities in coastal SWA during the last two decades. The decrease in pre-monsoon precipitation anomalies suggests the dominance of aerosol-saturated atmosphere, which could diminish the influence of atmospheric parameters on cloud microphysics and precipitation, likely exacerbated by proximity to the ocean. The findings highlight the possible impact on the region's hydrological system due to amplification in aerosol concentrations; therefore, policies on emission control and mitigation are encouraged.

1. Introduction

The evolving climate changes have intensified and varied precipitation patterns and streamflow, which are related to an increase in global atmospheric temperatures (Akter et al., 2019). The increased heating of the upper air can sustain substantial water vapor, leading to adverse extreme events such as droughts, flash floods, and tropical cyclones, which seriously constrain water resources and food security. More so, recent studies have noted a decline in precipitation trends (Ibebuchi and Abu, 2023; Persad, 2023; Nyasulu et al., 2024; Uwizewe et al., 2024).

The West Africa is most vulnerable to climate change impacts (IPCC, 2013). Most research on the climatology in southern West Africa (SWA) has looked at changes in the amount, frequency, and intensity of rain during the West African Monsoon (WAM) (Bichet and Diedhiou, 2018; Nkrumah et al., 2019; Okoro et al., 2019). Because agriculture in the area depends on heavy rainfall, delays at the start of rainy seasons, prolonged droughts, and strong atmospheric conditions that stop convection can have significant social and economic effects (Nicholson, 2013; Omotosho et al., 2000; Abiodun et al., 2008). The timing of the seasonal cycle is crucial for different phases of planting and farm yields (Vizy et al., 2015). The onset of pre-monsoon rainfall episodes in West

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Africa is critical for mapping food security policies because it marks the transition between an extended dry period and the onset of the WAM, which typically occurs from March to May (MAM) in southern West Africa and from May to June in the West African Sahel (Nkrumah et al., 2022). Drivers of West African climate conditions, such as the Africa easterly jet (AEJ), Tropical easterly jet (TEJ), Saharan heat low (SHL), and Intertropical convergence zone (ITCZ) have been fingered to influence the interannual variability of pre-monsoon rainfall in the region (Nicholson, 2013; Kumi et al., 2020; Nkrumah et al., 2022). Recent environmental changes have seen aerosol concentrations double over land compared to oceans (Meinrat, 2007). The weakening effect of aerosols on precipitation over wetlands might be more significant than over land (Jana et al., 2024). Increased aerosols can alter the size distribution of cloud droplets and delay raindrop formulation (Jion et al., 2024). Aerosol activities often suppress convective activity, resulting in precipitation anomalies (Jana et al., 2024), and strongly correlate with the onset of precipitation (Nyasulu et al., 2022). The AOD concentration anomalies can vary across regions and seasons (Wu, 2014; Ma and Guan, 2018; Matho Lontio et al., 2024), and is strongly associated with the decrease (increase) in rainfall trend (Yoon et al., 2010; Ali et al., 2020). A recent study had alluded that the AOD over the West African domain has shown a significant increase in concentration distribution between 0.3 and 0.8 over the recent decades (Mmame et al., 2023). Moreover, growing aerosol activities throughout the region have prompted the launch of numerous campaign projects, for example, Dynamics-Aerosol-Chemistry-Cloud Interactions in West Africa (DACCIWA) (Flamant et al., 2018), which specifically targeted the SWA region.

Several studies had made effort to investigate the impact of AOD on the precipitation over the West African region, however most of these studies presented the WAM periods. Some assessed the impacts of localized anthropogenic aerosols on WAM precipitation (Solmon et al., 2008; Lau et al., 2009; Di et al., 2015; Lavaysse et al., 2016; Menut et al., 2019) and also the effect of remote-sourced biomass-burning aerosols on WAM episodes (Sakaeda et al., 2011; Taylor et al., 2019; Ajoku et al., 2020; Pante et al., 2021). Most of these studies opined that the variation in the latitudinal shift of the WAM precipitation could be attributed to increases in aerosol emissions. However, the SWA pre-monsoon period harbors substantial suspended atmospheric dust minerals and organic carbon. To our knowledge, no study has examined the effects of long-term atmospheric aerosol anomalies on precipitation trends during this period (MAM) over SWA. Plumes from carbonaceous burning are likely elevated during this this time because their rise and persistence face minimal hindrance. When it becomes hydrophilic, it acts as cloud condensation nuclei (CCN) (Croft et al., 2005), which can impede convection and cloud formation (Huang et al., 2009; Jana et al., 2024) in the atmosphere. Also, the long period of dry spell at this season can aid the accumulation and transportation of dust minerals from source regions, leading to an increase in AOD concentration and subsequent lowering of precipitation (Berhane and Bu, 2021). It is therefore geographically unclear to what extent changes in aerosol levels will affect precipitation during an isolated wetting period. Moreover, a concern from recent research indicates a potential future decline in pre-monsoon precipitation (Deegala et al., 2023).

This study therefore intends to investigate the relationship between aerosol and precipitation anomalies over southern West Africa (SWA) during the MAM season. Aerosol radiative or microphysical effects can influence surface cooling and atmospheric heating and account for up to a 50% reduction in shortwave radiation over the SWA, which is associated with a decrease in convective processes (Huang et al., 2009; Ajoku et al., 2020). It has been shown that aerosols are highly linked with pre-monsoon onset season precipitation (Nyasulu et al., 2024). In addition to aerosols, meteorological atmospheric conditions influence cannot be isolated from the variation in moisture absorption, leading to temperature inversion and affecting precipitation trends (Grabowski, 2018; Nyasulu et al., 2024). This study further assesses the spatial relationship between low tropospheric atmospheric conditions and precipitation anomalies. The outcome of this research will elucidate the role of climate change's impact on precipitation anomalies and help to understand trend lines for future seasons.

