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How has aridity changed over West Africa in the past four decades?

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ABSTRACT

Notable dryland expansion from changes in global aridity has been documented in previous studies, particularly with the increase in global mean temperature. Here, we examined the changes in the aridity of the western region of Africa over the past four decades. Using the aridity index (P/PET) as an indicator, the Climate Research Unit (CRU TS) data was used to identify drying and wetting areas of the region. The result showed that intense warming of 0.018 °C per year has occurred which was more evident in the last two decades. The warming in the past two decades caused a significant increase in PET. The first two decades were the driest compared to the last decades, particularly the first decade which also had major drought occurrences across the region. The aridity index increased by 0.86 (x10^{-3}) per year within the past four decades, with the greatest change at the semi-arid zone. Result showed that precipitation exerts dominant control on aridity changes in the region despite a significant increase in PET. This was evident in the expansion of the wet areas between 2000 and 2019 compared to the 1979–1998 period.

1. Introduction

The environment we live in is experiencing several changes due to natural and human-induced factors. Changes in climate due to increased levels of atmospheric CO_2, which lead to warming of the earth's climate, is an issue of concern in our world today. The warming of the earth has been accompanied by changes in precipitation (Adler et al., 2017; Nguyen et al., 2018) which has also impacted the hydrological extremes such as droughts and flooding (IPCC et al., 2014). These changes affect the environment with threat to water resources planning and management (Singh et al., 2014).

Defined using the aridity index as areas where the precipitation to potential evapotranspiration ratio is less than 0.65, drylands are regions characterized with low annual precipitation and high potential evapotranspiration (Mortimore, 2009). Drylands cover about 46.2% of the global terrestrial areas (Mirzabaev et al., 2019), with one-third of the global population (Mortimore, 2009). With the increase in global temperature and changes in precipitation patterns, changes in aridity have been observed, with some areas getting drier and others getting wetter (Asadi Zarch et al., 2015; Huang et al., 2016). Global aridity increased as a decreasing trend in aridity index was observed between 1948 and 2005 and about 66% of the globe land area became drier (Huang et al., 2016). Dai (2011) also documented an increase in global aridity since the 1970s, attributing it to the drying over several regions of the globe. Studies also indicate that continuous warming in the 21st century will lead to increase in potential evapotranspiration, which exceeding precipitation will cause increased drying (Dai, 2011; Sherwood and Fu, 2014; Asadi et al., 2017).

Drylands have also expanded and the expansion is projected to continue in the current century (Feng and Fu, 2013). The expansion of drylands is regarded as one of the effects of global warming (Feng and Fu, 2013; Huang et al., 2016). Although drylands have generally become drier, the aridity pattern has shown varying spatial changes (Li et al., 2019; Daramola and Xu, 2022). Li et al. (2019) reported distinct spatial heterogeneity in the changes in aridity and drying and wetting areas indicating varying responses to climate change. For example, the regions of Northern Africa, East Asia, Eastern Australia, and the Southern part of Europe have become drier since the late 1940s, while some other regions

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like the western part of Australia, North America, and South America have become wetter (Feng and Fu, 2013). Ahmed et al. (2019) showed a greater percentage of the Pakistan region, a predominantly dry region, has become wetter as the aridity trend decreased. An expansion of the arid lands in Iran was reported by Pour et al. (2020) due to increasing aridity. Over China, some studies have also reported aridity changes and the effect in the region (Liu et al., 2013; Li et al., 2017). These studies revealed the controlling factor of precipitation and temperature on the aridity changes, with one effect dominant over the other.

Aridity changes with rising temperatures, and a fast-expanding global population, particularly in drylands, intensifies associated risks, including land degradation and desertification (Huang et al., 2016) with implications on the sustainability in the regions. Close to 20% of drylands are reported to have experienced severe land degradation, which is also expected to increase with changes in climate and population growth (Reynolds et al., 2007). Of particular emphasis is the dry areas in the developing countries, which account for close to 90% of the global dryland population (UN, 2011). Increasing aridity in these countries has far-reaching impacts, as it could lead to a number of issues, like increased food insecurity, poverty, migration, conflicts, and political instability (Prâvâlie et al., 2019).

West Africa is a region composed of several developing countries and is vulnerable to changes in climate as a result of high climate variability coupled with inadequate economic and institutional coping capacity (Quenum et al., 2019). Over west Africa, a number of studies have examined climate variability and dryness-related issues from observation and future projections (Diasso and Abiodun, 2017; Diedhiou et al., 2018; Quenum et al., 2019; Nouaceur and Murarescu, 2020). These studies focused on droughts occurrences and dry/wet spells across the region, and no particular emphasis has been made on the changes in aridity and expansion or shrinking of the dry/wet zones. Assessing these changes is crucial for understanding the shifting nature of the regional aridity with changes in climate. Expansion of dry areas in the region may increase the population vulnerable to water shortage and land degradation with agricultural and economic implications.

In this study, we examined the changes in aridity over the western region of Africa over the past four decades. Also, we assessed the recent changes in the regional climate in terms of precipitation and temperature variation. We evaluated the contribution of the climatic factors to the changes in aridity with a particular focus on the enhanced warming years. This study provides an assessment of the recent changes in the dry/wet conditions over the west African region, which has implications on the sustainability of life in the region.

2. Materials and methods

2.1. Study area

The western region of Africa is the focus area for this study, located at latitude 0°N – 20°N and longitude 17°W – 20°E (Fig. 1). West Africa comprises 16 countries with a total area of close to 6 million square Km and a population of over 381 million people, making up one-quarter of Africa and close to 5.16% of the global population (Jalloh et al., 2013). The region has complex geometry with high elevation areas in the eastern part and a few areas in the western part, which influence the region's climate.

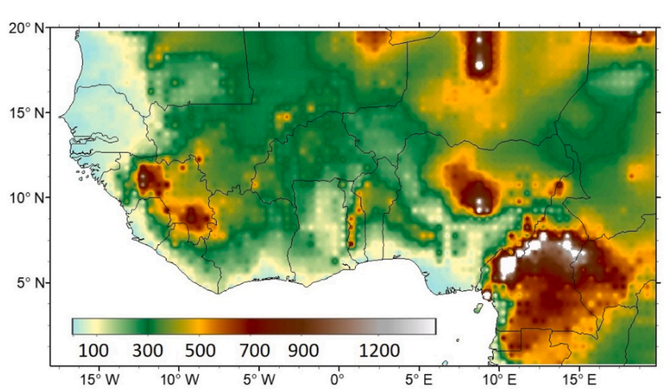

Fig. 1. Map of West Africa showing the elevation (m).

