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Long-range persistence of daily rainfall in south-western Nigeria

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Abstract. The study analysed the long-range persistence of daily rainfall over south-western Nigeria for the baseline period (1991–2020) and two future periods, 2041–70, and 2071–2100, representing the mid and late century, respectively. Using the IPSL-CM6A-LR model, the future long-range persistence was estimated for two socio-economic pathways (SSPs), SSP2-4.5 and SSP5-8.5, based on the rescaled adjusted range and modified rescaled range analysis methods. The results of the study indicate that the Hurst exponent is generally expected to be within the range $0.5<H\leq1$, implying that future daily rainfall is projected to vary between moderately persistent and strongly persistent, with some randomness ($H=0.5$) expected during the late century under SSP5-8.5. Information on the expected future long-range persistence of rainfall can serve as a useful forecasting tool to enhance sustainable water resources and agricultural management.

Key words:
long-term memory,
hydroclimatic,
water resources,
rainfall distribution,
climate change

Introduction

There is a general consensus that anthropogenic-induced global warming and climate change are leading to an intensification of the hydrological cycle and, by extension, changes in precipitation (Huntington 2010; Trenberth 2011; Madakumbura et al. 2019; Ficklin et al. 2022). The *Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC)* on Africa (Trisos et al. 2022) reported that, at 1.5 °C of global warming, West African rainfall is projected to decrease and increase in the western and eastern parts of the region, respectively, whereas, at 2 °C of warming, drier conditions are projected to be experienced in the last decades of the 21st century. This has the potential to affect the magnitude of surface runoff, streamflow, aquifer recharge and the general availability of water resources.

Under climate change conditions, different characteristics of rainfall, including the temporal behaviour of its time series, may be significantly altered. One such characteristic is its persistence, which according to Giles and Flocas (1984) is the tendency of successive or consecutive values of a time series to “remember” their preceding values and be influenced by them. Persistence is a feature of hydroclimatic variables such as rainfall, and the Hurst exponent (H), proposed by Hurst (1951), is one of the methods or approaches for quantifying the persistence or long-range dependence of hydroclimatic time series.

The Rescaled Range Analysis has been employed as one of the methods of investigating the persistence or long-range dependence of rainfall in different parts of the world to gain a better understanding of this phenomenon. Pal et al. (2020) analysed the persistence of long-term summer monsoon rainfall in north-eastern India and found that the Hurst exponent for the region was generally low and within the range of 0<H<0.5. This result was interpreted as the rainfall amounts switching between high and low and was considered to be rough and volatile.

The analyses of monthly rainfall of the Amazonian region of Brazil by Vega et al. (2019) showed that persistence varied across different parts of the region from moderate persistence to moderate anti-persistence. Persistence was associated with the tendency of present and future daily rainfall patterns to continue to the near future, whereas anti-persistence was attributed to deforestation and drought conditions. A similar study in north-eastern Brazil by Miranda and Andrade (1999) established the presence of persistence in the rainfall time series, with lower persistence in the southern portion when compared with the northern part. The lower persistence in the southern part was attributed to occasional migration of the Inter-tropical Convergence Zone (ITCZ) to that part of the region and to the influence of central Brazil's climatic zone. The stronger persistence in the northern part was linked to the influence of the equatorial regime.

The results of the study by Valle et al. (2013) on the daily rainfall time series of Zacatecas, Mexico revealed that daily rainfall in the area for the study period was anti-persistent. The anti-persistent behaviour of rainfall during the rainy season was attributed to the magnitude of the rainfall events and temporal distribution, which gave rise to the mid-summer drought in the area. The analyses of the characteristics of heavy rainfall and anomalously dry events in Mauritius by Seebocus et al. (2021) revealed significant persistence for both events, with the drought conditions experienced between 1995 and 1999 ascribed to La Nina events.