2. Data and method

2.1. Study domain

The West African domain covers between Latitude 2°N - 25°N and Longitude 20°W - 15°E (Fig. 1). it is climatologically divided into two zones i.e., the Sahel and the Guinea coast (Ajibola et al., 2020). These climate regions is majorly influenced by two trade winds that control the location and movement of the ITCZ: the moist Atlantic wind and the dry Saharan wind (Laux et al., 2007; Nicholson, 2013). This region's climate is projected as a hotspot for extreme climate events such as drought and flooding (Nkrumah et al., 2019; Klutse et al., 2021; Ndehedehe et al., 2022). The region experiences two periods of precipitation onset: the West African Sahel experiences a single regime, while most SWA region experiences a bimodal regime (Nkrumah et al., 2022). The major onset occurs between March and May. The precipitation in the SWA is driven by the variations in moisture flux at the lower troposphere primarily due to its proximity to the Ocean (Druyan and Fulakeza, 2015) and sea surface temperatures (Nguyen et al., 2011). The SWA region covers 0°N - 10°N (latitude) and 15°W to 15°E (longitude) (Okoro et al., 2019). Fig. 1 indicates that the coastal part of southern West Africa has the highest annual mean precipitation (up to 3500 mm) from 1981 through 2020, particularly in Nigeria, Sierra Leone, Liberia, and Guinea.

2.2. Materials

The sparse network of observation stations and limited use of automatic stations in West Africa pose challenges to the quality of gridded datasets. The study uses monthly precipitation data from the Climate Hazards Group InfraRed Precipitation with Stations (CHIRPS) from 1981 to 2020. CHIRPS coverage reaches up to 50°N and 50°S latitude, with a spatial horizontal resolution of 0.05° × 0.05°. CHIRPS incorporates additional blended station data to enhance its performance

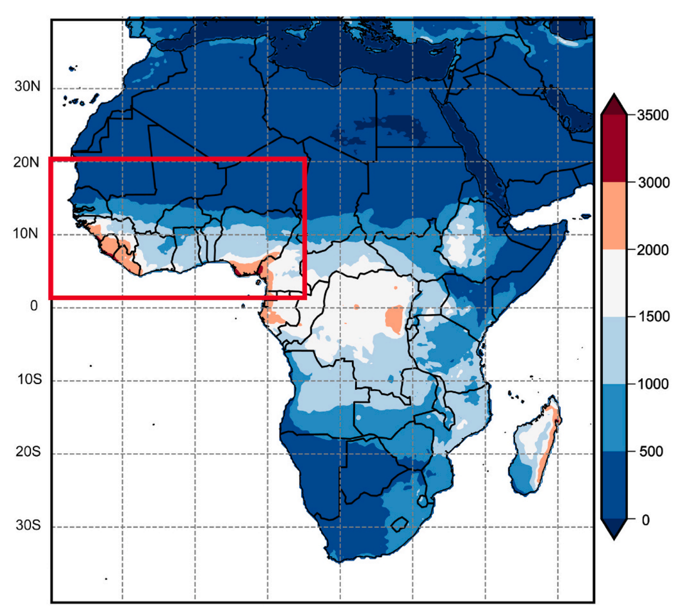

Fig. 1. Spatial distribution of annual mean precipitation (mm) from 1981 to 2020 from CHIRPS data over Africa. The rectangle red box represents the West African region. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

(funk et al., 2015). Ground/satellite gauges have validated long-term CHIRPS datasets, which have found extensive use in West Africa (Bichet and Diedhiou, 2018; Kumi et al., 2020; Nkrumah et al., 2022).

According to GMAO (2015), the Aerosol Optical Depth (AOD) data used comes from MERRA-2 and is collected every month at collection 6.1 (C 6.1) Level 3 at 550 nm wavelength and 0.5° x 0.625° spatial resolution for the years 1981–2020. NASA's online visualization tool (https://giovanni.gsfc.nasa.gov/giovanni/) provides access to these MODIS products. While the MERRA-2 product's performance varies by region, researchers consistently use it over West Africa to detect long-term trends in the atmospheric aerosol (Ajoku et al., 2020; Pante et al., 2021).

The Copernicus Climate Change Service (C3S) obtained datasets such as geopotential height, zonal wind, and relative humidity from the fifth generation ECMWF atmospheric reanalysis of the global climate (ERA5) to provide a deeper climatological perspective on the statistical relationship between atmospheric conditions and precipitation. The spatial horizontal resolution is 0.25° x 0.25° at the monthly temporal scale from the European Centre for Medium-range Weather Forecast (ECMWF) model (Hersbach et al., 2020). The CHIRPS and AOD datasets are remapped to a resolution of 0.25° x 0.25°, the same as the ECMWF datasets, so they can be used for statistical analysis (Kim et al., 2019).

2.3. Trend detection and anomaly analysis

The trend analysis describes the present (recent) and past climatic changes. To detect the changes in precipitation trends between the periods 1981–2000 and 2001–2020, a non-parametric statistical Mann-Kendal (MK) test based on the rank system is used to detect long and short-term precipitation time series trends (Hamed and Rao, 1998; Yue and Wang, 2004). Some advantages of the MK test are its low sensitivity to outliers (Gummadi et al., 2018) and can neglect of missing values without assumptions for specific distribution (Fang et al., 2015). Also, the Modified Mann-Kendall trend test is taken to account in case of auto correlation factors in the time series (Hamed and Rao, 1998). The positive or negative values indicate an increasing or a decreasing trend.

$$Mk = \Sigma_{i=1}^{n-1} \Sigma_{j=i+1}^{n} sgn(x_j - x_i) \quad (1)$$

$sgn(x_j - x_i)$ is the sign function

$$sgn(x_j - x_i) = \begin{cases} +1 \ if \ x_j - x_i > 0 \\ 0 \ if \ x_j - x_i = 0 \\ -1 \ if \ x_j - x_i < 0 \end{cases}$$

x_j, x_i are the data points where $i < j$, compare the data points and count the number of positive and negative differences.

Precipitation Anomaly analysis is used to evaluate the deviation and variation pattern of short-term MAM precipitation datasets (1981–2000 and 2001–2020) from the long-term MAM average (1981–2020). This analysis complements the precipitation trends analysis based on the identification of variation patterns between the short-term datasets.

The formula is given as

$$U_{\partial t} = U_t - \overline{U} \quad (2)$$

$U_{\partial t}$ MAM precipitation anomaly

U_t MAM precipitation dataset (1981–2000 or 2001–2020)

$\overline{U}$ MAM precipitation dataset (1981–2020)Where t = 1, 2 … n.

Note; positive precipitation anomaly indicates that the short-term precipitation period is higher than the long-term, implying wetter than normal, and negative anomaly signifies drier than normal conditions (Berhane and Bu, 2021).