2.2. Data

We used the gridded data from the Climate Research Unit (CRU TS) for this study. This consists of global monthly time series data derived from a worldwide network of ground observation stations and has a spatial resolution of 0.5° (Harris et al., 2020). It is an extensively used dataset for climate studies at global and regional levels. The variables temperature, precipitation, and potential evapotranspiration were obtained from the recent version (CRU TS v. 4.05) over a period of forty-one years between 1979 and 2019. Land cover data was obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS).

2.3. Aridity index classification

To assess the dry-wet conditions, we used the Aridity Index (AI). AI is the ratio of precipitation and potential evapotranspiration (P/PET), which characterizes the available rainfall in relation to the atmospheric evaporative demand (Feng and Fu, 2013). The precipitation and PET data from CRU TS were used to obtain the aridity index and classified into the hyper-arid, arid, semi-arid, dry subhumid, and humid zones following the AI classification (Table 1).

2.4. Contribution of factors to AI change

The contributions of both precipitation and PET were estimated using the following equation following Feng and Fu (2013);

$$\Delta AI = \frac{\Delta P}{PET} - \frac{P(\Delta PET)}{PET^2} + \frac{P(\Delta PET)^2}{PET^3} \quad (1)$$

Where ΔAI represents the change in P/PET, the contribution of precipitation to P/PET is the first term on the right-hand side (ACP) and the other two represent the contribution of PET (ACPET).

2.5. Trend analysis

The significance of monotonic trend can be determined using several non-parametric methods, including the Mann Kendall test (Mann, 1945; Kendall, 1975), Spearman's rho test (Spearman, 1904; Lehmann, 1975; Sneyers, 1990), Onyutha test (Onyutha, 2020), and Sen's Innovative Trend method (Şen, 2012). The main advantage of the non-parametric methods is that they are not affected by the assumption of normality of the data as required by the parametric approach. Each of the non-parametric methods has its advantages and disadvantages. Here, we chose the Mann-Kendall test, a non-parametric test, for brevity and robustness. The Mann kendall trend test has been extensively used over West Africa for detecting trends in hydrological and climatic time series, such as precipitation and evapotranspiration (Akinsanola et al., 2018; Ndehedehe et al., 2018; Adeyeri and Ishola, 2021). For the variables, the

Table 1
AI classification and area coverage for each zone.

Classification	Zone	Area (10^4 Km^2)	Percentage (%)
0–0.05	Hyper-arid	2.01	16
0.05–0.2	Arid	2.65	21
0.2–0.5	Semi-arid	2.13	17
0.5–0.65	Dry SubHumid	0.81	6
>0.65	Humid	5.05	40

Mann Kendall trend was calculated using the following equations;

$$\text{Statistic}, S = \sum_{i=1}^{n-1}\sum_{j=i+1}^{n}\text{sign}\left(x_j - x_i\right) \quad (2)$$

where,

$$\text{sign}\left(x_j - x_i\right) = \begin{cases} -1, \text{if } \left(x_j - x_i\right) < 0 \\ 0, \text{if } \left(x_j - x_i\right) = 0 \\ 1, \text{if } \left(x_j - x_i\right) > 0 \end{cases} \quad (3)$$

The Statistic, S is asymptotically normally distributed which under the null hypothesis is as follows;

$$E(S) = 0 \quad (4)$$

$$\text{Var}(S) = \frac{n(n-1)(2n+5) - \sum_{b=1}^{a} t_b(b-1)(2b+5)}{18} \quad (5)$$

n represents the number of data points, x_j and x_i are the values for each year in the times series i and j, a represents the total number of tied groups, t_b is the number of ties with b.

$$\text{Statistic}, Z = \begin{cases} \frac{S-1}{\sqrt{\text{Var}(S)}}, \text{if } S > 0 \\ 0, \text{if } S = 0 \\ \frac{S+1}{\sqrt{\text{Var}(S)}}, \text{if } S < 0 \end{cases} \quad (6)$$

This tests for significance in the trend, which is indicated by the positive and negative values when compared against the critical values $(Z_{1-\alpha})$

Sen's slope (Theil, 1950; Sen, 1968) was used to determine the extent of change in the trends;

$$\text{Sen's Slope}, \beta = \text{median}\left(\frac{x_j - x_i}{j - i}\right), i < j \quad (7)$$

3. Results

3.1. Distribution of AI and temperature trend across AI

The annual mean aridity index and precipitation over West Africa is shown in Fig. 2. The spatial distribution reveals a latitudinal gradient of wet-dry conditions over the region. Precipitation and AI decrease with latitude as the wetter areas are predominant over the southern region and drier areas towards the Northern part. The southern part of the region is bordered by the Atlantic Ocean, which influences the monsoon and rainfall distribution of the region. The precipitation distribution, which plays a key role in the aridity condition, is largely controlled by the seasonal movement of the Inter-Tropical Discontinuity (ITD) (Nicholson, 2013). The latitudinal variation and resident time of the ITD over an area primarily account for the precipitation activity over the area (Nicholson, 2013). For example, the southern part experiences a bimodal pattern of rainfall while the northern part experiences a unimodal pattern with more precipitation in the south than in the north.

No vegetation characterizes the drier areas, while the wetter areas in the south are marked by the savanna and forests, as revealed by the land cover distribution (Fig. 2c). Following the classification of AI, the West Africa region is mostly dominated by the humid zone (Table 1), which has an area coverage of 5.05×10^4 Km^2, representing 40% of the region. Hyper-arid represents 16%, arid 21%, semi-arid 17%, and dry subhumid 6% coverage for the dryland zones.

