Historical changes in rainfall patterns over the Congo basin and impacts on runoff (1903-2010)

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Abstract
The Congo basin is one of the most hydrologically active and pristine locations with limited understanding of how precipitation changes impacts on stream flow dynamics and variations in catchment stores. Given that the basin is among the three prominent convective regions that dominates global rainfall climatology during transition seasons, historical space-time variability of rainfall (1901-2014) over the basin in relation to river discharge is analysed in order to understand significant hydro-climatic shift. Based on advance multivariate analyses, the total variability of the leading modes (annual variations) of rainfall increased during the 1931-1960 (56.3%) and 1961-1990 (57.3%) periods compared to the 1901-1930 baseline period (51.3%). It varied less between 1991 and 2014 (55.4%) as opposed to the two climatological periods between 1931 and 1990. Furthermore, the total variability in the multi-annual rainfall signals declined from 16.5% at the start of the century (1901-1930) to 13.6% in the 1991-2014 period while the total variability accounted for by other short-term meteorological signals oscillated between 4.0% and 2.7% during the entire period. Between 1995 and 2010 there seems to be a change in the hydrological regimes of the Congo river as the cumulative departures of rainfall and discharge were in opposite directions. The considerable association of discharge with rainfall in catchments characterised by strong annual and seasonal amplitudes in rainfall implies that the wetland hydrology of the basin is largely nourished by rainfall, in addition
to possible exchange of fluxes within the Congo floodplain wetlands. Notably, a significant proportion of changes in the dominant rainfall patterns is still not explained by those of river discharge. This information signals the threshold of complex hydrological processes in the region, and perhaps suggest the influence of anthropogenic contributions (e.g., deforestation) and strong multi-scale ocean-atmosphere phenomena as key secondary drivers of hydrologic variability.
Keywords: Climate variability, drought, rainfall, floodplain, river discharge, flood

1. Introduction

Rainfall is a major source of freshwater availability for the functioning of ecosystems and sustainability of both hydrological and agricultural systems. Indeed, rainfall is an important aspect of the hydrological cycle that shows an increasing acceleration owing to climate change. As the climate warms, the hydrological cycle accelerates, causing an increase in the spatiotemporal variability of precipitation and also in the duration and intensity of extreme events such as droughts, storms, and floods (e.g., Ndehedehe, 2019). The need to assess the response of surface water hydrology to changes in climate is therefore crucial.

The rise in extreme events, especially drought frequency, duration and severity across several African domain in recent times (see, e.g., Ndehedehe et al., 2019; Haile et al., 2019; Mpelasoka et al., 2018; Agutu et al., 2017; Ndehedehe et al., 2016b,c; Hua et al., 2016; AghaKouchak, 2015; Shiferaw et al., 2014; Zhou et al., 2014) are strong indications of climatic disturbance and perhaps the increasing vulnerabilities of the African sub-region to the impacts of extreme climatic conditions. These extreme drought events have been the direct result of prolonged limited or below average rainfall. Among other factors, they have been attributed mostly to the perturbations of the surrounding oceans, natural variability, important processes of oceanic variability and human actions, e.g., land use change, deforestation, among others (e.g., Haile et al., 2019; Ndehedehe, 2019; Nicholson et al., 2018; Andam-Akorful et al., 2017; Ndehedehe et al., 2016c,b; Epule et al., 2014). Based on regional climate model simulation, deforestation in the Congo basin, for example, will locally produce a heat low and lead to reduced precipitation (Nogherotto et al., 2013). Assessing evolutionary changes in rainfall patterns is therefore essential to improve knowledge on the interactions between climate systems and globally significant hydro-ecological domains such as the Congo basin.

The critical hydrological features of the Congo basin make it one of those globally significant domains given it key roles in global climate and the huge ecosystem services it provides on mutli-scales (e.g., Ndehedehe et al., 2018; Bell et al., 2015; Verhegghen et al., 2012; Washington et al., 2013). For example, the sensitivity of climate to the loss of the Congo basin rainforest and other ecological disturbance through extensive land cover change and human interaction with the ecosystem is well known (e.g., Bell et al., 2015; Malhi et al., 2013; Verhegghen et al., 2012). Numerical simulations from climate models have demonstrated the importance of the Congo forest to its local hydrology. For instance, the study by Bell et al. (2015) show that deforestation in the Congo basin results in increase albedo and will lead to cooler and drier climate conditions over the entire basin. They noted that the absolute depletion of the Congo basin forest will decrease rainfall by 42% in the western part with a slight increase of 10% in the basin's eastern section. This ecological disturbance of the African rainforest biome could have implications on regional hydrology, especially modulating local rainfall regimes. In fact, it is argued that more than 50% of the total atmospheric moisture contribution to local precipitation emanates from within the Congo basin (Sorí et al., 2017). Furthermore, the Indian
Ocean and evaporation from the Congo basin are perceived as important moisture sources for the basin. Dyer et al. (2017) argued that the Indian Ocean contributes about 21% of the moisture while 25% of the moisture is recycled within the Congo Basin. They also noted that much of the wet season Congo basin rainfall was derived from the Indian Ocean moisture, stressing the need to understand links between circulation patterns over the Indian Ocean and the local circulation over the basin to aid the optimisation of future climate projections.

The Congo basin (Figs. 1a-c) is one of the most hydrologically active and pristine locations in the world with limited understanding of how precipitation changes impact on stream flow dynamics and variations in catchment stores. Although rainfall variability in different climatic zones of Congo-Brazzaville over the common period 1932–2007 has been studied (Samba and Nganga, 2012), limited and lack of complete and/or continuous observational data is a key challenge to quantitative assessment and characterization of the Congo river basin hydrology (Munzimi et al., 2015; Conway et al., 2009). This was the basis for assessing the performance of satellite precipitation in the Democratic Republic of Congo (Munzimi et al., 2015) and several other studies that relied on multi-satellite and global reanalysis data to aid the characterization of surface water hydrology, hydro-climatic, and land surface conditions in the region (see, e.g., Ndehedehe et al., 2018, 2019; Zhou et al., 2014; Lee et al., 2011, 2014; Nogherotto et al., 2013; Asefi-Najafabady and Saatchi, 2013; O'Loughlin et al., 2013; Conway et al., 2009; Crowley et al., 2006).

While simulating discharge of the Congo River is challenging (Santini and Caporaso, 2018), semi-distributed rainfall-runoff models have been employed to understand processes of runoff generation and study the impacts of climate and human actions on water resources availability (e.g., Tshimanga and Hughes, 2014). However, the response of the Congo river to historical changes in rainfall patterns over different climatological periods (1903-2010) is not well known. Apart from the lack of sufficient gauge data for hydrological applications, Tshimanga and Hughes (2014) also argued that the complexity of natural processes limits our understanding of surface water hydrology. The connection between Congo spring discharge and Gulf of Guinea SST (Materia et al., 2012) and the coupled interactions of the nearby oceans with precipitation patterns, provide important considerations for the rainfall-discharge relationship over the Congo basin. A key hypothesis this study aims to address is that 'despite known variations in the discharges of the Congo river, previous rainfall amounts have varied comparatively less across the Congo basin'. This important hypothesis requires an assessment of the historical relationship of changes in river discharge with those of precipitation. In light of the proposed water transfer from the Congo basin to nourish the Lake Chad (see, e.g., Ndehedehe et al., 2016b; Lemoalle et al., 2012), understanding key hydrological metrics related to rainfall-runoff relationship are important issues to be considered. In addition to environmental impact assessments of this project on the donor basin, addressing technological and socio-cultural constraints that may impede the actualization of this project are also crucial. Ultimately, the knowledge of evolutionary patterns of river flow and potential socio-hydrological problems that could be linked to climate change can be used to improve diplomacy and regional cooperation by stake holders and riparian countries of both river basins to adapt and seek for innovative solutions on this project.