2.4. Statistical analysis

The changes in precipitation in the 1981–2000 and 2001–2020 periods are assessed with specific dynamical atmospheric conditions and AOD during the same period to investigate their linkage and significance in the precipitation anomaly. The correlation coefficient, Slope, and P-value spatial statistical significance indices were used overall grid boxes in the study domain.

The correlation coefficient, r

$$r = \frac{\Sigma(x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\Sigma(x_i - \overline{x})^2 \Sigma(y_i - \overline{y})^2}} \quad (3)$$

The slope, s

$$s = \frac{\sum_{i=1}^{n}(x_i - \overline{x})(y_i - \overline{y})}{\Sigma_{i=1}^{n}(x_i - \overline{x})^2} \quad (4)$$

n is the number of grid points

x_i and y_i are the individual grid points

$\overline{x}$ and $\overline{y}$ are the means of the variables

The correlation coefficient indicates the strength of the linear relationship in variables. The slope value explains the changes in the response for an increase or decrease in the predictor, and the P-value tells if the correlation could have occurred by random chance.

3. Result

3.1. Variations in trends and anomalies of precipitation and aerosol distribution

This research looked at how the rainfall patterns in southern West Africa changed from 1981 to 2020 during the pre-monsoon seasons (MAM). It focuses on the trends and outliers in rainfall over two climate periods: 1981–2000 and 2001–2020 (Fig. 2).

In the first twenty years (1981–2000), we observed positive precipitation trends ($\leq$12 mm/yr) and anomalies ($\leq$60 mm) across most of the study domain. The only places where these trends and anomalies decreased were central Cote d'Ivoire and parts of Togo and Benin (Fig. 2a and c). However, Fig. 2b and d showed a significant reduction in precipitation during the last two decades (2001–2020), both in trend and anomaly, over the typically high wet regions of the southern West African Coast (Fig. 1), particularly in southern Nigeria, Ghana, Cote d'Ivoire, Liberia, Sierra Leone, and Guinea.

Fig. 3a (i.e., 1981–2000) showed that the entire study area witnessed negative AOD anomaly patterns ($0 < AOD \leq -0.08$). Notably, the Sierra Leone, Nigeria, Togo, Benin, and Ghana regions showed the most substantial negative spatial pattern (up to −0.08). Conversely, the last two decades showed a positive anomaly distribution across the entire SWA, with the strongest values observed (up to 0.08) over similar locations as the high negative anomaly areas (Fig. 3b). Increases in carbonaceous activities over these regions may be linked to this climatological anomaly change of AOD, particularly in areas of oil exploration fields (Nduka et al., 2016). Here, we could point out that the likely increase in local anthropogenic aerosol may have influenced the decrease in precipitation trends and anomalies in most major coastal cities (such as Nigeria, Ghana, Cote d'Ivoire, Liberia, and Sierra Leone) over the last two decades. Other studies have documented similar observations on the contributing effect of aerosol absorption on precipitation reduction due to proximity to the coastline (e.g., Perlwitz and Miller, 2010; Guhathakurta and Rajeevan, 2008; Berhane and Bu, 2021; Nyasulu et al., 2024). The season, location, and result of this study are very comparable to the results of Huang et al. (2009); however, this referred study was only for the short term. Our finding also noticed that while some regions, like Togo and Benin, experienced significant increases in AOD, they also showed positive trends in precipitation. This could suggest the influence of other local factors and warrant further investigation in future research.

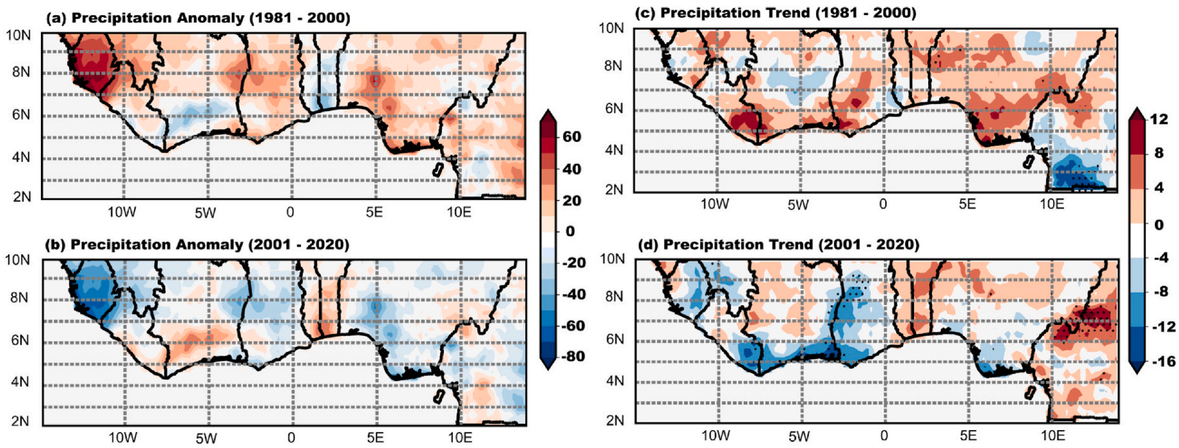

Fig. 2. CHIRPS Seasonal Precipitation during March, April, and May from 1981 to 2020. (a) 1981–2000 precipitation anomaly (mm) (b) 2001–2020 precipitation anomaly (mm) (c) 1981–2000 precipitation trends (mm/yr), and (d) 2001–2020 precipitation trends (mm/yr) over SWA.