Despite the several studies that have investigated different temporal characteristics of rainfall in Nigeria, very few studies have examined the long-range persistence of rainfall in the country. The existing studies (Nnaji 2011; Yaya 2015) examined the persistence on the monthly time scale, and the selected locations were inadequate to represent the climatic zones of Nigeria. Furthermore, there are no studies that have focused exclusively on investigating the long-range persistence of rainfall in south-western Nigeria – neither retrospectively using observed rainfall datasets, nor for the future using Global Climate Models. Consequently, there is a need to address the research gap of the paucity of knowledge about characteristics of long-range persistence of rainfall in south-western Nigeria.

This study therefore assesses the baseline and future long-term persistence of daily rainfall under two SSPs. The importance of this study lies in its potential to enhance understanding of the current and future rainfall dynamics of the study area. By examining the long-range persistence of daily rainfall datasets, this study aims to provide valuable insights into the expected future behaviour of daily rainfall under climate change conditions, which is crucial for effective water resources management and preparedness for extreme events such as floods and droughts in an important hydrologic region such as the south-western littoral basins where the study area is located. The necessity for this study stems from the increasing frequencies of prolonged dry and wet spells that have characterised the south-western region of Nigeria in recent years and what they portend for soil moisture, streamflow, groundwater storage, agriculture, and water resources availability and management.

Study area

The south-western region of Nigeria (Fig. 1) lies approximately between latitudes 6°00'N and 9°15'N and longitudes 2°45'E and 6°00'E and occupies an areal extent spanning 76,852 km2, which is about 8.5 percent of the country's landmass (Fasona et al. 2018). The topography of the area is predominantly undulating, descending gradually from an altitude above 1,600 ft (488 m) in the north to 400 ft (122 m) in the south. The region is located within the south-western littoral basin of the country, which is the third largest of the four main surface water basins of Nigeria, in an area spanning 10,802 km2 (Food and Agriculture Organisation [FAO] 2016). The area is drained by a series of north–south-flowing rivers, the major ones being the Ogun, Oshun and Shasha, which flow into the Lagoons and the Owena River. These rivers are mostly perennial with marked seasonal variation in the volume of flow (Udo 1981).

Climatically, the region is located within the Tropical Rainforest Climate (Af) Zone (Adejuwon 2023) in an area influenced by three major air masses – the Tropical Maritime (Tm), Tropical Continental (Tc), and the Equatorial Easterlies. The dry season in the area is between November and March, whereas the rainy season is between