Given that the basin is among the three prominent convective regions that dominates global rainfall climatology during transition seasons (e.g., Washington et al., 2013), historical space-time variability of rainfall (1901-2014) over the basin in relation to river discharge is analysed in order to understand significant hydro-climatic shift. As we still know little about the nature of climate and anthropogenic influence on the basin, outcomes from model simulation studies, though largely contrasting (e.g., White and Toumi, 2014; Materia et al., 2012), are insufficient, warranting more research. In fact, the skills of several global climate models to simulate historical precipitation over central Africa is considerably limited (Aloysius et al., 2016). Hence, assessing the unique interactions between rainfall and discharge during the last century is essential to improve our understanding of the likely threats of climate change on hydro-ecological assets and freshwater of the Congo basin.

]Figure 1]

2. Materials and method

2.1. Precipitation

The Global Precipitation Climatology Centre (GPCC, Schneider et al., 2014; Becker et al., 2013) was used to assess the spatial and temporal patterns of rainfall over the Congo basin. The data provides reliable monthly gridded data sets of global land-surface precipitation at 0.5∘ x 0.5∘, covers the period from 1901 to 2014, and can be downloaded from the GPCC data portal (www.ftp.dwd.de/pub/data/gpcc/html/downloadgate.html). The updated CRU precipitation data (Harris et al., 2014) was also used in this study. This version of the data (CRU TS3.10) includes the number of stations used in the interpolation, thus allowing an objective determination of the reliability of values. Apparently, the two datasets go back as far as 1901 and we acknowledge the limitations of GPCC gauge distribution over the Congo basin, which may not be as dense as other tropical regions. However, the GPCC has more gauge locations than CRU over the region. Given that this study is over the entire Congo basin region (about 3.7 million km2), the spatial resolution of 0.5∘ is suitable in resolving the sources of variability in the Congo region. Also, the error variance in GPCC and CRU is significantly less compared to satellite products (Ndehedehe et al., 2019). We used the GPCC data in all our analysis because of its reliability and as it is the most commonly used product with more ground observations from stations worldwide in the validation of global precipitation data sets. But a key limitation of the CRU data as highlighted by its data providers is uncertainties and unreliability in estimated trends. Overall, the uncertainties and ambiguities surrounding the Congo precipitation is still an ongoing discussion and it is open to further conversation in future studies.

2.2. River discharge

The river discharge used in this study was obtained from the GRDC (Global Runoff Data Centre) archive (www.bafg.de/GRDC). The gauge station at the Congo Kinshasa station was used to study hydrological response of the Congo river to rainfall conditions. GRDC has several discontinuous and abandoned gauges distributed across the basin, however, the gauge at the Congo river in Kinshasa station has complete historical data (1903–2010) with no gaps. Because of its numerous discharges from tributaries that originates from Eastern Africa, this hydrological station is one of the most significant in the basin. Also, this gauge station showed considerable strong amplitude in monthly discharge and explained considerable multi-annual changes (more than 80% of variability) in the GRACE-hydrological signal of the Congo basin Ndehedehe et al. (2018). It is therefore logical to conclude that the discharge at Kinshasa station encapsulates most of the flows within the basin. Moreover, our analyses of observed relationship of discharge with rainfall were based on the common period for which both data are available.

2.3. Evolutionary patterns of rainfall and discharge

Three different multivariate methods were employed to analyse the spatial and temporal patterns of rainfall and discharge. First, the principal component analysis (PCA, e.g., Jolliffe, 2002) was used to decompose time series of GPCC-based precipitation into spatial and temporal patterns. PCA is an important tool to assess the spatio-temporal variability of continuous climate data such as rainfall due to its simplicity and capability to isolate both inter-annual signals, and long-term periodic variations (Ndehedehe et al., 2016a). The method reduces the dimensions of multivariate data by creating new variables that are linear functions of the original variables. Significant modes of variability for each climatological period (1901-2014) were assessed based on the statistical rotation of PCA. To understand the spatio-temporal variability of rainfall during each climatological period with a 30-year window, rainfall grids for each window were decomposed using this technique. This window allows a
reasonable conclusion of climate change or climate variability impacts on rainfall and river discharge, especially whether the latter has changed significantly in response to the former. The singular spectrum analysis (SSA, Ghil et al., 2002) was employed to decompose monthly river discharge through a singular value decomposition (SVD) of the lagged covariance matrices. The reconstructed discharge time series (i.e., matrix of reconstructed principal components of discharge) obtained from the SSA scheme were compared with the leading temporal patterns of PCA-derived rainfall using correlation and regression analyses (next sections) for the common period. Second, to assess the relationship between local rainfall and discharge, rainfall was further localised over the Congo basin using the independent component analysis (ICA, e.g., Cardoso, 1999; Cardoso and Souloumiac, 1993). The ICA method employed here is based on the JADE (Joint Approximate Diagonalisation of Eigen matrices) algorithm, which exploits the fourth order cumulants of the data matrix and is fully detailed in Cardoso and Souloumiac (1993). Several applications of PCA and ICA methods in droughts and hydro-climatic studies and localization of groundwater signals have been documented (e.g., Agutu et al., 2017, 2019; Montazerolghaem et al., 2016; Ndehedehe et al., 2016b, 2017; Sanogo et al., 2015). The temporal variations of rainfall associated with the localised spatial patterns were correlated with
discharge to determine the influence of local rainfall on discharge. Using the ICA method, rainfall grids were localised as:

$$X_{GPCC}(x,y,t)=TS;(1)$$

where (*x*, *y*), and *t* are grid locations and time steps (months), respectively. **T** is the temporal patterns and is unit-less since it has been normalised using its standard deviation while the spatial patterns **S** associated with **T** have been scaled using the standard deviation of its temporal patterns. **T** and **S** are interpreted together and integrated to form what is traditionally called the ICA mode of variability (e.g., Ndehedehe et al., 2017).