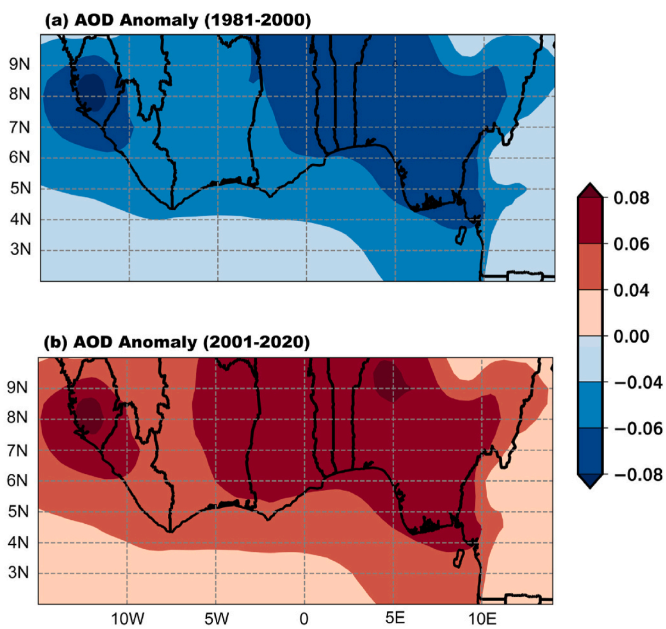

Fig. 3. Spatial distribution of AOD seasonal anomaly during March, April, and May from 1981 to 2020: (a) 1981–2000 (b) 2001–2020 anomaly.

3.2. Relationship between aerosol and precipitation changes

The effect of AOD concentration can extend cloud lifetime, potentially triggering high precipitation events (Xu et al., 2017). Still, it can also decrease precipitation when this increased AOD above the boundary layer delays raindrop formation (Jana et al., 2024). Fig. 4 describes the forty-year seasonal variation between AOD and precipitation during MAM. The first two decades (1981–2000) indicate that highest precipitation (max. approx. 5.3 mm) corresponds to lower AOD values (min. approx. 0.3), while the last two decades (2001–2020) witnessed a reversal in the variation of the temporal pattern. The last two decades have seen aerosol dominating, with a maximum AOD of up to 0.6 and maximum precipitation of approx. 4.6 mm. A study over the Sahel also alluded to the recent aerosol increase in the recent decades and was linked to precipitation decreases in the region (Marvel et al., 2020), while Ibebuchi and Abu (2023) linked this decrease in SWA precipitation to warning trends over the region. This section further examines the statistical relationships between aerosol and precipitation based on the correlation coefficient, slope, and p-value.

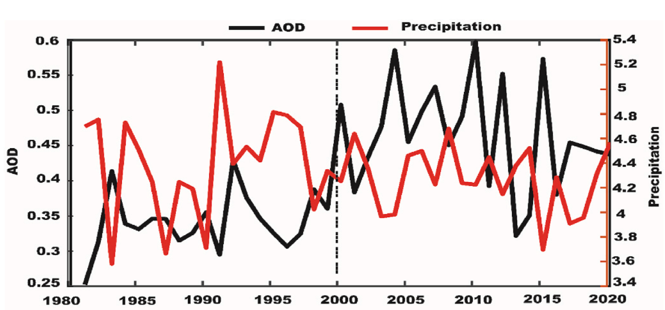

Fig. 4. Time series variation of mean seasonal AOD and precipitation (mm) during MAM period from 1981 to 2020 over Southern West Africa.

According to Fig. 5a and c, a positive correlation and slope distribution pattern was observed between AOD and precipitation in the first two decades ($r \leq 0.6$ and $s \leq 0.05\ yr^{-1}$), particularly across the western SWA region (Liberia, Sierra Leone, and Cote d'Ivoire), while a strong negative correlation and slope pattern is indicated ($r \leq -0.6$ and $s \leq -0.15\ yr^{-1}$) in parts of Nigeria and Ghana. During the last two decades (2001–2020), there was a significant spatial increase in positive correlation and slope patterns and a decrease in the negative relationship between the precipitation and AOD (Fig. 5b and d). The p-value, which determines the significance of the relationship, indicates a statistically significant distribution pattern ($p \leq 0.05$) for both the 1981–2000 and 2001–2020 periods, particularly over SWA coastal regions (Fig. 5e and f). This clearly shows a strong inverse causal relationship between aerosol and precipitation anomalies over the SWA region.

3.3. Relationship between changes in atmospheric parameters and precipitation

An unstable atmospheric condition can amplify changes in precipitation and aerosol during the pre-monsoon period (Nyasulu et al., 2024). Therefore, investigating the statistical relationship between atmospheric conditions in the lower troposphere and precipitation changes during seasons of significant aerosol concentrations could help to elucidate patterns of cohesion and responses. Fig. 6 demonstrates the relationship between relative humidity (RH) and precipitation changes. The correlation coefficient during the 1981–2000 period indicates a strong favorable spatial distribution ($r \leq 0.6$) over the entire inland and extending from the coast of Nigeria to Ghana, while a negative pattern is observed in parts of coastal Cote d'Ivoire to Liberia ($r \leq -0.6$). However, in the last two decades, Nigeria, Ghana, Cote d'Ivoire, and Liberia experienced more spread in negative correlation pattern and slope ($r \leq$