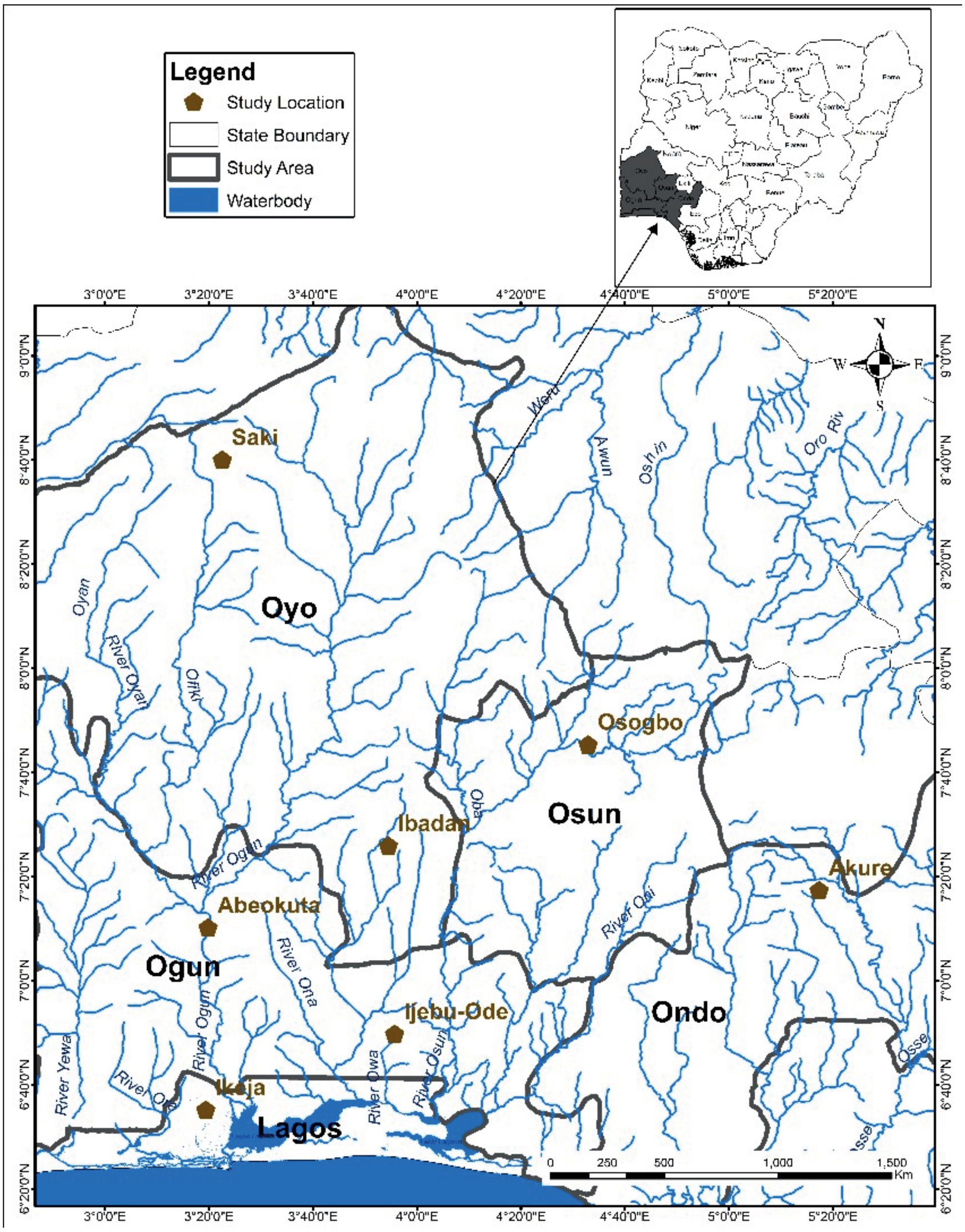

Fig. 1. The study locations within south-western Nigeria

April and October. The wet season is interrupted by a short break for some weeks between July and August by a phenomenon referred to as the "August break" (Ayandele et al. 2017). The rainfall is subject to synoptic-scale disturbances such as line-squalls, thunderstorms and monsoons, which are embedded within the south-westerlies (Olaniran 1988), and the annual rainfall varies between 1,500 mm and 3,000 mm (Adeagbo et al. 2023).

Data and methods

Data sources

The daily observational rainfall data used for this study was sourced from the Climate Hazard Group Infrared Precipitation with Stations (CHIRPS) version 2.0. This was downloaded from data.chc.ucsb.edu/products/CHIRPS-2.0/ for the baseline period 1991 to 2020, the most recent recommended climatic normal period stipulated by the World Meteorological Organisation (WMO). The choice of this dataset is based on the generally high level of correlation between the CHIRPS dataset and the in-situ rainfall data for south-western Nigeria, as shown by Akinyemi et al. (2020). Analyses of the future were based on the use of daily rainfall projection data from IPSL-CM6A-LR, which was downloaded from https://esgf-node.ipsl.upmc.fr/search/cmip6-ipsl/ for seven representative stations comprising Abeokuta, Akure, Ibadan, Ijebu-Ode, Ikeja, Oshogbo and Saki. The model was selected due to its high ability to replicate rainfall characteristics over Nigeria based on an earlier study by Shiru and Chung (2021). A single ensemble (r11i1p1f1) for two SSPs, namely SSP2-4.5 and SSP5-8.5, was employed for analysis for two sub-periods: 2041–70 (representing the mid-century) and 2071–2100 (representing the late century).