2.4. Multi-linear regression analysis

The MLRA (multi-linear regression analysis), a statistical technique used to model the relationships between a dependent variable and one or more independent variables was used to characterize, trends, annual and semi-annual amplitudes in rainfall. It uses a least square approach and has been widely applied in hydrology and climate science to explain the possible relationships between key variables (see, e.g., Ndehedehe et al., 2016a; Rieser et al., 2010). The focus here is to separate the harmonic components (mean annual and semi-annual amplitudes) of rainfall over different 30-year climatological periods (1901-2014) and then compare whether they are statistically different or have different means using analysis of variance (ANOVA). ANOVA is a prominent statistical method that is employed to assesses if the means of two or more groups (in our case, trends, mean annual and semi-annual rainfall patterns from each climatological period) are significantly different from each other. In the MLRA technique, the trends and harmonic components (mean annual and semi-annual amplitudes) for each climatological period (1901-1930; 1931-1960; 1961-1990; 1991-2010) were compartmentalised from the precipitation time series (*P*) through parameterizations as (e.g., Ndehedehe and Ferreira, 2020; Rieser et al., 2010),

$$\mathbf{P}\,(l, k, t) = \beta_0 + \beta_1 t + \beta_2 sin(2\pi t) + \beta_3 cos(2\pi t) + \beta_4 sin(4\pi t) + \beta_5 cos(4\pi t) + \varepsilon(t); \qquad (2)$$

where (l; k) are the grid locations, t is the time component, β_0 is the constant offset, β_1 is the linear trend, β_2 and β_3 account for the annual signal, β_4 and β_5 represent the semi-annual signal, while $\varepsilon(t)$ is the random error term. The amplitudes of rainfall (i.e., mean annual and semi-annual) over the region are then estimated as,

$$Annual = \left[(\beta 2)^2 + (\beta 3)^2\right]^{\frac{1}{2}} \text{ and } Semi\,Annual = ¿\left[(\beta 4)^2 + (\beta 5)^2\right]^{\frac{1}{2}} \qquad (3)$$

2.5. Linear rates, correlations, and cumulative departures

A non-parametric method such as the Sen's slope (Sen, 1968) estimator was used to estimate the linear rates in rainfall since it is robust and resistant to outliers. Sen slope (S_k) is the median overall values of the whole data and is estimated as,

$$S_k = Median\left(\frac{Y_j - Y_i}{j - i}\right), for\ (1 \leq i < j \leq n)\ 4$$

where Y_j and Y_i represents data values at time j and i ($j > i$), respectively while n is the number of data. The slope can be positive indicating increasing trend or negative, indicating decreasing trend. Trend analysis for precipitation grids used a 20-year window different from the MLRA of GPCC-based precipitation (Section 2.4), which focused on trends based on 30-year climatological windows. Detecting changes in rainfall in a relatively short window is crucial for better understanding of significant climate trends and developing adaptation and mitigation measures at a regional and local scale. Given that the assessment of linear rates in rainfall is a key aspect of long-term water resource evaluations strategy, cumulative rainfall departure (Weber and Stewart, 2004) was estimated. The concept of cumulative rainfall departures (Weber and Stewart, 2004) was also applied to estimate cumulative departures of river discharge. Generally, cumulative departures are useful when employed as a general indicator of rainfall/discharge trends, with the upward and downward gradient indicating relatively a rise and decline in rainfall, respectively (e.g., Ndehedehe et al., 2017). Cumulative departures were both employed to evaluate trends in river discharge against those of rainfall. All temporal relationships between rainfall and discharge were based on the Pearson's

correlation coefficient and are deemed significant at α = 0.05. Although it was not the main stay of this study, the
grid based comparison of GPCC and CRU precipitation data was also undertaken. Using correlation and ANOVA in this regard provided a bit of perspective as to the inherent differences and similarities between the widely used GPCC observational reference and the CRU data over the region.

3. Results

3.1. Historical changes in precipitation patterns over the Congo basin

3.1.1. GPCC vs CRU based precipitation estimates

The Congo basin precipitation estimates and its uncertainties are important issues that sometimes results in polarized debates and divergent opinions amongst climate researchers who have worked in the region (Ndehedehe et al., 2019). The challenging terrain, environmental conditions, and limited gauge observations in the Congo basin are some reasons for the poor understanding of precipitation estimates. Although time constraints (i.e., availability of historical observations) was a deciding factor in our choice of precipitation, as earlier mentioned (Section 2.1), the error variance in GPCC and CRU is significantly less compared to satellite products. Apart from disturbance of ecological assets and alteration to the Congo forest through prolonged drought and deforestation, the influence of topography on the Central African hydrology and its neighbouring East African countries cannot be overlooked. As with the influence of topographical variability and gauge density on precipitation products in the surrounding East African countries (Agutu et al., 2020), the Rift valley highlands in East Africa was earlier identified as an important driver of considerable anomaly in precipitation over the Congo basin (Bell et al., 2015). But the availability of in situ data to improve process-based knowledge on these drivers and monitor these conditions, including land surface conditions, local water recycling activity and contributions from oceanic hot spots is an issue for the Congo basin. It is true that a history of hydrological measurement exists in the Congo basin (Alsdorf et al., 2016).

[Figure 2]

However, the decline and significant gaps in gauge measurement, coupled with the unavailability of historical meteorological data for research are key constraints that limits knowledge in the Congo basin. Hence, the intricacies surrounding precipitation distribution over the Congo basin was therefore assessed by comparing two observational reference gauged precipitation products, the Global Precipitation Climatology Centre (GPCC, Schneider et al., 2014) and Climate Research Unit (CRU TS4.01, Harris et al., 2014) derived precipitation (http://badc.nerc.ac.uk/data/cru/) using analysis of variance and other metrics (linear rates, correlations, and cumulative departures). GPCC and CRU precipitation estimates over the Congo basin during different climatological periods seem to be somewhat consistent with a range of correlation values between 0.80 and 1.00 (Fig. 2a).

[Figure 3]

However, correlation values between GPCC and CRU fluctuated between 0.40 and 0.80 in the low elevation areas of the Cuvette central (cf. Fig. 1b) during the period (Fig. 2a). The considerable change in correlation values around the Cuvette central during the different climatological periods can be attributed to dynamics in the availability of gauged stations. Further, the analysis of variance also confirms there is no significant difference in the mean of these products in all climatological periods (Fig. 2b). The spatio-temporal distribution of meteorological stations is expected to vary, especially in regions with poor investment in meteorological stations. GPCC is still nonetheless, the largest gauge-observation data available globally and has been found suitable in the characterization of agricultural and hydrological drought in the African sub-regions, including the Congo basin (see, e.g., Ndehedehe et al., 2019, 2020; Agutu et al., 2017).

[Figure 4]

3.1.2. Spatio-temporal variations and trends in precipitation

The spatial distribution of annual and seasonal precipitation (1901-2013) based on seasonal rainfall climatology of the region (March-May (MAM); June-August (JJA); September-November (SON); and December- February (DJF)) indicate considerable rainfall in the southern and central sections of the basin in DJF and SON periods, respectively (Fig. 3). Just for exploratory purposes, these seasonal distributions are considered for the first and second halves of the century. There is significant amount of rainfall all through the year in the Congo basin except in the JJA period for the south and DJF for the north (Fig. 3). In terms of direct water availability from rainfall, these sections of the Congo basin, including the northern flank can be described as the water tower of central Africa. The evidence of strong spatial distribution of mean monthly and seasonal rainfall in the low elevation areas of the Cuvette central and the in-terconnectedness of multiple stream networks attest to the Congo basin being a freshwater rich hydrological region (Figs. 3 and cf. Figs. 1a-b). Furthermore, the MLRA and analysis of variance show that there is statistically significant change in observed trends (F = 442.7; p = 0.000), annual (F = 8.85; p = 0.000), and semi-annual (F = 4.93; p = 0.002) amplitudes of rainfall during different climatological periods (1901-1930, 1931-1960, 1961-1990 and 1991-2014) over the Congo basin (Figs. 4a-b). Consistent with Fig. 3, the southern section of the Congo basin is characterized by strong annual amplitudes in rainfall while towards the east, there is considerable mean semi-annual amplitude of rainfall (Fig. 4a).