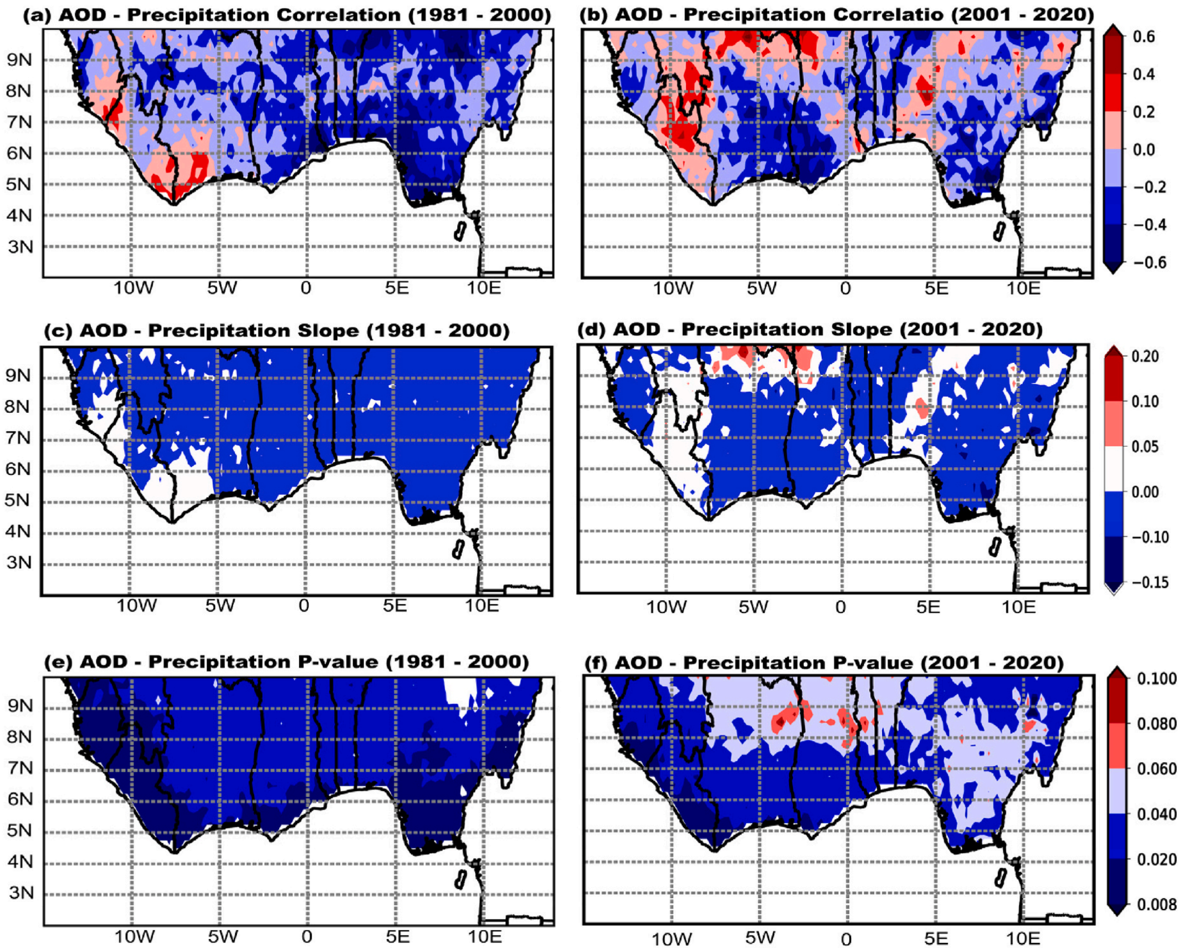

Fig. 5. Spatial relationship between AOD and Precipitation from 1981 to 2000 and 2001–2020. (a & b) Correlation coefficients, (c & d) slope (yr^{-1}), and (e & f) P-value statistical significance.

-0.6 and $s \leq -4$ mm/%) between RH and precipitation (Fig. 6b and d). Notably, the study observed a decrease in positive correlation spatial patterns during this period compared to the first two decades; also, their p-value distribution pattern ($p > 0.05$) is not statistically significant (Fig. 6e and f).

Geopotential height (GH) is an essential atmospheric dynamic that determines the mass of water vapor in the atmosphere. Studies (Türkeş, 1998; Tymvios et al., 2010; Okoro et al., 2019) have found that GH anomalies influence fluctuations in precipitation changes. Fig. 7 shows the plot of GH and precipitation changes. The first two decades witnessed a positive correlation coefficient and slope ($r \leq 0.6$ and $s \leq 75$ mm/m respectively) spread over most southern and inland parts of Nigeria and Ghana, as well as isolated coastal parts of Cote d'Ivoire. Over the last two decades, a more significant negative correlation coverage has been observed across southern Nigeria and Ghana ($r \leq -0.6$ and $s \leq -75$ mm/m respectively) (Fig. 7b and d). The p-value distribution indicated that there was no statistically significant relationship ($p > 5$) between GH and precipitation changes across the entire study period and domain (Fig. 7e and f).

Zonal wind speed (ZWS) plays a crucial role in influencing rainfall patterns through mechanisms such as moisture transport. ZWS can also carry pollutants from their source to remote regions, thereby affecting precipitation changes in those areas (Berhane and Bu, 2021; Nyasulu et al., 2024).

Fig. 8a and c shows that during the 1981–2000 period, a positive correlation coefficient and slope spatial pattern ($r \leq 0.6$ and $s \leq 1.2$ mm/ms^{-1} resp.) are largely observed over Nigeria and Ghana, while a negative spatial distribution ($r \geq -0.6$ and $s \leq -1$ mm/ms^{-1}) is seen from Cote d'Ivoire to Sierra Leone. In the 2001–2020 phase, negative correlation spread ($r \geq -0.6$) was largely observed over the southern regions of Nigeria to Liberia, with a general decrease in the positive correlation and slope relationship. Against earlier observations in Figs. 6 and 7, we note that the coastal regions of Togo and Benin indicate negligible spatial correlation and slope changes between both periods. The p-value distribution indicated no statistically significant relationship ($p > 0.05$) between ZWS and precipitation changes (Fig. 8e and f).

4. Discussion

Changes in cloud properties and particle interactions during the West African pre-monsoon (MAM) season in West Africa contribute to the depletion of the latitudinal precipitation band, typically located along the Southern West African Coast in June before shifting northward to the Sahel. Coastal activities such as oil exploitation, gas flaring, and the advection of biomass-burning aerosols from Central Africa have been suggested to be responsible for the increasing dominance of anthropogenic pollutants in the region over the past two decades (Nduka et al., 2016). These anthropogenic aerosols in the high troposphere exhibit higher heating efficiency than natural dust (Talukdar et al., 2019), which could diminish the lapse rate, inhibiting cloud precipitation processes (Jana et al., 2024).

Fig. 1 demonstrates that the longer duration of the ITCZ in the SWA region contributes mostly to the entire West African total precipitation amount. Studies, however, have reported that the West African Sahel has been experiencing more precipitation than SWA after the 1970s and 1980s drought episodes. Researchers have attributed this recovery to the