Data analysis

The IPSL-CM6A-LR dataset was bias-corrected for the baseline and future periods using the delta method of bias-correction (equation 1). The bias-corrected daily rainfall data for the baseline period for the observed and model data were evaluated using the Modified Willmot Index of Agreement (MWIA) (Willmot 2011), Volumetric Efficiency (VE) tests Mean Absolute Error (MAE) and equations 2 to 4.

$$P_{cor,d} = P_{bsl(fut),d}\, X\, \frac{\bar{P}_{obs,bsl\,(fut)}}{\bar{P}_{GCM,bsl\,(fut)}} \qquad (1)$$

Where $P_{cor,d}$ is the corrected precipitation of the d^{th} day for the baseline (future) period, $P_{bsl(fut),d}$ is the uncorrected corresponding data, and $\bar{P}_{obs,bsl(fut)}$ and $_{(GCM,bsl(fut)}$ are the mean values of daily observed and predicted data for the baseline (future) period.

$$MWIA = 1 - \frac{\sum_{i=1}^{n} |P_{i,obs} - P_{i,pred}|}{\sum_{i=1}^{n} |P_{i,pred} - \bar{P}_{i,obs}| + |P_{i,obs} - \bar{P}_{i,obs}|} \qquad (2)$$

$$MAE = \frac{\sum_{i=1}^{n} |P_{i,obs} - P_{i,pred}|}{n} \qquad (3)$$

$$VE = 1 - \frac{\sum_{i=1}^{n} (P_{i,pred} - P_{i,obs})}{\sum_{i=1}^{n} (P_{i,obs})} \qquad (4)$$

Where $P_{i,obs}$ and $P_{i,pred}$ are the i^{th} observed and predicted precipitation, $\bar{p}_{i,obs}$ is the mean of observed precipitation, and n is the total number of observations.

A MWIA value of 1 signifies a perfect match between the predicted and observed data, and a value of 0 indicates no agreement. The MAE indicates the average model prediction error with less sensitivity to large errors. Values of MAE range between 0 and +∞, with a value close to zero indicating an unbiased prediction, meaning that there is a good fit between the observed and the predicted data. VE computes the ratio between the observed data and predicted data over the specified period. A VE value of 1 suggests a perfect match between the observed and predicted data (Fang et al. 2015; Shiru and Chung 2021; Kaur and Kaur 2023).

The skewness and kurtosis and normality of the distribution of the bias-corrected daily rainfall data for the baseline and future periods were analysed using Karl Pearson's coefficient of skewness (equation 5) and Karl Pearson's measures of kurtosis (equation 6) for the skewness and kurtosis, and the Shapiro–Wilk (equation 7) and Jarque–Bera tests (equation 8) for the normality of the distribution. These analyses were carried out in XLSTAT statistical software.

$$\beta_2 = \frac{\mu_4}{{\mu^2}_2} \qquad (5)$$

$$S_k = \frac{Mean - Mode}{\sigma} \qquad (6)$$

Where μ_2 is the second-order central moment distribution and μ_4 is the fourth-order central moment distribution.

$$W = \frac{(\sum_{i=1}^{n}(a_i\, x_{(i)})^2}{(\sum_{i=1}^{n}(x_i - \bar{x})^2} \qquad (7)$$

$$JB = \frac{n}{6}\left(S^2 + \frac{(k-3)^2}{4}\right) \qquad (8)$$

Where n is the number of observations, s is the sample skewness and k is the sample kurtosis. For the normality tests, the null hypothesis (H_0) of normality of the daily rainfall distribution was tested against the alternative hypothesis (H_a) of non-normality of the daily rainfall distribution at a significance level α=0.05, with the null hypothesis rejected if the computed p-value is lower than the level of significance.