[Figure 5]
[Figure 6]

The spatio-temporal variability of rainfall using the PCA technique was based on climatological classification similar to Fig. 4. Based on the Bartlett's test statistics (e.g., Snedecor and Cochran, 1989) more than five significant modes explaining non-random variations in rainfall at 95% confidence level were identified. But for purposes of physical interpretability, we focus on three of those rainfall modes. Leading rainfall modes in the Congo basin are characterised by annual, multi-annual and short-term seasonal signals (Figs. 5a-b and 6a-b). There is a strong dipole patterns in dominant mode where strong spatial patterns of rainfall on the opposite side of the equator are notable (EOF-1, Figs. 5a-b and 6a-b). These spatial patterns show the different wet seasons in the basin. From the time series associated with these spatial patterns, the wet season (positive phase) in northern section coincides with the dry season (negative phase) of the southern region (EOF-1/PC-1, Figs. 5a-b and 6a-b). The multi-annual signal, which corresponds to the bimodal rainfall patterns and short-term seasonal signals are relatively stronger on the West and in regions encompassing Congo, Equatorial Guinea, and Gabon (EOF-2 and EOF-3, Figs. 5a-b and 6a-b). Generally, there is significant difference in the observed spatial loadings (averaged spatial distribution) of the first orthogonal mode of rainfall over different climatology (EOF-1, Figs. 5a-b and 6a-b) and confirms the extensive impacts of extreme and severe droughts, which affected more than 50% of the basin between 1901 and 1930 (Ndehedehe et al., 2019). The total variability of the leading modes (annual variations) of rainfall increased during the 1931-1960 (56.3%) and 1961-1990 (57.3%) periods compared to the 1901-1930 baseline period (51.3%). It varied less between 1991 and 2014 (55.4%) as opposed to the two climatological periods between 1931 and 1990. Furthermore, the total variability in the multi-annual rainfall signals declined from 16.5% at the start of the century (1901-1930) to 13.6% in the 1991-2014 period while the total variability accounted for by other short-term meteorological signals oscillated between 4.0% and 2.7% during the entire period.

[Figure 7]
[Figure 8]

The MLRA of rainfall for each 30-year climatological window (Fig. 4) show that there are significant differences (F = 442.7; p = 0.000) in observed trends during these periods. However, multi-decadal (e.g., 20 years) trends based on these window lengths were also explored as part of an overall assessment of changes in rainfall in the basin. A further analysis on the spatial distribution of trends in annual (Fig. 7a) and maximum (Fig. 7b) rainfall confirms the strong increase in rainfall between 1960 and 1963 in the south. Widespread negative trends in annual rainfall during the 1981-2000 and 2001-2013 periods around the Democratic Republic of Congo and the Cuvette central (Fig. 7a) coincides with drought/dry episodes already reported in the literature (Ndehedehe et al., 2019; Ndehedehe, 2019; Zhou et al., 2014). Additionally, there is inconsistency in the distribution of spatial trends in annual and maximum rainfall (Figs. 7a-b). For example, during the 1981-2000 period there was a widespread decrease in annual rainfall (Fig. 7a) compared to the distribution of trends in maximum annual rainfall in the central Congo basin area (Fig. 7b).

[Table 1]

[Figure 9]

3.2. Rainfall vs river discharge

Similar to rainfall, observed river discharge was also statistically decomposed using the singular spectral analysis. This approach is warranted because unlike rainfall, the discharge time series is a one column vector unit and decomposing it similar to rainfall allows comparison between their leading modes. The temporal patterns of the leading modes of rainfall and discharge were compared with one another (Figs. 8a-b). The relationship between leading modes (PC-1) of rainfall and river discharge show marked fluctuations during the entire period (1901-2010). The strongest linear correlation (r = 0.71) was observed during 1991-2010 period while the lowest (r = 0.59) was observed at the start of the century (1903-1930). The other two climatological periods show moderately strong correlations (r = 0.68 and 0.64 for the 1930-1960 and 1961-1990 periods, respectively). Maximum correlation between the second modes of rainfall and discharge is also linear and strong but with a one-month phase lag. For example, the second modes of rainfall and discharge during the 1903-1930 (r = 0.71)
and 1991-2010 (r = 0.66) were found to be well associated at one-month lag. The total variability accounted for by the two leading modes of rainfall and discharge are summarised in Table 1. The annual signal in GPCC explains an average of 42.7% of variability in discharge while the multi-annual signal accounts for about 50% at 1-month lag. During all climatological periods, temporal relationships between the first modes of rainfall and discharge are moderately strong and significant (r = 0.05). At the start of the century, more of the variability in rainfall were rather consistent with those of discharge (92% and 96.7% total variability for rainfall and discharge, respectively) as opposed to the 1990-2010 period (91% and 98.3% total variability for rainfall and discharge, respectively) when there was increased variability in discharge (Figs. 8a-b). Similar to rainfall (Figs. 5a-b and 6a-b), the variability in leading modes of discharge fluctuated during the century (between 69% and 76%). This suggests that apart from rainfall, Congo river discharge is driven by other factors, which may include the influence of human activities through deforestation and sand mining. While the interaction and exchange of fluxes within wetlands could disturb the variability of the Congo river, Conway et al. (2009) confirmed the dominant control of inter-annual and decadal rainfall variability in river flows whilst acknowledging the key roles of human interventions. Notably, a significant proportion of changes in the dominant discharge patterns is still not explained by those of rainfall. This information signals the threshold of complex hydrological processes in the region, and perhaps suggest the influence of anthropogenic contributions and strong multi-scale ocean-atmosphere phenomena as key secondary drivers of hydrologic variability.

[Figure 10]
[Figure 11]

The inter-annual variations and cumulative departures of rainfall and discharge were also explored to understand their interactions in the Congo basin (Fig. 9). The inter-annual variations during the 1901-2010 period was consistent and captures the wettest period (1960-1970) in the basin (Fig. 9a).

Their cumulative departures are somewhat similar but show an apparent inconsistent trend during the 1930-1950 and post 1999-2010 periods (Figs. 9b-c). Generally, there seems to be a change in the hydrological regimes of the Congo river, (especially after 1994) owing to the rather pervasive influence of extreme droughts. This again could be the aftermath of extreme droughts, which fluctuated between 50% (i.e., affected areas) in the early years of the century and 40% during the 1994-2014 period (Ndehedehe et al., 2019). This change is reflected in the observed temporal relationship between maximum rainfall and discharge (Figs. 10a-d). For example, the rainfall-discharge relationship was stronger in 1961-1990 (r = 0.77) and 1991-2010 (r = 0.69) compared with other climatological periods when correlations were weak (Figs. 10c and d). Moreover, the temporal series associated with the ICA-localised spatial rainfall patterns over the Congo basin are correlated with discharge (Fig. 11). As shown in the leading independent modes (Fig. 11), the discharge-rainfall relationship is strongest at the extreme south (r = 0.65) and north (r = 0.64) of the basin. These sections of the basin are characterised by considerable amplitudes in annual and seasonal rainfall (EOF-1, Figs. 5a-b, 6a-b and cf. 3). The relationship (rainfall and discharge) is also significant in other catchments where correlations of 0.56, 0.59 and 0.51 have been observed although temporal relationships of localised rainfall at the equator with discharge are poor and insignificant (α= 0.05). Given the trajectory of water inflow in the Congo basin, the considerable association of rainfall with discharge implies that the wetland hydrology of the Cuvette central is nourished mostly by rainfall, in addition to exchanges of fluxes in the floodplain wetlands.