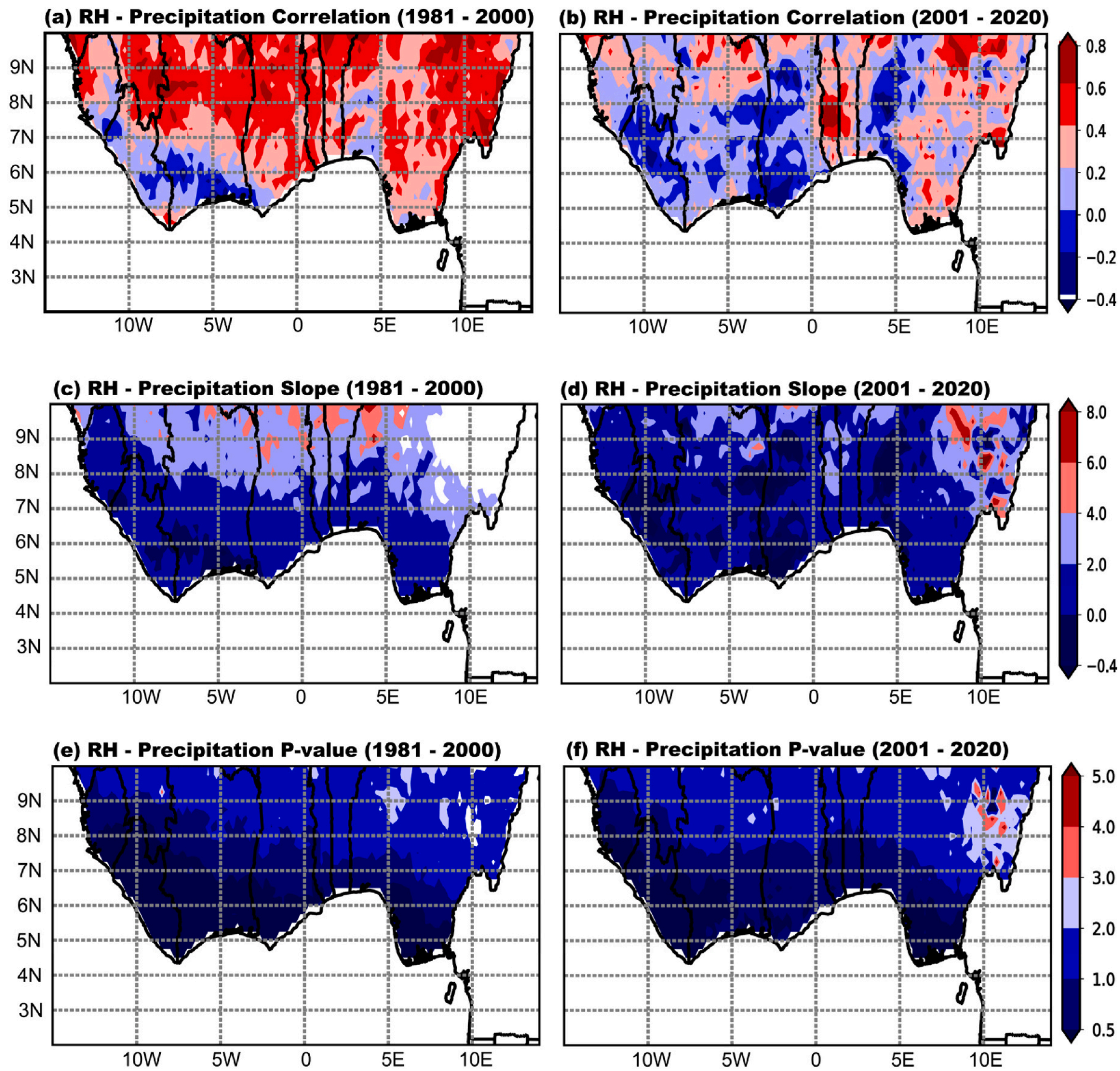

Fig. 6. Spatial relationship between Relative humidity and Precipitation from 1981 to 2000 and 2001–2020. (a & b) Correlation coefficients, (c & d) slope (mm/%), and (e & f) P-value statistical significance.

direct influence of anthropogenic aerosols (Biasutti, 2013; Dong and Sutton, 2015), sea surface temperature anomalies (Biasutti, 2019), and natural variability (Mohino et al., 2011). Nonetheless, there has been a lack of detailed investigations into the possible distortion of the SWA precipitation system due to particle infiltrations during the pre-monsoon period, which is dominated by elevated aerosols (Huang et al., 2009).

The AOD anomaly analysis revealed a contrasting anomaly between the studied periods (i.e., 1981–2000 and 2001–2020) (Fig. 3). During these periods, the increase (or decrease) in AOD anomalies over the inland areas does not significantly change the precipitation trend and anomalies. This observation aligns with findings elsewhere (Berhane and Bu, 2021; Nyasulu et al., 2024; Jana et al., 2024) that the weakening effect of aerosols on convection is more significant over coastal regions than inland areas. A further collaboration in Trenberth (2011), posited that aerosols acting as cloud condensation nuclei (CCN) help retain more water vapor, increasing precipitation in wetter regions. Also, our results show that the SWA precipitation responded with more negative spatial distribution anomalies and trends to the increase in AOD concentration, particularly in the recent two decades over Cote d'Ivoire, southern and central Nigeria, Liberia, Ghana, Guinea, and Sierra Leone. Interestingly, the study notes a positive precipitation response to AOD increases over small regions of Togo and Benin. This may support the local influence of anthropogenic aerosols on precipitation (Knippertz et al., 2015; Menut et al., 2019). This influence could stem from population growth to increased regional coastal activities (United Nation, 2019; Pante et al., 2021). Moreover, studies on pre-monsoon precipitation have reaffirmed that local factors other than aerosols can influence precipitation patterns (Haghtalab et al., 2019; Nyasulu et al., 2024).

The response changes in precipitation could be evident, as indicated in the AOD/precipitation relationship, which is statistically significant ($p < 0.05$) along the coasts of the study areas during both periods. In addition, the strong negative correlation and slope patterns seen in SWA correspond to places where precipitation patterns and trends have decreased, especially in the last two decades (2001–2020). This reiterates the opposite response relationship between precipitation and aerosols established in previous investigations (Ajoku et al., 2020; Berhane and Bu, 2021; Pante et al., 2021; Nyasulu et al., 2024). The study found an increase in the negative correlation and slope relationships between RH, ZWS, and GH with precipitation from the first two to the last two decades, particularly over southern Nigeria and Ghana. This indicates negative feedback from these atmospheric conditions in these locations, as we observed a decrease in precipitation anomalies.