The long-range persistence (Hurst exponent) of the daily rainfall time series for the baseline and the future period {$\mathbf{P}_1$, $\mathbf{P}_2$ ...$\mathbf{P}_n$} was analysed in OriginPro software using the rescaled adjusted range method (classical Hurst exponent) (equation 9), and the modified rescaled range analysis (Modified Hurst exponent) (equation 10). The rescaled adjusted range method is expressed as:

$$\left(\frac{R\ (n)}{S\ (n)}\right) = C_n{}^H \ as\ n \rightarrow \infty \qquad (9)$$

Where *C* is a constant, the brackets signify the expected value, *S(n)* is the standard deviation of the first *n* data of the series {$\mathbf{P}_1$, $\mathbf{P}_2$ ...$\mathbf{P}_n$}, and *R(n)* is their range: *Rn* = max {$\mathbf{P}_1$, $\mathbf{P}_2$ ...$\mathbf{P}_n$} – min {$\mathbf{P}_1$, $\mathbf{P}_2$ ...$\mathbf{P}_n$} (Valle et al. 2013). The modified rescaled range analysis proposed by Lo (1991) is expressed as:

$$V(q) = \frac{1}{\sqrt{n}} * \frac{R}{\sigma\ (q)} \qquad (10)$$

The value of the Hurst exponent (H) varies between 0 and 1, with the value of H revealing the long-term memory of the rainfall time series. The value $0 \leq H < 0.5$ signifies anti-persistent, $0.5 < H \leq 1$ indicates a persistent time series and H=0.5 is an indication of a random time series (Farsang et al. 2017; Seebocus et al. 2021; Koycegiz 2024).

Results and discussion

Model evaluation

The results obtained from the evaluation tests as presented in Table 1 show that the values are within the acceptable range. This indicates that the bias-corrected daily rainfall of the IPSL-CM6A-LR dataset has a high level of agreement with the observed dataset (CHIRPS) for the baseline period. This high level of agreement is supported by the results from the study of Shiru and Chung (2021), who showed that IPSL-CM6A-LR is the highest-performing Global Climate Model (GCM) for replicating rainfall over Nigeria. The graphical representation of the mean annual daily rainfall for the bias-corrected and observed dataset is as shown in Figure 2.

Skewness, kurtosis and normality of rainfall distribution

The results of the skewness and kurtosis analyses (Tables 2 to 4) indicate that the distribution of daily rainfall for the observed baseline and the future periods are positively skewed. For many hydrologic and hydroclimatic variables such as rainfall, the time series is often positively skewed (Machiwal and Jha 2012). In addition, the degree of kurtosis of the rainfall distribution relative to the normal distribution curve is leptokurtic, as indicated by the computed β values, which are greater than 3. Furthermore, all the P-Values (p=<0.0001) for the normality tests are lower than the significance level α=0.05; hence, the null hypothesis was rejected and the alternative hypothesis of the rainfall distribution not following a normal distribution was accepted.

Long-range persistence of daily rainfall

The estimated Hurst exponent based on the rescaled adjusted range method (classical Hurst exponent) and the modified rescaled range analysis (Modified Hurst exponent) are shown in Table 5. As shown in Table 5, the Hurst exponent for the observed daily rainfall for the baseline period indicated that daily rainfall was mainly strongly persistent, as revealed by the relatively high H value. The relatively lower H values of 0.58 and 0.59 at Ikeja, however, indicate that rainfall was relatively less strongly persistent compared to the other locations. The strong persistence associated with the baseline period suggests that antecedent daily rainfall strongly influenced successive daily rainfall. The persistent nature of rainfall in this

Table 1. Results of evaluation of IPSL-CM6A-LR model for the baseline period

	Locations						
Test	Abeokuta	Akure	Ibadan	Ijebu-Ode	Ikeja	Osogbo	Saki
MWIA	0.99	0.99	0.99	0.99	0.99	0.99	0.99
MAE	0.10	0.20	0.00	0.00	0.20	0.10	0.10
VE	1.03	1.05	0.97	1.00	0.96	0.98	1.03