As expected with the recent warming in global climate attributable to increased atmospheric CO_2 concentrations and other natural forcings (IPCC, 2013), the region has also experienced significant warming within the past four decades (Fig. 3). Over the past four decades, the region has warmed by 0.018 °C/year. Relative to the base period, the recent years from 2001, have warmed more than the previous years. We examined the change in temperature across the aridity zones and observed a greater temperature increase at the drier areas which decreased along the aridity gradient. Classifying the AI to different zones, the temperature increased by 0.019 °C/year at hyper-arid and arid zones, 0.018 °C/year at the semi-arid and dry subhumid zones, and 0.017 °C/year at the humid zone.

3.2. Aridity index anomaly and trend

The decadal anomaly of AI is shown in Fig. 4. Relative to the base period, the first decade was the driest compared to the other decades with notable dryness along the western parts. The dry condition changed in the second decade with above average conditions in previously dry areas. However, below average (dry) conditions persisted in some parts along the southwestern area. In the third decade, most areas experienced an increase in wet conditions. In the fourth decade, this was also a similar condition, with increased wet conditions observed across large areas except along the southern region. Splitting the decadal anomaly by

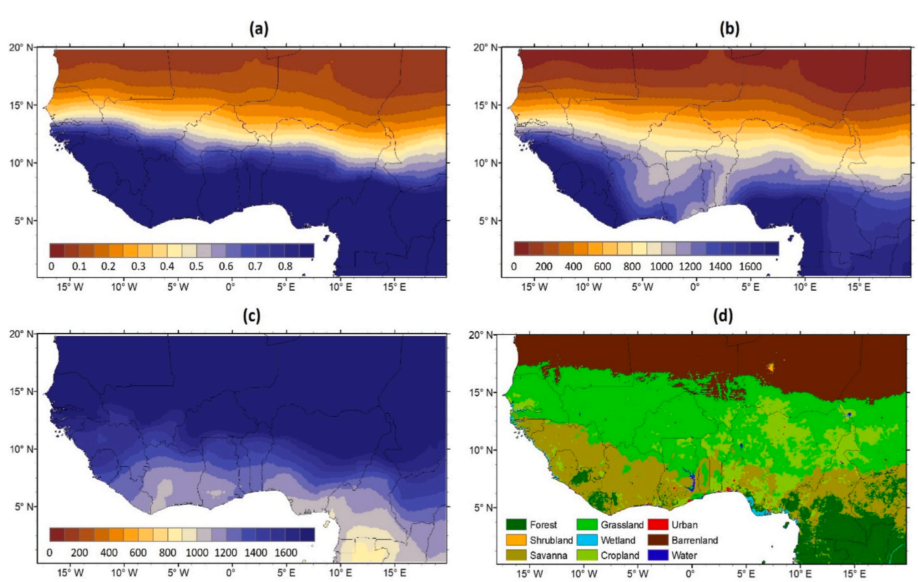

Fig. 2. Mean annual distribution of (a) AI, (b) precipitation (mm) (c) potential evapotranspiration (mm) and (d) land cover distribution of across West Africa.

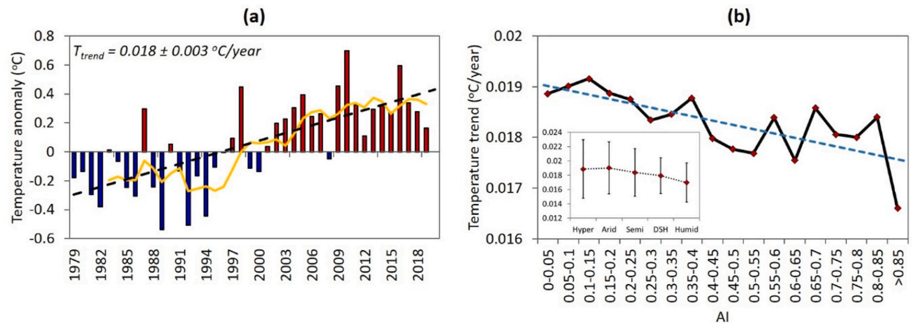

Fig. 3. (a) Temperature anomaly over West Africa from 1979 to 2019 using the base period 1981–2010. The Dash line represents the trend line; the solid yellow line represents the 5-year moving average, (b) Temperature trend across aridity index.

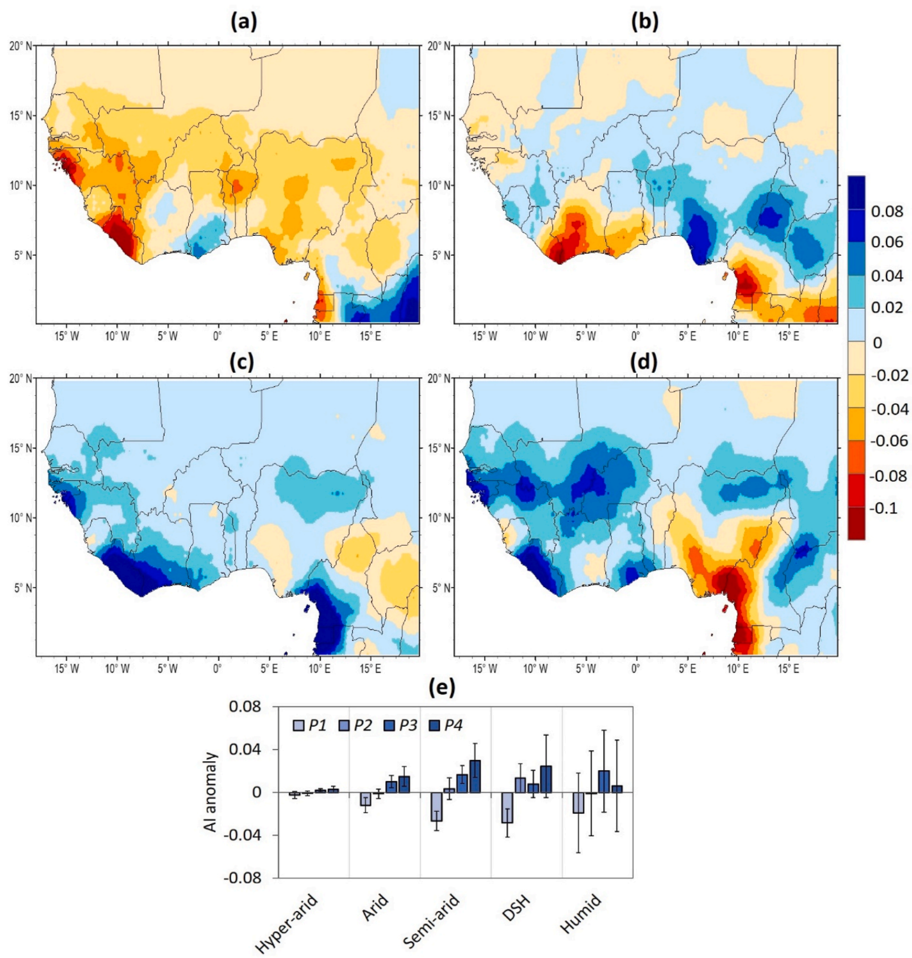

Fig. 4. Decadal anomaly of aridity index (a) 1989–1988, P1 (b) 1989–1998, P2 (c) 1999–2008, P3 (d) 2009–2019, P4 and (e) across the zones.