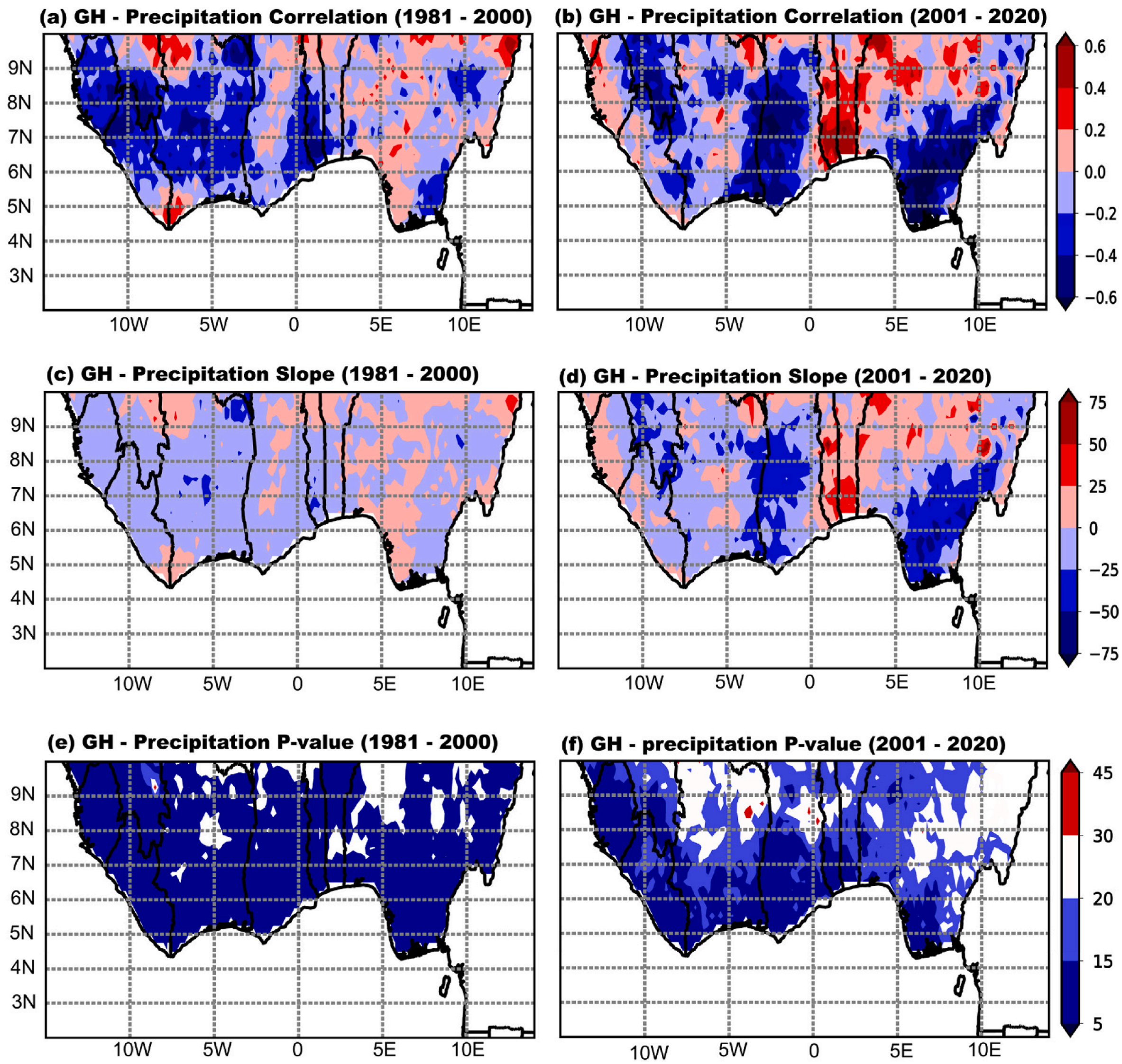

Fig. 7. Spatial relationship between Geopotential height and Precipitation from 1981 to 2000 and 2001–2020. (a & b) Correlation coefficients, (c & d) slope (mm/m), and (e & f) P-value statistical significance.

Moreover, in both analysis periods, their relationships were not statistically significant ($p > 0.05$). This finding suggests that changes in aerosol concentration, rather than fluctuations in atmospheric conditions at low tropospheric levels, are more responsible for long-term precipitation anomalies.

Notwithstanding, some of these atmospheric parameters play a crucial role in determining the sources of aerosol emissions and their transport (Berhane and Bu, 2021; Nyasulu et al., 2024; 2024). However, our finding suggests that some aerosols, particularly the hygroscopic types, can impede atmospheric instabilities. This could be due to the short lifespan of most particles in dry air, and hence, their exposure to high moisture could potentially weaken zonal winds and reduce the advection of moist air mass. This assertion supports that of Nyasulu et al. (2024) that the aerosol concentration has been the main influencing factor in rainfall reduction, even when other convective system conditions were favorable. Therefore, the study established that changes in aerosol anomalies alone may primarily affect the entire hydrological processes over the SWA region during the pre-monsoon period. The present study is however limited in countifying the aerosol types, such as dust particulate, carbons, or sulfates that inhibit the precipitation processes, as the relationship is determined by the total concentration of aerosols over the domain. Further studies are therefore necessary to classify the dominant aerosol type that influences precipitation over the study domain, which can help to understand its source emissions and establish suitable measures that control aerosol effects. The major drivers of aerosol anomalies were seen as the main concern in assessing AOD total column concentration (He et al., 2018; Chatterjee et al., 2020; Xu et al., 2024). Furthermore, application of models that simulate precipitation by combining chemical processes in the atmosphere is required, which can help to quantify the contribution of aerosols in predicting precipitation over the region. Also, investigating the interaction of the planetary boundary layer with surface emissions and its evolution can boost understanding for predicting aerosol lifetimes.

5. Conclusion

Previous investigations into precipitation anomalies related to aerosol impacts have primarily focused on the West African Monsoon (WAM). It is well known that the location of the West African domain is especially susceptible to the intrusion of carbonaceous or sea salt aerosols from coastal regions and soil dust particles from the Sahara Desert, particularly during periods of solitary rainfall. Hence, we investigated the impact of aerosol concentration anomalies on long-term precipitation changes during the pre-monsoon period in southern West Africa.