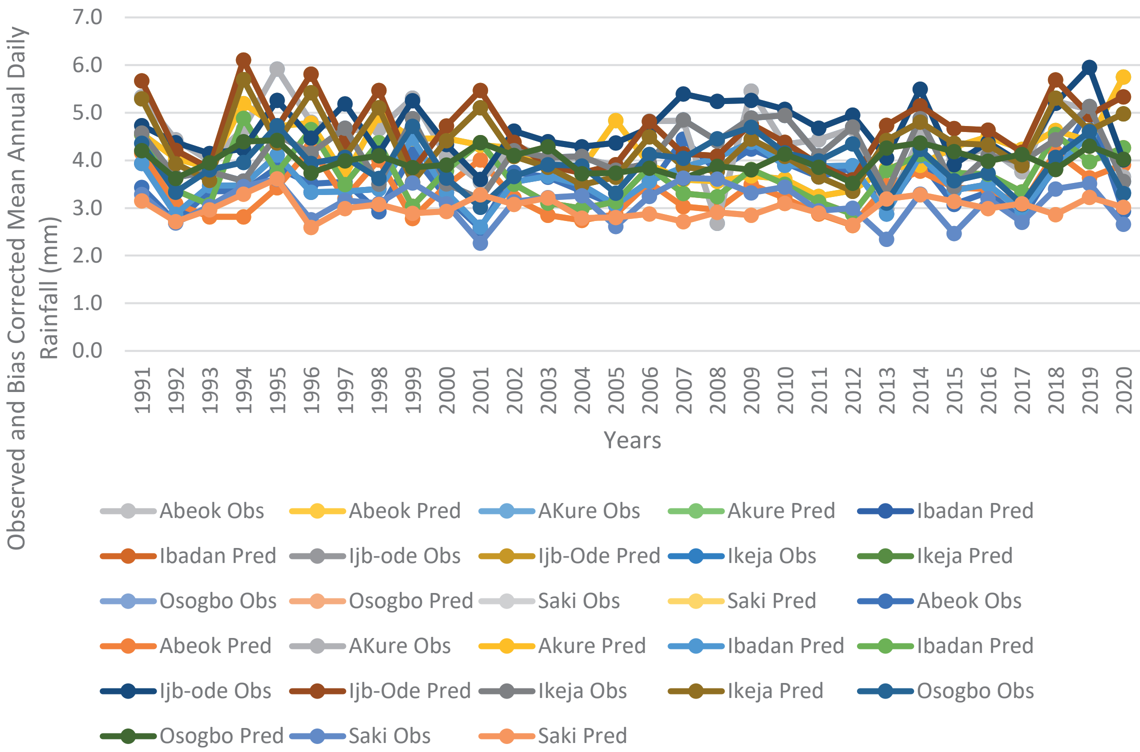

Fig. 2. Mean annual daily rainfall for bias-corrected predicted and observed rainfall for the baseline period

region may be due to the length of the rainy season, which generally varies between March/ April and October. This result is consistent with those obtained in the neighbouring Benin Republic by Biao and Alamou (2017), who used the same methods of analysis to provide evidence of persistent behaviour in the rainfall time series for the period of analysis. The results of this study are also similar to those obtained by Ussalu and Bassrei (2023) in Mozambique, where the long memory of rainfall generally exhibited persistence, with the southern region exhibiting the strongest persistence.

Under SSP2-4.5, the projected daily rainfall for the mid-century is expected to be generally moderately persistent except at Osogbo and Saki, where a strong level of persistence is expected. During the late century, the daily rainfall is also projected to be predominantly strongly persistent, except at Akure, where the projected daily rainfall is expected to be less strongly persistent (Classical H=0.54; Modified H=0.52) in comparison with the other locations. The projected persistence is an indication that antecedent daily rainfall events will not only influence those of the near future but will also impact long-term rainfall at various locations within the study area. This further implies a probable high level of severity of extreme events such as flooding, which could arise due to prolonged wet spells. The expected future

Table 2. Skewness, kurtosis and normality of observed daily rainfall for the baseline period

	Locations						
Test	Abeokuta	Akure	Ibadan	Ijebu-Ode	Ikeja	Osogbo	Saki
S_k	3.01	2.70	3.25	2.96	3.32	2.68	2.89
β	13.89	9.86	18.49	11.60	15.56	11.24	10.75
W	0.60	0.63	0.60	0.59	0.54	0.65	0.59
JB	104743.10	57649.56	175467.87	77445.15	130773.88	70842.56	67904.51
P-Values for W and JB = <0.0001							