zones, decreased aridity (dry condition) was dominant in decade 1, with most dryness occurring at the dry subhumid (−0.029) and semi-arid (−0.028) zones. The dry subhumid experienced the most wetness in the second decade (0.013), while the other zones except semi-arid experienced decreased aridity. All the zones experienced increased aridity at the third and fourth decade, with the most wetness observed at the semi-arid in the fourth decade. For the whole region, AI anomaly was −0.017, 0.0006, 0.014 and 0.013 at the first, second, third, and fourth decades. Continuous wetness was observed at the hyper-arid, arid, and semi-arid zones from the first to the fourth decade.

The changes in AI and the contributions of precipitation and PET are shown in Fig. 5. Attributing the changes in AI to the contribution of precipitation and PET, the decrease in precipitation and PET contributed to the decrease in AI in the first two decades. Although PET decreased, the decrease in precipitation had a more dominating effect on the change in AI, which caused AI to decrease. In the last two decades characterized by enhanced warming, PET increased, contributing to the decrease in AI. However, due to the increase in precipitation, AI increased. The changes in precipitation dominated and contributed more to the changes in the AI than changes in PET at both periods.

Fig. 6 shows the spatial trend of AI, precipitation, and potential evapotranspiration (PET) across West Africa for the entire period. The result reveals an extensive increase in aridity index, indicating wetter conditions across the region. Significant increase in aridity occurred

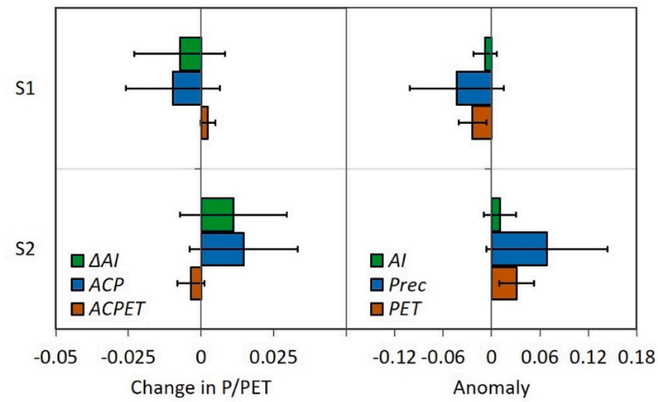

Fig. 5. Changes in AI and the contributions of precipitation and PET at two different periods. S1 represents 1979–1998, S2 represents 2000–2019.

mostly between 10°N and 18°N, which falls within the arid to dry subhumid zones. Although large-scale increase in aridity index occurred, some parts experienced dry conditions, such as the southeastern part of Nigeria. The change in AI across the zones showed the most increase at the semi-arid (0.0017). At the hyper-arid, AI increased by 0.00014, 0.00083 at the arid, 0.0015 at the dry subhumid, and 0.00014 at the humid zone. The spatial trend of precipitation reveals a similar pattern with that of aridity, as precipitation increased over most parts of the region. Precipitation increased significantly predominantly across the region except in the southern parts. The change in precipitation was 0.35 mm/year at the hyper-arid, 1.93 mm/year at the arid, 3.6 mm/year at the semi-arid, 2.9 mm/year at the dry subhumid and 1.63 mm/year at the humid zone. For PET, the spatial trend showed increased PET across most parts of the region, with the most increase towards the north-eastern and western parts of the region. Across the zones, PET increased the most at the hyper-arid (1.29 mm/year). The change in PET was 0.9 mm/year at the arid, 0.73 mm/year at the semi-arid, 0.64 mm/year at the dry subhumid, and 0.35 at the humid zone.

3.3. Variation in the areal coverage for each zone

The interannual variation of the area coverage for each zone is shown in Fig. 7. It is shown that the area coverage of the zones has changed within the past four decades. The humid zone increased by 0.007×10^4 Km^2 per year within this period, indicating an increase in the wet regions and a decrease in the dryland areas. Semi-arid and dry subhumid zones increased by 0.0067×10^4 Km^2 and 0.0024×10^4 Km^2 per year, while the hyper-arid and arid zones decreased by -0.0099×10^4 Km^2 and -0.0017×10^4 Km^2 per year. In general, the dryland areas of the region experienced a decrease in the area coverage of -0.0062×10^4 Km^2 per year. Taking two periods and comparing the change in area coverage (Table 2), it was observed that hyper-arid and arid zones decreased by -0.28×10^4 Km^2 and -0.02×10^4 Km^2, representing a 12%