4. Discussion and conclusion

The Congo basin is one of the most hydrologically active and pristine locations with limited understanding of how precipitation changes impacts on stream flow dynamics and variations in catchment stores. This poor understanding in the hydro-climatic processes of the basin is most often the results of gaps in hydrological information and insufficient observational networks for hydrological applications (e.g., Ndehedehe, 2019; Tshimanga and Hughes, 2014; Conway et al., 2009). Due to limited hydro-meteorological observation network in the basin, Munzimi et al. (2015) mentioned that much is still unknown about the Congo river basin's hydrological behaviour. The comparative assessment of precipitation estimates from GPCC and CRU data over the Congo basin was therefore undertaken to improve quantitative knowledge of Congo basin precipitation and its influence on river discharge. There are still some ongoing debates regarding the uncertainties and ambiguities in precipitation estimates from various products over the Congo basin. While that is not the focus of this chapter, results indicate both products (GPCC and CRU) are generally consistent with high correlation values and statistically insignificant difference in their means. However, the poor association between
these data in the Congo Cuvette central during the period could suggest dynamics in the availability of gauged stations. The GPCC is a widely used observational reference data unlike the CRU precipitation. The distribution of gauges is expected to vary in time and space and the GPCC-based precipitation product has more gauged observations available globally compared to the CRU-based precipitation.

The spatial distribution of rainfall in the Congo basin takes the form of a north–south dipole patterns. These patterns result in wet and dry seasons with opposite phase in the south and north of the basin. That is, the wet season in the south (December-February) coincides with dry season in the north and vice versa. The dipole patterns are caused by the difference in seasons, the more reason why the northern section is wet between May and October. The south on the other hand, remains relatively dry during the same period. The dipoles and this alternating seasonal rainfall patterns have been attributed to the position of the Congo basin across the equator (Munzimi et al., 2015). Be it trends, annual, or semi-annual amplitudes, rainfall during different climatological periods (1901-1930, 1931-1960, 1961-1990 and 1991-2014) over the Congo basin has undergone significant changes. These changes were also echoed by Samba and Nganga (2012) who reported on considerable declines in Congo rainfall between 1980 and 1990. The surrounding oceans, especially the Indian Ocean have been identified as an important source of observed precipitation experienced in wet years in the Congo basin (Dyer et al., 2017). Generally, the Congo basin and much of central Africa are hydrologic hotspots or web of climatic influence. For instance, the SST anomalies along the Benguela Coast, and warming or cooling of the three oceans (Atlantic, Indian, and Pacific) and indices of oceanic variability have been identified as key factors that govern the complex changes in precipitation patterns over West Central Africa (e.g., Ndehedehe et al., 2019; Balas et al., 2007).

As opposed to West Africa where 3-4 significant modes of rainfall variability have been identified (e.g., Ndehedehe et al., 2016a; Sanogo et al., 2015), there are actually more than five statistically significant modes of orthogonal rainfall modes of variability over the Congo basin. Physical interpretation and attribution could be challenging for some of these modes. However, we found that rainfall in the Congo basin is characterised by annual, multi-annual (or bimodal), trends, short term seasonal signals and those resulting from regional factors and atmospheric-ocean interactions and large-scale processes. Locally generated moisture and the interactions of the nearby oceans (Sorí et al., 2017; Dyer et al., 2017) with land surface processes in the basin could also contribute to the magnitude of seasonal variations observed in the Congo rainfall. Sorí et al. (2017) argued that the various sources of moisture for the Congo basin makes nourishment possible during extreme climate events (e.g., flood) thus modulating water balance within the region. On the one hand, this could be the reason for significant amount of rainfall in the Congo basin all through the year except during the June-July period in the southern catchment. On the other hand, the observed multiple significant modes of the Congo basin rainfall can be attributed to signals emanating from the combined influence of climate, natural variability, ocean interactions and the influence of land surface processes. As an example of the influence of land surface conditions on Congo precipitation, locally generated heat low and reduced precipitation were identified as the direct consequence of decreased evaporation over deforested area in Central Africa (Nogherotto et al., 2013). Arguably, this reassert the important role of land surface processes in the Congo basin (Koster et al., 2004). In this era of anthropogenic-induced climate change, the skills of global and regional climate models in reproducing the Congo basin climatology (spatial patterns, seasonality, and magnitude of precipitation) could be restricted due to uncertainties (Aloysius et al., 2016). However, the question of how the interactions of increasing anthropogenic pressure on the Congo forest and important processes of inter-annual variability impact surface water hydrology are therefore interesting future research directions.

So, has rainfall amounts varied comparatively less across the Congo basin despite known variations in the Congo river flow? In the analysis of historical space-time variability of rainfall (1901-2014) over the Congo basin we found that previous rainfall (1931-1990) varied more compared to the 1991-2014 period. As opposed to the two climatological periods between 1931 and 1990, rainfall varied less between 1991 and 2014. It is not clear if the time slice during this last climatological period contributed to this as it was not up to 30 years. However, there were more dry spells and drought events during this period (1991 and 2014) in the Congo basin compared to the last two climatological periods prior to 1991 (Ndehedehe et al., 2019; Hua et al., 2016). The strong positive anomalies of rainfall in extreme wet years are usually captured in the annual component and show strong spatial distributions (loadings) in the northern and southern sections. Although the analysis for the latter climatological period used only 23 years (1991-2014), the spatial distribution and amplitudes of rainfall is consistent and similar to other periods with relatively higher modes of variability. Generally, there seems to be a shift in the hydrological regimes of the Congo river, (especially after 1994). This change can be attributed to the rather pervasive influence of extreme droughts, which fluctuated between 50% (i.e., affected areas) in the early years of the century and 40% during the 1994-2014 period (Ndehedehe et al., 2019). To further support this argument, the rainfall analysis by Samba and Nganga (2012) in Congo-Brazzaville (Congo) during 1932–2007 period indicates that the largest rainfall deficits were observed in the 1980s and 1990s. And since 1985, Zhou et al. (2014) observed a consistent drying of the Congolese forest, which was attributed to gradual decline in precipitation. The change in rainfall trajectory in the post 1994 period is consistent with observed drought and drying in the region. In view of inconsistent trends between rainfall and discharge as evidenced in their cumulative departures, this suggests other key secondary drivers of hydrologic variability that are non-climatic exist in the basin.

The considerable association of discharge with rainfall in catchments characterised by strong annual and seasonal amplitudes in rainfall implies that the wetland hydrology of the basin is largely nourished by rainfall, in addition to possible exchange of fluxes within the Congo floodplain wetlands. Notably, a significant proportion of changes in the dominant rainfall patterns is still not explained by those of river discharge. This information signals the threshold of complex hydrological processes in the region. Importantly, it also suggests the influence of anthropogenic contributions (e.g., deforestation, changes in land cover states, surface water developments, etc.) and strong multi-scale ocean-atmosphere phenomena as key secondary drivers of hydrologic variability. Ultimately, it is obvious nonetheless, that several African regions have been identified as a hot spot with considerable influence of several climate teleconnections (e.g., El-Niño Southern Oscillation and Atlantic Multi-decadal Oscillation, Indian Ocean Dipole, etc.). Given the impacts of these multi-scaled climate indices
on rainfall variability and extreme climatic events (droughts and floods) in Africa (see, e.g., Ndehedehe et al., 2020; Gizaw and Gan, 2017; Diatta and Fink, 2014; Paeth et al., 2012), the combined influence of climate and human activities on hydrological variability is thus palpable and multi-faceted.