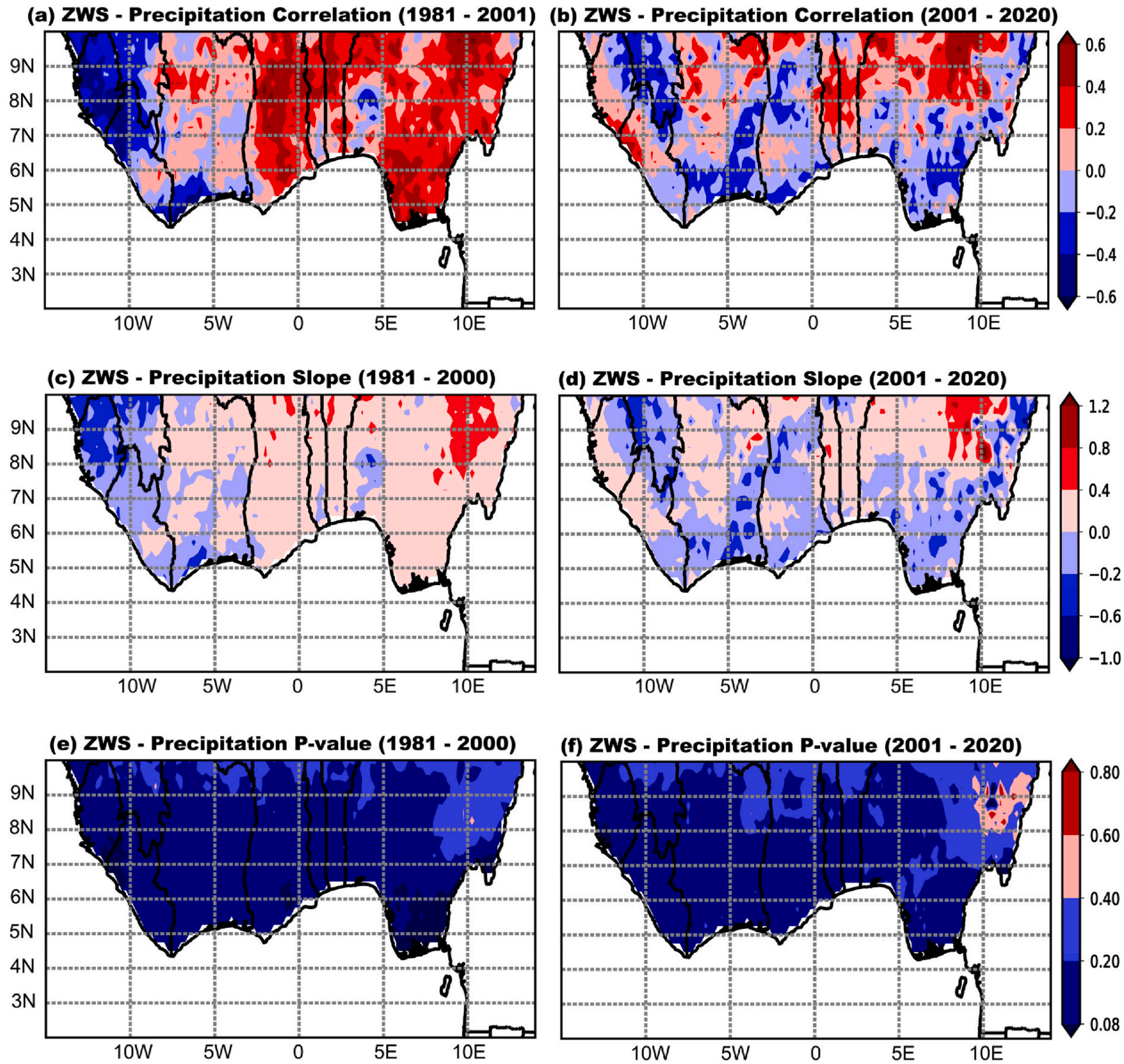

Fig. 8. Spatial relationship between Zonal wind and Precipitation from 1981 to 2000 and 2001–2020. (a & b) Correlation coefficients, (c & d) slope (mm/ms^{-1}), and (e & f) P-value statistical significance.

Our findings reveal the following.

1. There was a significant decrease in precipitation anomalies and trends over major coastal regions in southern West Africa during the last two decades (2001–2020) compared to the first two decades (1981–2000). Increases or decreases in aerosol concentration levels, rather than variations in atmospheric parameters, primarily influenced the observed precipitation anomalies in southern West African regions (such as Nigeria, Ghana, Cote d'Ivoire, Liberia, and Sierra Leone) in an inverse relationship. Notably, the aerosol-precipitation relationship was statistically significant ($p < 0.05$).
2. This finding challenges the traditional narrative that wet regions will become wetter and dry areas drier. In this instance, suspended aerosols seem to have absorbed isolated pre-monsoon precipitation, therefore reducing the penetration of shortwave radiation, inhibiting cloud formation, and lowering precipitation through aerosol-cloud-precipitation interactions across this typical high-precipitation regions.
3. In the recent two decades, there has been a significant spatial increase in the negative correlation and slope relationship between precipitation and atmospheric conditions in coastal southern West Africa, coinciding with a positive anomaly pattern in aerosol concentrations. This suggests a negative feedback mechanism between precipitation and atmospheric parameters, indicating that the type of aerosol emissions (e.g., hygroscopic aerosols) might have influenced the transport and advection of dry or moist air masses.
4. A presumable concern of local factors such as urban land-use effects dominating over aerosol emission in modulating the location and amount of precipitation. This could be identified as one of the elements contributing to the negative feedback resulting from positive (negative) aerosol and precipitation anomalies observed in regions such as southern Benin and Togo.

The findings from this study signal that the increasing warming trend might continue to influence the variability in aerosol concentration anomalies. As a result, the concern over a potential decrease in pre-monsoon precipitation trends linked to increased aerosol levels could have significant implications on agricultural practices and the entire WAM event (i.e., onset, duration, and cessation periods). Therefore, mitigation measures need to be implemented to address artificial coastal activities.

CRediT authorship contribution statement

Anselem Onyejuruwa: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Zhenghua Hu:** Writing – review & editing, Supervision, Methodology. **Abu Reza Md Towfiqul Islam:** Writing – review & editing, Validation, Supervision. **Matthews Nyasulu:** Software, Data curation. **Kyaw Than Oo:** Validation, Methodology.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Data availability

CHIRPS, AOD and ERA5 data are available in public domain.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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