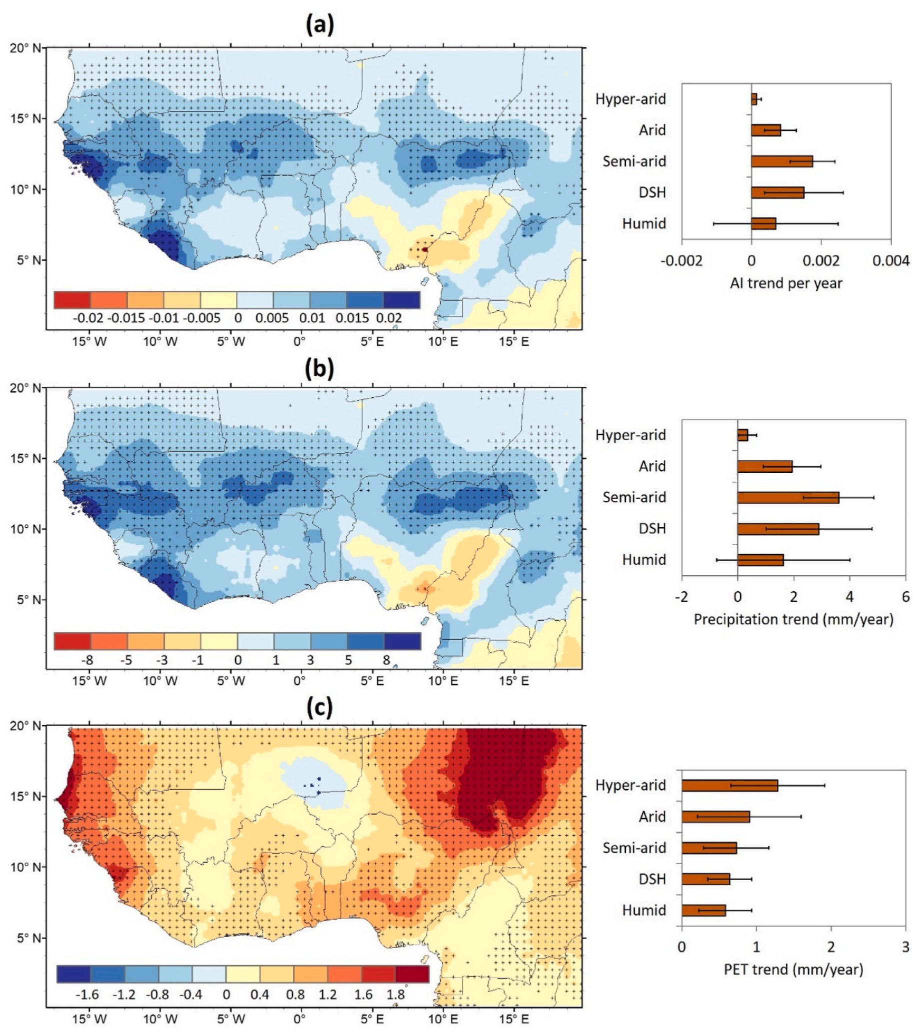

Fig. 6. Trend of (a) AI, (b) precipitation (c) PET across West Africa and the different zones between 1979 and 2019.

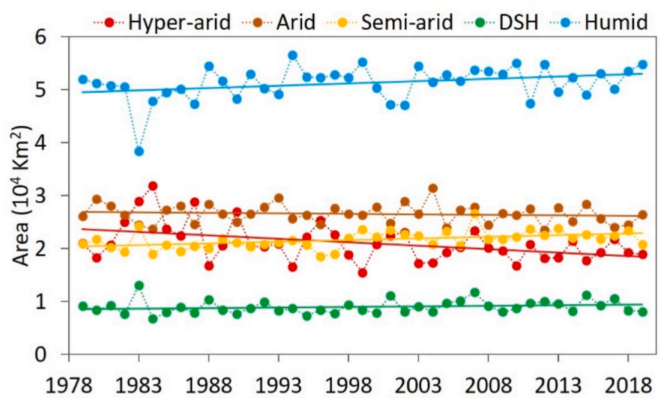

Fig. 7. Temporal variation of the area extent of aridity index zones.

Table 2
Changes in area coverage for each zone at two different periods.

	Hyper-arid	Arid	Semi-arid	DSH	Humid
1979–1998	2.26	2.66	2.06	0.87	5.06
2000–2019	1.98	2.65	2.26	0.93	5.18
Difference (%)	−0.28 (−12%)	−0.02 (−1%)	0.19 (9%)	0.06 (7%)	0.12 (2%)

and 1% decrease respectively between the 1979–1998 and 2000–2019. Semi-arid, dry subhumid and humid zones increased by 0.19×10^4 Km^2, 0.06×10^4 Km^2 and 0.12×10^4 Km^2, representing a 9%, 7% and 2% increase in the area coverage respectively. The most change occurred at the hyper-arid with a change from 2.26×10^4 Km^2 to 1.98×10^4 Km^2.

4. Discussion

Previous studies across different regions have reported changes in the regional aridity, such as the intensified aridity observed in the Volta River basin (Oguntunde et al., 2006), Togo (Koffi and Komla, 2015) and Rwanda (Muhire and Ahmed, 2016). Here, we assessed the changes in dry-wet conditions over the western part of Africa over forty-one years between 1979 and 2019 and the areal changes associated with the dry-wet conditions. We used the aridity index (AI) as an indicator and classified the region into zones based on the AI classification. Based on the region's climatology, the dryland areas cover approximately 60% of the entire region, with the arid zone as the largest area of the dryland. The results showed that the region's aridity exhibits a zonal gradient, which follows the precipitation distribution. The southern region experiences more annual rainfall, decreasing northward, revealing a gradient from wet to dry zones.

The temperature change was assessed, and the result shows that more warming has occurred in the recent few years than in the previous. The region has experienced significant warming, which also showed a decrease along the aridity gradient as the drier areas have warmed more than the wet areas. Across the global aridity zones, Huang et al. (2016) showed that warming in more significant in drylands than in humid areas which if it continues, may have significant implications on the expansion of drylands and carbon cycle. The dry areas are characterized by low soil moisture content, and intense warming may further aggravate the dry conditions through soil-atmosphere feedback (Huang et al., 2017). This may also impact the dust propagation, particularly around the Sahel, with direct and indirect implications on the regional climate (Camara et al., 2010; Marcella and Eltahir, 2014; N'Datchoh et al., 2018).

Relative to the climatological mean of 1981–2010, the decadal anomaly of the aridity index revealed an increase in the wetness over the west Africa region. The first decade was the driest period as most of the region experienced below-average conditions and was also a period with several drought occurrences across the region (Giannini et al., 2008; Kasei et al., 2009; Dai, 2011). Below average rainfalls caused severe dryness with several people affected and economic implications (Masih et al., 2014). Apart from the human-induced factors, these dry episodes have been linked to the ocean dynamics of Sea Surface Temperature and El Nino-Southern Oscillation (ENSO) (Masih et al., 2014; Ayugi et al., 2022). Ocean dynamics have been observed to influence the climate of drylands through large scale atmospheric circulation (Guan et al., 2019). Onyutha (2018) showed this by identifying the impact of the Atlantic Ocean Sea surface temperature variation on the precipitation variability in the West African region. The interaction and dynamics of the ocean play a crucial role in the rainfall variability over the region (Nicholson, 2000; Rodríguez-Fonseca et al., 2015). For instance, the dry periods in the first decade have been attributed to the Indian Ocean SSTs due to the El Nino event in 1982/1983 (Bader and Latif, 2011). From the second decade, the region has experienced more wetness, which is linked to the precipitation recovery after the dry periods of the first decade (Sylla et al., 2016; Dike et al., 2020).