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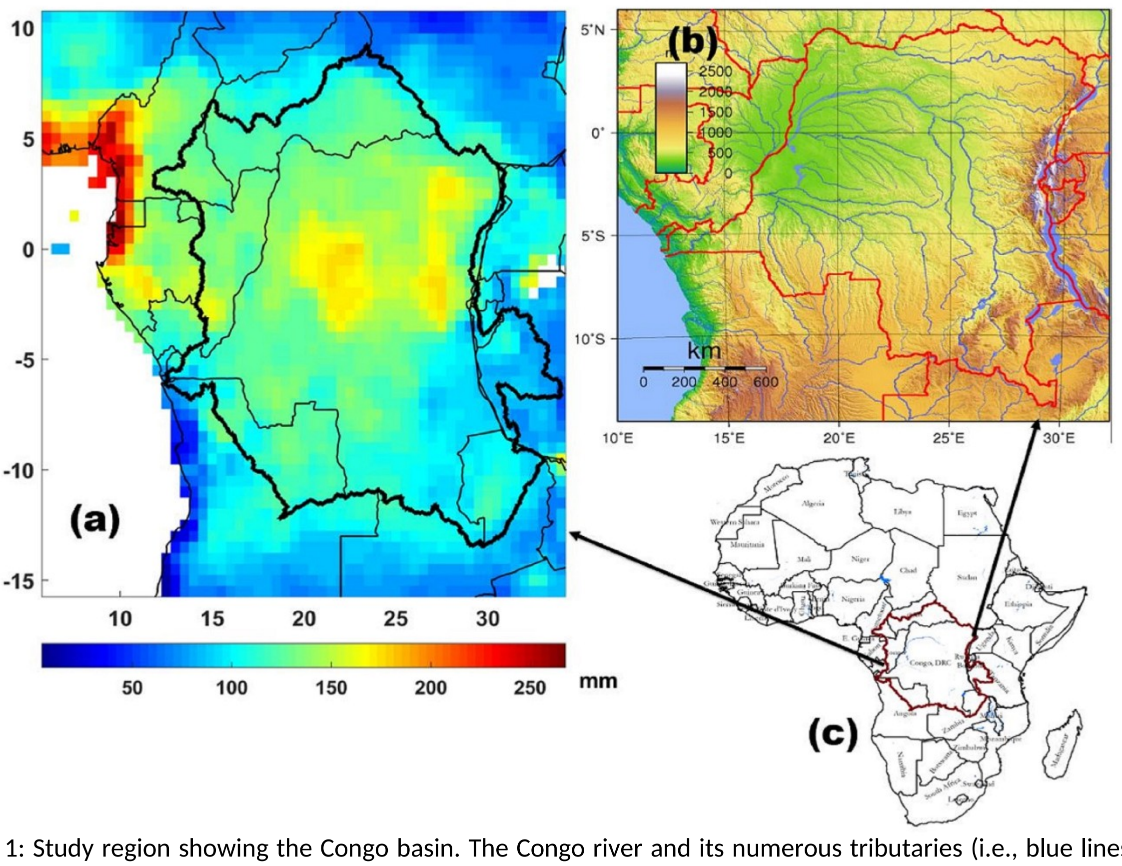

Figure 1: Study region showing the Congo basin. The Congo river and its numerous tributaries (i.e., blue lines on the left) are also indicated. (a) The aerial averaged monthly rainfall (mm), (b) topographic map of the Congo basin adapted from https://commons.wikimedia.org/wiki/File:Congo_Kinshasa_Topography.png, and (c) the location of the Congo basin in Africa. The blue lines and polygons in (b) are the river networks and water bodies in the Congo basin.

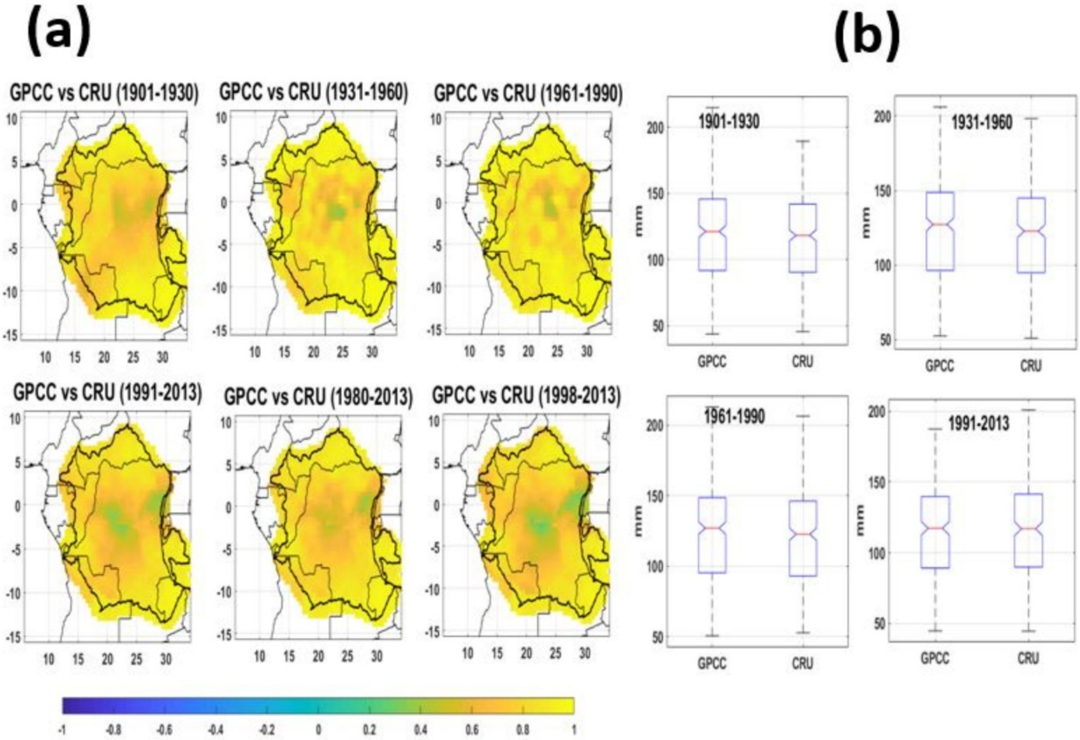

Figure 2: Relationship between GPCC and CRU-based precipitation over the Congo basin during different climatology. (a) Spatial distribution of correlation coefficients (*r*) and (b) analysis of variance (temporal patterns) between GPCC and CRU.