Table 3. Skewness, kurtosis and normality of daily rainfall for the future under SSP2-4.5

	SSP2-4.5 in the mid-century						
	Locations						
Test	Abeokuta	Akure	Ibadan	Ijebu-Ode	Ikeja	Osogbo	Saki
S_k	9.83	8.47	9.83	9.83	9.83	9.01	9.01
β	118.3	88.49	118.34	118.34	118.34	113.25	113.25
W	0.27	0.29	0.27	0.27	0.27	0.39	0.39
JB	6569107.86	370581.32	6569107.86	9895212.70	6569107.86	6002746.03	6002746.03
	SSP2-4.5 in the late century						
	Locations						
Test	Abeokuta	Akure	Ibadan	Ijebu-Ode	Ikeja	Osogbo	Saki
S_k	10.30	8.85	10.30	10.30	10.30	8.01	8.01
β	145.64	122.50	145.64	145.64	145.64	118.17	118.17
W	0.24	0.27	0.24	0.24	0.24	0.34	0.34
JB	9895212.70	7029174.13	9895212.70	9895212.70	9895212.70	3510452.26	3510452.26
P-Value for W and JB = <0.0001							

Table 4. Skewness, kurtosis and normality of daily rainfall for the future under SSP5-8.5

	SSP5-8.5 in the mid-century						
	Locations						
Test	Abeokuta	Akure	Ibadan	Ijebu-Ode	Ikeja	Osogbo	Saki
S_k	10.19	9.96	10.19	10.19	10.19	8.85	8.85
β	136.55	98.54	136.55	136.55	136.55	107.32	107.32
W	0.24	0.26	0.24	0.24	0.24	0.35	0.35
JB	8701040.40	4579469.50	8701040.40	8701040.40	8701040.40	5400952.27	5400952.27
	SSP5-8.5 in the mid-century						
	Locations						
Test	Abeokuta	Akure	Ibadan	Ijebu-Ode	Ikeja	Osogbo	Saki
S_k	10.77	9.85	10.77	10.77	10.77	9.35	9.35
β	145.64	122.50	145.64	145.64	145.64	118.17	118.17
W	0.23	0.27	0.24	0.24	0.24	0.34	0.34
JB	9895212.70	7029174.13	9895212.70	9895212.70	9895212.70	6534628.15	6534628.15
P-Value for W and JB = <0.0001							

Table 5. Estimated long-range persistence daily rainfall for the study area

Baseline period (observed daily rainfall)							
Test	Abeokuta	Akure	Ibadan	Ijebu-Ode	Ikeja	Osogbo	Saki
H (Classical)	0.69	0.72	0.63	0.61	0.59	0.77	0.96
H (Modified)	0.68	0.70	0.61	0.59	0.58	0.75	0.95
SSP2-4.5 (mid-century)							
Test	Abeokuta	Akure	Ibadan	Ijebu-Ode	Ikeja	Osogbo	Saki
H (Classical)	0.59	0.58	0.58	0.58	0.58	0.79	0.79
H (Modified)	0.57	0.57	0.57	0.57	0.57	0.79	0.79
SSP2-4.5 (late century)							
Test	Abeokuta	Akure	Ibadan	Ijebu-Ode	Ikeja	Osogbo	Saki
H (Classical)	0.69	0.54	0.70	0.70	0.70	0.84	0.84
H (Modified)	0.69	0.52	0.69	0.69	0.69	0.83	0.83
SSP5-8.5 (mid-century)							
Test	Abeokuta	Akure	Ibadan	Ijebu-Ode	Ikeja	Osogbo	Saki
H (Classical)	0.59	0.51	0.59	0.59	0.59	0.86	0.86
H (Modified)	0.57	0.50	0.57	0.57	0.57	0.86	0.86
SSP5.8.5 (late century)							
Test	Abeokuta	Akure	Ibadan	Ijebu-Ode	Ikeja	Osogbo	Saki
H (Classical)	0.50	0.57	0.50	0.50	0.50	0.64	0.64
H (Modified	0.50	0.56	0.50	0.50	0.50	0.63	0.63

persistence also has the potential to influence streamflow dynamics in the region by causing prolonged high flows during periods of flooding and low flows under drought conditions. Under such conditions, hydraulic structures such as dams and agricultural productivity may be negatively impacted.