According to the temperature anomaly with more enhanced warming since the 2000s, we split the years into two periods, a period before the enhanced warming and that during the more recent warming to examine the contribution of precipitation and PET to changes in AI. Precipitation has dominant control over the changes in aridity across the region. Although the recent years are characterized with more significant warming which leads to enhanced PET (Huang et al., 2016), the effect of PET was dominated by the changes in precipitation. The increase in PET did not weaken the effect of precipitation. This suggests that precipitation exerts dominant control on the dry-wet condition even with elevated warming effect on PET over the west Africa region. This was also revealed in the spatial trend across the region for the whole study period. PET increased mostly across the entire region which leads to decrease in AI (Feng and Fu, 2013); however, precipitation increased more over most parts which caused an increasing trend in AI. The increase in AI led to an expansion of the wetter zones as there was an increase in the area extent of the wetter areas. This led to the shrinking of the drier zones like the hyper-arid and arid zones as parts of these zones became wetter.

The recent results show increased wetness in a warming climate; however, with the continuous warming of the earth's climate, heightened levels of PET are expected under climate projection which may be greater than precipitation change (Sherwood and Fu, 2014). Increased PET may therefore dominate the effect of precipitation on the dry-wet condition. This may cause a reversal of the wetness over the region and lead to more drying and an expansion of the dry areas. This may also lead to an increase in associated dry conditions such as droughts and heatwaves, which will have severe implications on the region's population, especially with the expected increase in population (Mehboob et al., 2020). The expansion of dry areas due to strengthening aridity may have socio-economic and environmental impacts, which calls for more attention to effective land management practices (Onyutha, 2021). As a result of the dependency of several sectors on climate, such as agriculture, drying conditions will significantly affect the region (Oguntunde et al., 2020). The expansion of dry areas may also contribute to local/regional conflicts by affecting moisture availability and cattle feed. Vegetation is tightly coupled to moisture availability (Huber et al., 2011). Expanding dry areas may affect livestock feed and cause the migration of pastoralists from the dry areas to more vegetated areas, which may contribute to conflicts between the locals and the migrating pastoralists (Ajaero et al., 2015; Olaniyan, 2015).

5. Conclusion

Here in this study, we examined the aridity changes over the west Africa region in the past four decades characterized by elevated warming. We showed that the aridity change in the region is largely controlled by precipitation. Unlike the weakening effect of increased potential evapotranspiration (PET) on global dryland aridity changes in recent decades (Pan et al., 2021), precipitation dominates the aridity changes in west Africa. This indicates regional changes within the context of global aridity changes. It shows why it is important to continuously monitor aridity changes at the regional level, especially with the expected changes in global climate extremes (Stocker et al., 2013). At what point will elevated warming through enhanced PET weaken the effect of precipitation over the region? If global warming crosses the 2 °C or 3 °C mark, how vulnerable will the region be to aridity changes? These are questions that still need to be answered. Therefore, future projection of aridity changes over the region in a warming climate is critical to building coping and mitigation strategies for the vulnerable areas to achieve sustainability of life on land.

It is important to note that the data used in this study is a gridded dataset, which may include some bias, especially over the data-limited areas like the hyper-arid regions. This bias in the data may affect the derived aridity index estimations. It is therefore suggested that more datasets could be used for a more robust assessment for further studies on regional aridity conditions. Here, we presented the regional assessment of the regional aridity changes over West Africa, a study that has not received much attention. We, therefore, call for more attention to focus on the dry-wet conditions associated with the recent enhanced warming using more robust datasets.

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.

Data availability

The data used are freely available in the data repositories

References

Adeyeri, O.E., Ishola, K.A., 2021. Variability and trends of actual evapotranspiration over West Africa: the role of environmental drivers. Agric. For. Meteorol. 308–309, 108574.

Adler, R.F., Gu, G., Sapiano, M., Wang, J.-J., Huffman, G.J., 2017. Global precipitation: means, variations and trends during the satellite era (1979–2014). Surv. Geophys. 38, 679–699.

Ahmed, K., Shahid, S., Wang, X., Nawaz, N., Khan, N., 2019. Spatiotemporal changes in aridity of Pakistan during 1901–2016. Hydrol. Earth Syst. Sci. 23, 3081–3096.

Ajaero, C., Mozie, A., Okeke, I.C., Okpanachi, J.P., Onyishi, C., 2015. The drought-migration nexus: implications for socio-ecological conflicts in Nigeria. Mediterr. J. Soc. Sci. 6.

Akinsanola, A.A., Ajayi, V.O., Adejare, A.T., Adeyeri, O.E., Gbode, I.E., Ogunjobi, K.O., Nikulin, G., Abolude, A.T., 2018. Evaluation of rainfall simulations over West Africa in dynamically downscaled CMIP5 global circulation models. Theor. Appl. Climatol. 132, 437–450.

Asadi Zarch, M.A., Sivakumar, B., Sharma, A., 2015. Assessment of global aridity change. J. Hydrol. 520, 300–313.

Asadi, Z.M.A., Sivakumar, B., Malekinezhad, H., Sharma, A., 2017. Future aridity under conditions of global climate change. J. Hydrol. 554, 451–469.

Ayugi, B., Eresanya, E.O., Onyango, A.O., Ogou, F.K., Okoro, E.C., Okoye, C.O., Anoruo, C.M., Dike, V.N., Ashiru, O.R., Daramola, M.T., Mumo, R., Ongoma, V., 2022. Review of meteorological drought in Africa: historical trends, impacts, mitigation measures, and prospects. Pure Appl. Geophys. 179, 1365–1386.

Bader, J., Latif, M., 2011. The 1983 drought in the West Sahel: a case study. Clim. Dynam. 36, 463–472.