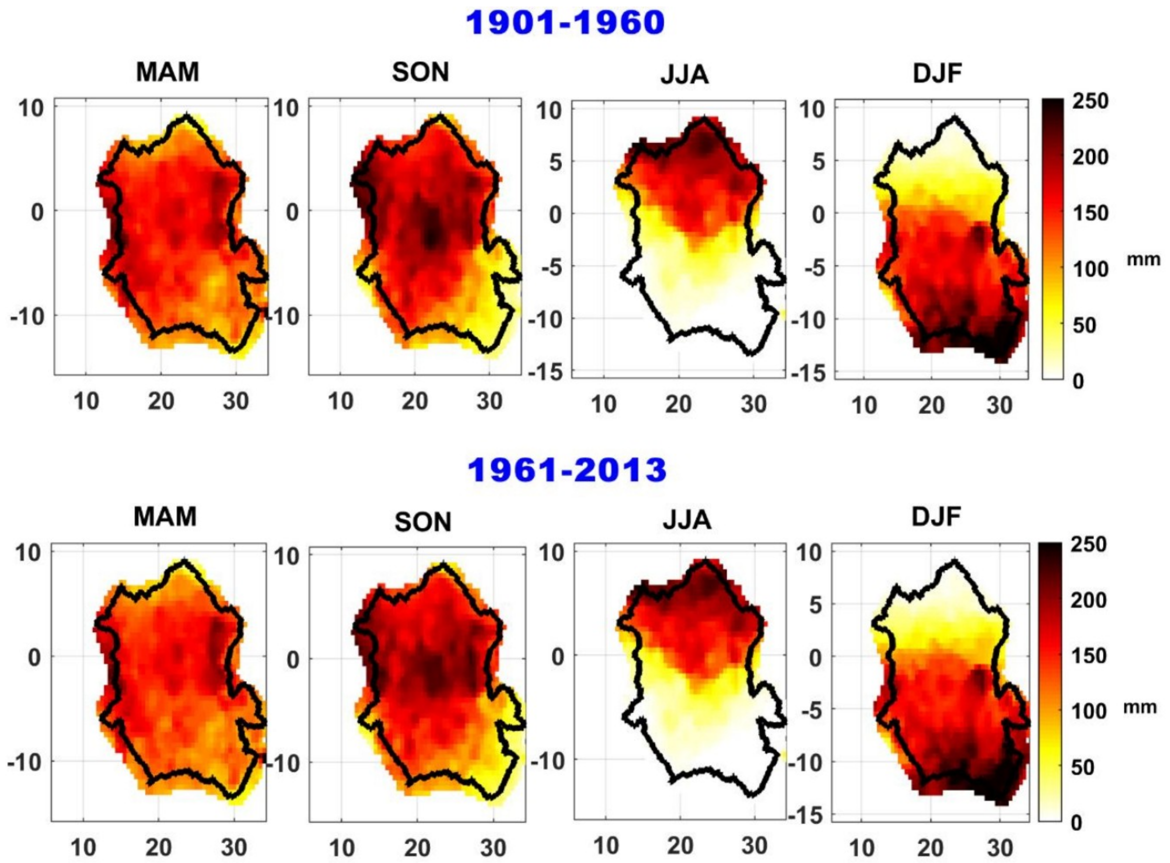

Figure 3: Spatial distribution of GPCC-based precipitation (mm) over the Congo basin during the 1901-1960 and 1961-2013 periods. The seasonal precipitation (March-May (MAM); June-August (JJA); September-November (SON); and December- February (DJF)) are classified based on the rainfall climatology of the region and is adapted with full permission from Ndehedehe et al. (2019).

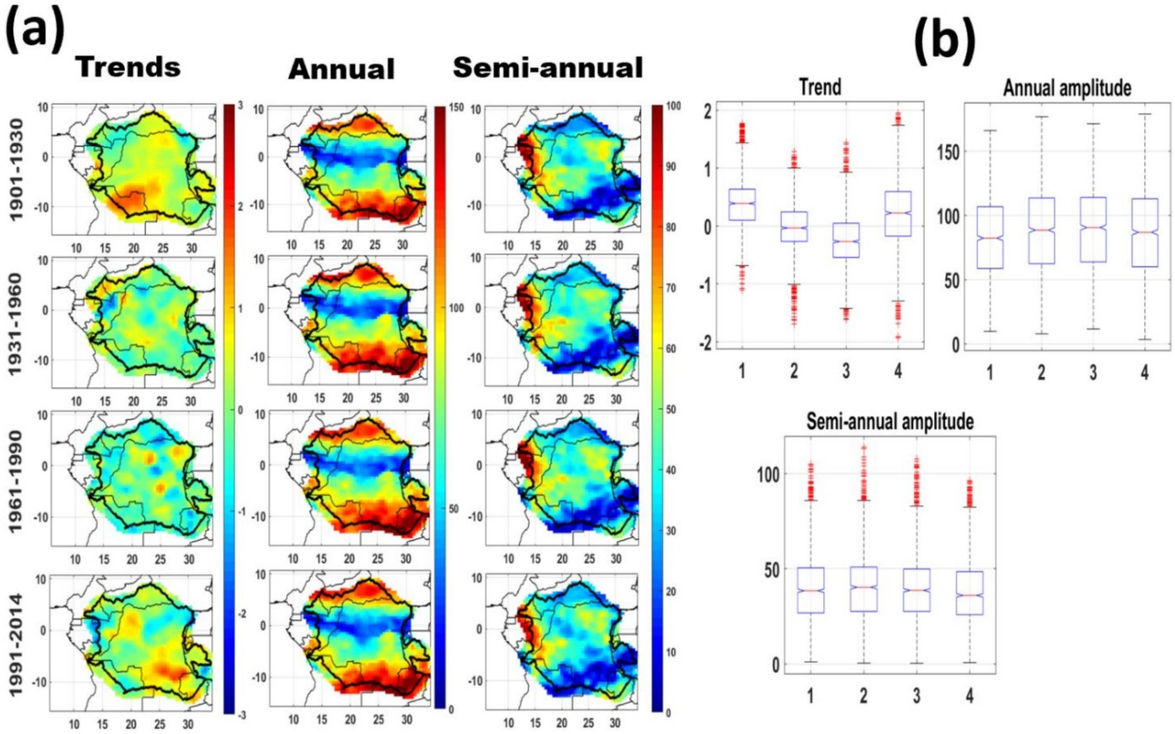

Figure 4: Analysis of (a) trends (mm/yr) and harmonic components (mean annual and semi-annual amplitudes) of rainfall (mm) based on the multiple linear regression (MLRA) technique and (b) their (trend, annual and semi-annual amplitudes) corresponding means over different climatology using analysis of variance.