Under SSP5-8.5, the mid-century is also projected to be moderately persistent, similar to the projections for the mid-century under SSP2-4.5. For the late century, the projected daily rainfall is expected to be mostly random (H=0.50) with randomness expected at Abeokuta, Ibadan, Ijebu-Ode and Ikeja, while persistence is expected at Akure, Osogbo and Saki. Such randomness is an indication of non-persistence or independence among the expected daily rainfall time series, implying that the projected antecedent and successive daily rainfall events will be serially uncorrelated. This also means that the rainfall time series is free from deterministic components of trends, jumps or cycles (Stone 2001). In Nigeria, the distribution of monthly, seasonal and annual rainfall has been reported to exhibit varying magnitudes of fluctuations and non-significant persistence or randomness, as shown by the works of Ayandike (1993) and Nnaji (2011).

The projected future randomness of daily rainfall has implications for water resources, agriculture, disaster preparedness and development of adaptation strategies. Firstly, the unpredictability associated with the randomness of the rainfall time series could make forecasting of water availability very difficult due to the high levels of fluctuations that water resources are subjected to. Such fluctuations could result in inconsistency and high variability in streamflow and aquifer recharge, difficulty in designing appropriate hydro-agricultural infrastructures, and general challenges in the management of water resources systems.

Secondly, the projected randomness and the corresponding uncertainty could likely make it more challenging for the existing hydroclimatic early-warning institutions and systems such as AgroMet Early Warning System of the Nigerian Meteorological Agency (NiMet), the Nigerian Hydrological Services Agency (NHISA) and National Emergency Management Agency (NEMA) to function optimally in mitigating the consequences of future extreme events.

Thirdly, such randomness could make agricultural planning more difficult, especially under rainfed agriculture, which is the most common practice in south-western Nigeria and the country as a whole. This has the potential to negatively impact crop yields and food security.

Lastly, developing adaptation strategies in addressing the potential unpredictability of water resource availability is likely to be more challenging due to the complexity of incorporating and modelling random rainfall time series in hydrological and climate models.

Conclusion

For sustainable planning and operation of the water resources systems and the agricultural sector of south-western Nigeria, having information on the future dynamics of rainfall, especially its long-term persistence is very important. In achieving this, salient statistical characteristics of the daily rainfall distribution and the likely future Hurst behaviour of daily rainfall were analysed. The study also analysed these characteristics for the baseline period from 1991 to 2020.

The results of the study showed that daily rainfall distribution for both the baseline period and the future are positively skewed and leptokurtic, whereas the Hurst exponent showed levels of persistence ranging from moderate to strong, except for some randomness expected during the late century under SSP5-8.5. The projected persistence and the implied predictability could assist water resources managers in designing appropriate water management strategies and serve as a basis for farmers to choose the appropriate crop varieties better-suited to the expected level of persistence to optimize crop growth, improve adaptation measures and reduce the risk of losses. For the projected randomness expected at some locations in the study area, increased and improved monitoring of rainfall would be essential in implementing adaptation strategies and increasing resilience to some of the challenges posed by unpredictable variations in rainfall patterns.

The estimated long-range persistence bridges the knowledge gap on the historical and future long-term memory effect of daily rainfall in south-west Nigeria. The available information on the projected persistence of rainfall provides insights into the expected long-memory behaviour of rainfall under conditions of changing climate. Such information could not only have the potential to serve as a scientific basis for planning, operations and decision making in the water resources sector of the region, but it can also contribute to forecasting, thereby reducing uncertainty and helping in preventing economic losses, especially in the agricultural sector.

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