Camara, M., Jenkins, G., Konaré, A., 2010. Impacts of dust on west African climate during 2005 and 2006. Atmos. Chem. Phys. Discuss. 10.

Dai, A., 2011. Drought under global warming: a review. WIREs Clim. Change 2, 45–65.

Daramola, M.T., Xu, M., 2022. Recent changes in global dryland temperature and precipitation. Int. J. Climatol. 42, 1267–1282.

Diasso, U., Abiodun, B.J., 2017. Drought modes in West Africa and how well CORDEX RCMs simulate them. Theor. Appl. Climatol. 128, 223–240.

Diedhiou, A., Bichet, A., Wartenburger, R., Seneviratne, S.I., Rowell, D.P., Sylla, M.B., Diallo, I., Todzo, S., Touré, N.d.E., Camara, M., Ngatchah, B.N., Kane, N.A., Tall, L., Affholder, F., 2018. Changes in climate extremes over West and Central Africa at 1.5 °C and 2 °C global warming. Environ. Res. Lett. 13, 065020.

Dike, V.N., Lin, Z.-H., Ibe, C.C., 2020. Intensification of summer rainfall extremes over Nigeria during recent decades. Atmosphere 11.

Feng, S., Fu, Q., 2013. Expansion of global drylands under a warming climate. Atmos. Chem. Phys. 13, 10081–10094.

Giannini, A., Biasutti, M., Verstraete, M.M., 2008. A climate model-based review of drought in the Sahel: desertification, the re-greening and climate change. Global Planet. Change 64, 119–128.

Guan, X., Ma, J., Huang, J., Huang, R., Zhang, L., Ma, Z., 2019. Impact of oceans on climate change in drylands. Sci. China Earth Sci. 62, 891–908.

Harris, I., Osborn, T.J., Jones, P., Lister, D., 2020. Version 4 of the CRU TS monthly high-resolution gridded multivariate climate dataset. Sci. Data 7, 109.

Huang, J., Yu, H., Dai, A., Wei, Y., Kang, L., 2017. Drylands face potential threat under 2 °C global warming target. Nat. Clim. Change 7, 417–422.

Huang, J., Yu, H., Guan, X., Wang, G., Guo, R., 2016. Accelerated dryland expansion under climate change. Nat. Clim. Change 6, 166–171.

Huber, S., Fensholt, R., Rasmussen, K., 2011. Water availability as the driver of vegetation dynamics in the African Sahel from 1982 to 2007. Global Planet. Change 76, 186–195.

IPCC, 2013. Technical Summary, Climate Change 2013: the Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC, 2014. Summary for policymakers. In: Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L. (Eds.), Climate Change 2014: Impacts,Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jalloh, A., Nelson, G.C., Thomas, T.S., Zougmoré, R., Roy-Macauley, H., 2013. West African Agriculture and Climate Change: A Comprehensive Analysis. IFPRI Research Monograph. International Food Policy Research Institute, Washington, D.C.

Kasei, R., Diekkrüger, B., Leemhuis, C., 2009. Drought frequency in the Volta basin of West Africa. Sustain. Sci. 5, 89.

Kendall, M.G., 1975. Rank Correlation Methods. Griffin, London.

Koffi, D., Komla, G., 2015. Trend analysis in reference evapotranspiration and aridity index in the context of climate change in Togo. J. Water Clim. Change 6, 848–864.

Lehmann, E.L., 1975. Nonparametrics, Statistical Methods Based on Ranks. Holden-Day Inc., San Francisco, CA, USA.

Li, Y., Chen, Y., Li, Z., 2019. Dry/wet pattern changes in global dryland areas over the past six decades. Global Planet. Change 178, 184–192.

Li, Y., Feng, A., Liu, W., Ma, X., Dong, G., 2017. Variation of aridity index and the role of climate variables in the southwest China. Water 9.

Liu, X., Liu, W., Xia, J., 2013. Comparison of the streamflow sensitivity to aridity index between the Danjiangkou Reservoir basin and Miyun Reservoir basin, China. Theor. Appl. Climatol. 111, 683–691.

Mann, H.B., 1945. Nonparametric tests against trend. Econometrica 13, 245–259.

Marcella, M.P., Eltahir, E.A.B., 2014. The role of mineral aerosols in shaping the regional climate of West Africa. J. Geophys. Res. Atmos. 119, 5806–5822.

Masih, I., Maskey, S., Mussá, F.E.F., Trambauer, P., 2014. A review of droughts on the African continent: a geospatial and long-term perspective. Hydrol. Earth Syst. Sci. 18, 3635–3649.

Mehboob, M.S., Kim, Y., Lee, J., Um, M.-J., Erfanian, A., Wang, G., 2020. Projection of vegetation impacts on future droughts over West Africa using a coupled RegCM-CLM-CN-DV. Climatic Change 163, 653–668.

Mirzabaev, A., Wu, J., Evans, J., García-Oliva, F., Hussein, I.A.G., Iqbal, M.H., Kimutai, J., Knowles, T., Meza, F., Nedjraoui, D., Tena, F., Türkeş, M., Vázquez, R.J., Weltz, M., 2019. Desertification. In: Shukla, P.R., Skea, J., Calvo Buendia, E., Masson-Delmotte, V., Pörtner, H.O., Roberts, D.C., Zhai, P., Slade, R., Connors, S., van Diemen, R., Ferrat, M., Haughey, E., Luz, S., Neogi, S., Pathak, M., Petzold, J., Portugal Pereira, J., Vyas, P., Huntley, E., Kissick, K., Belkacemi, M., Malley, J. (Eds.), Climate Change and Land: an IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems. Intergovernmental Panel on Climate Change (IPCC) (in press).

Mortimore, M., 2009. Dryland Opportunities: a New Paradigm for People, Ecosystems and Development. IUCN, IIED, UNDP, Gland, Switzerland.

Muhire, I., Ahmed, F., 2016. Spatiotemporal trends in mean temperatures and aridity index over Rwanda. Theor. Appl. Climatol. 123, 399–414.

N'Datchoh, E.T., Diallo, I., Konaré, A., Silué, S., Ogunjobi, K.O., Diedhiou, A., Doumbia, M., 2018. Dust induced changes on the West African summer monsoon features. Int. J. Climatol. 38, 452–466.

Ndehedehe, C.E., Okwuashi, O., Ferreira, V.G., Agutu, N.O., 2018. Exploring evapotranspiration dynamics over sub-sahara Africa (2000–2014). Environ. Monit. Assess. 190, 400.

Nguyen, P., Thorstensen, A., Sorooshian, S., Hsu, K., Aghakouchak, A., Ashouri, H., Tran, H., Braithwaite, D., 2018. Global precipitation trends across spatial scales using satellite observations. Bull. Am. Meteorol. Soc. 99, 689–697.

Nicholson, S.E., 2000. The nature of rainfall variability over Africa on time scales of decades to millenia. Global Planet. Change 26, 137–158.

Nicholson, S.E., 2013. the West African Sahel: a review of recent studies on the rainfall regime and its interannual variability. ISRN Meteorol. 2013, 453521.

Nouaceur, Z., Murarescu, O., 2020. Rainfall Variability and Trend Analysis of Rainfall in West Africa (Senegal, Mauritania, Burkina Faso). Water 12.

Oguntunde, P.G., Abiodun, B.J., Lischeid, G., Abatan, A.A., 2020. Droughts projection over the Niger and Volta River basins of West Africa at specific global warming levels. Int. J. Climatol. 40, 5688–5699.
Oguntunde, P.G., Friesen, J., van de Giesen, N., Savenije, H.H.G., 2006. Hydroclimatology of the Volta River basin in west Africa: trends and variability from 1901 to 2002. Phys. Chem. Earth 31, 1180–1188. Parts A/B/C.
Olaniyan, A., 2015. The fulani–konkomba conflict and management strategy in gushiegu, Ghana. J. Appl. Secur. Res. 10, 330–340.
Onyutha, C., 2018. Trends and variability in African long-term precipitation. Stoch. Environ. Res. Risk Assess. 32, 2721–2739.
Onyutha, C., 2020. Graphical-statistical method to explore variability of hydrological time series. Nord. Hydrol 52, 266–283.
Onyutha, C., 2021. Trends and variability of temperature and evaporation over the african continent: relationships with precipitation. Atmósfera 34, 267–287.
Pan, N., Wang, S., Liu, Y., Li, Y., Xue, F., Wei, F., Yu, H., Fu, B., 2021. Rapid increase of potential evapotranspiration weakens the effect of precipitation on aridity in global drylands. J. Arid Environ. 186, 104414.
Pour, S.H., Wahab, A.K.A., Shahid, S., 2020. Spatiotemporal changes in aridity and the shift of drylands in Iran. Atmos. Res. 233, 104704.
Prăvălie, R., Bandoc, G., Patriche, C., Sternberg, T., 2019. Recent changes in global drylands: evidences from two major aridity databases. Catena 178, 209–231.
Quenum, G.M.L.D., Klutse, N.A.B., Dieng, D., Laux, P., Arnault, J., Kodja, J.D., Oguntunde, P.G., 2019. Identification of potential drought areas in west Africa under climate change and variability. Earth Syst. Environ. 3, 429–444.
Reynolds, J.F., Smith, D.M., Lambin, E.F., Turner 2nd, B.L., Mortimore, M., Batterbury, S. P., Downing, T.E., Dowlatabadi, H., Fernandez, R.J., Herrick, J.E., Huber-Sannwald, E., Jiang, H., Leemans, R., Lynam, T., Maestre, F.T., Ayarza, M., Walker, B., 2007. Global desertification: building a science for dryland development. Science 316, 847–851.
Rodríguez-Fonseca, B., Mohino, E., Mechoso, C.R., Caminade, C., Biasutti, M., Gaetani, M., Garcia-Serrano, J., Vizy, E.K., Cook, K., Xue, Y., Polo, I., Losada, T., Druyan, L., Fontaine, B., Bader, J., Doblas-Reyes, F.J., Goddard, L., Janicot, S., Arribas, A., Lau, W., Colman, A., Vellinga, M., Rowell, D.P., Kucharski, F., Voldoire, A., 2015. Variability and predictability of West african droughts: a review on the role of Sea surface temperature anomalies. J. Clim. 28, 4034–4060.
Sen, P.K., 1968. Estimates of the regression coefficient based on kendall's tau. J. Am. Stat. Assoc. 63, 1379–1389.
Şen, Z., 2012. Innovative trend analysis methodology. J. Hydrol. Eng. 17, 1042–1046.
Sherwood, S., Fu, Q., 2014. A drier future? Science 343, 737.
Singh, V.P., Khedun, C.P., Mishra, A.K., 2014. Water, environment, energy, and population growth: implications for water sustainability under climate change. J. Hydrol. Eng. 19, 667–673.
Sneyers, R., 1990. On the Statistical Analysis of Series of Observations. Secretariat of the World Meteorological Organization, Geneva, Switzerland.
Spearman, C., 1904. The proof and measurement of association between two things. Am. J. Psychol. 15, 72–101.
Stocker, T.F., Qin, D., Plattner, G., Alexander, L.V., Allen, S.K., Bindoff, N.L., Bréon, F.M., Church, J.A., Cubasch, U., Emori, S., Forster, P., Friedlingstein, P., Gillett, N., Gregory, J.M., Hartmann, D.L., Jansen, E., Kirtman, B., Knutti, R., Krishna Kumar, K., Lemke, P., Marotzke, J., Masson-Delmotte, V., Meehl, G.A., Mokhov, I.I., Piao, S., Ramaswamy, V., Randall, D., Rhein, M., Rojas, M., Sabine, C., Shindell, D., Talley, L.D., Vaughan, D.G., Xie, S.P., 2013. Technical summary. In: Climate Change 2013: the Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
Sylla, M.B., Nikiema, P.M., Gibba, P., Kebe, I., Klutse, N.A.B., 2016. Climate change over West Africa: recent trends and future projections. In: Yaro, J., J, H. (Eds.), Adaptation to Climate Change and Variability in Rural West Africa. Springer, Cham.
Theil, H., 1950. A rank-invariant method of linear and polynomial regression analysis. Nederlandse Akademie van Wetenschappen, Series A 53, 386–392.
UN, 2011. Global Drylands: a UN System-wide Response. United Nations; Environment Management Group, Nairobi.