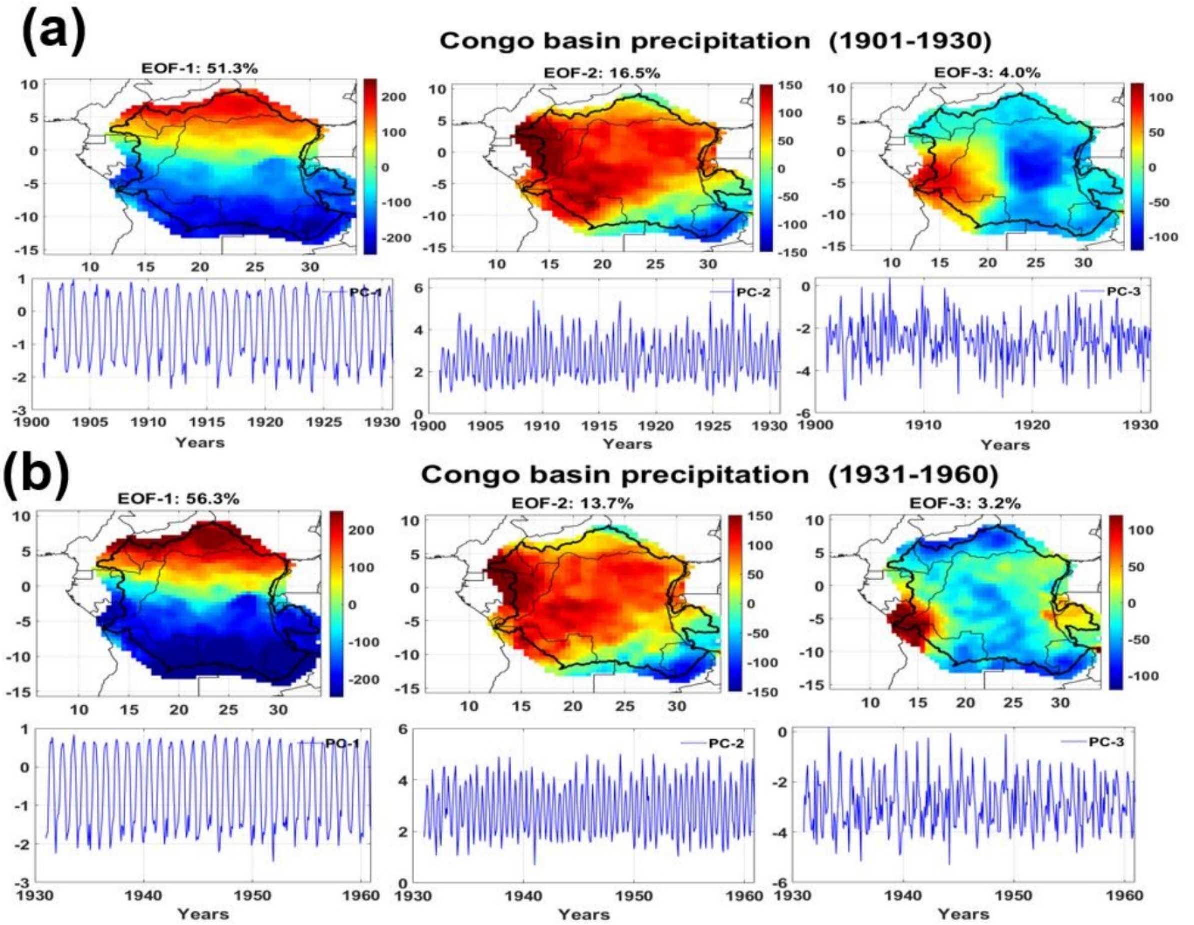

Figure 5: Spatial and temporal variability in the Congo basin rainfall (mm). The average spatial distributions of rainfall (top panels) and their corresponding temporal patterns (bottom panels) are indicated for different climatological periods (30-year interval). (a) Changes in the Congo precipitation during the (a) 1901-1930 and (b) 1931-1960. Spatial (EOF) and temporal (PCs) patterns are jointly interpreted. The total variability accounted for by each orthogonal modes of rainfall are expressed in percentages while the y-axes of the PCs are in standardised units.

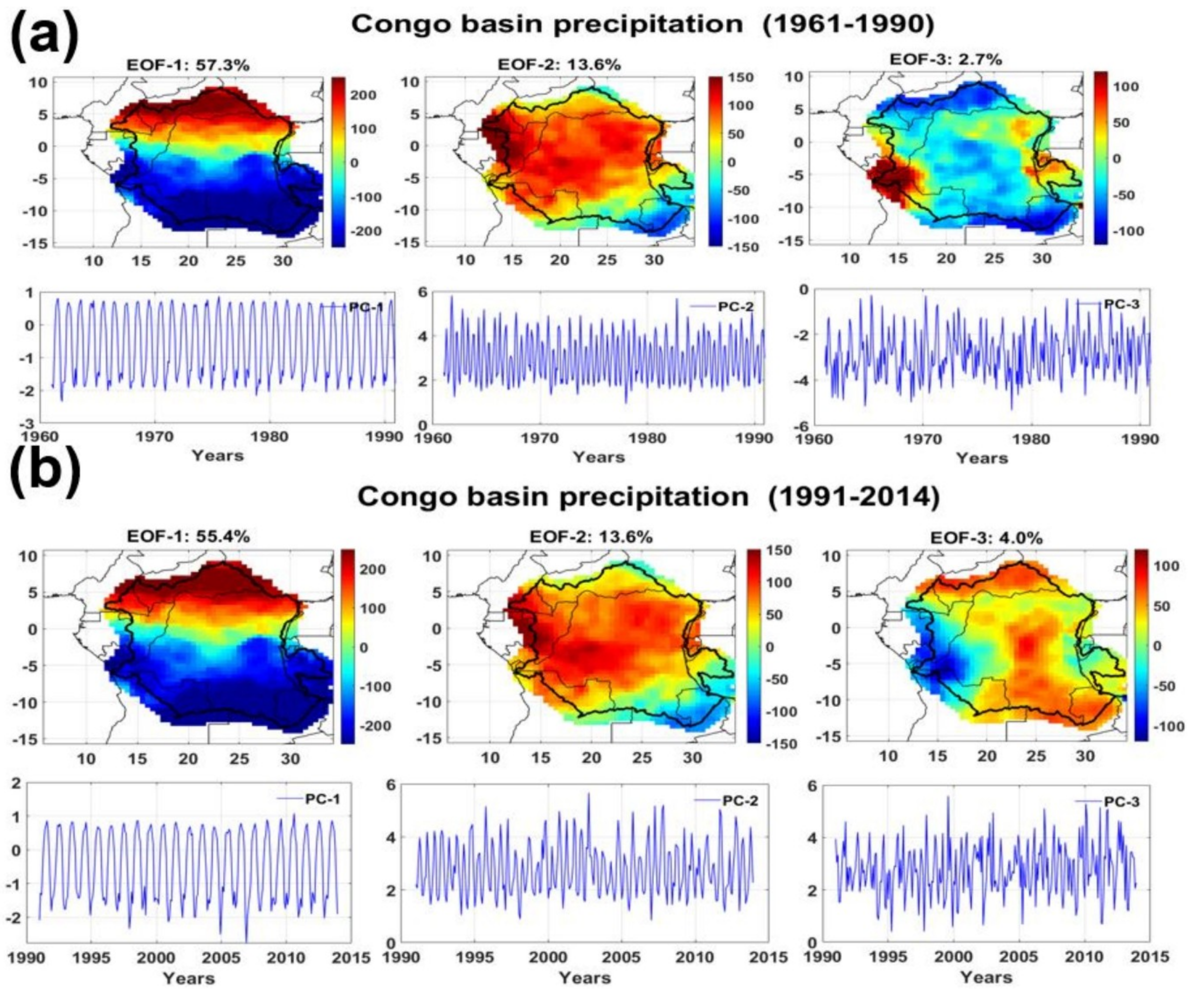

Figure 6: Spatial and temporal variability in the Congo basin rainfall (mm) similar to Fig. 5. (a) Changes in the Congo precipitation during the (a) 1961-1990 and (b) 1991-2014. The total variability accounted for by each orthogonal modes of rainfall are expressed in percentages while the y-axes of the PCs are in standardised units.

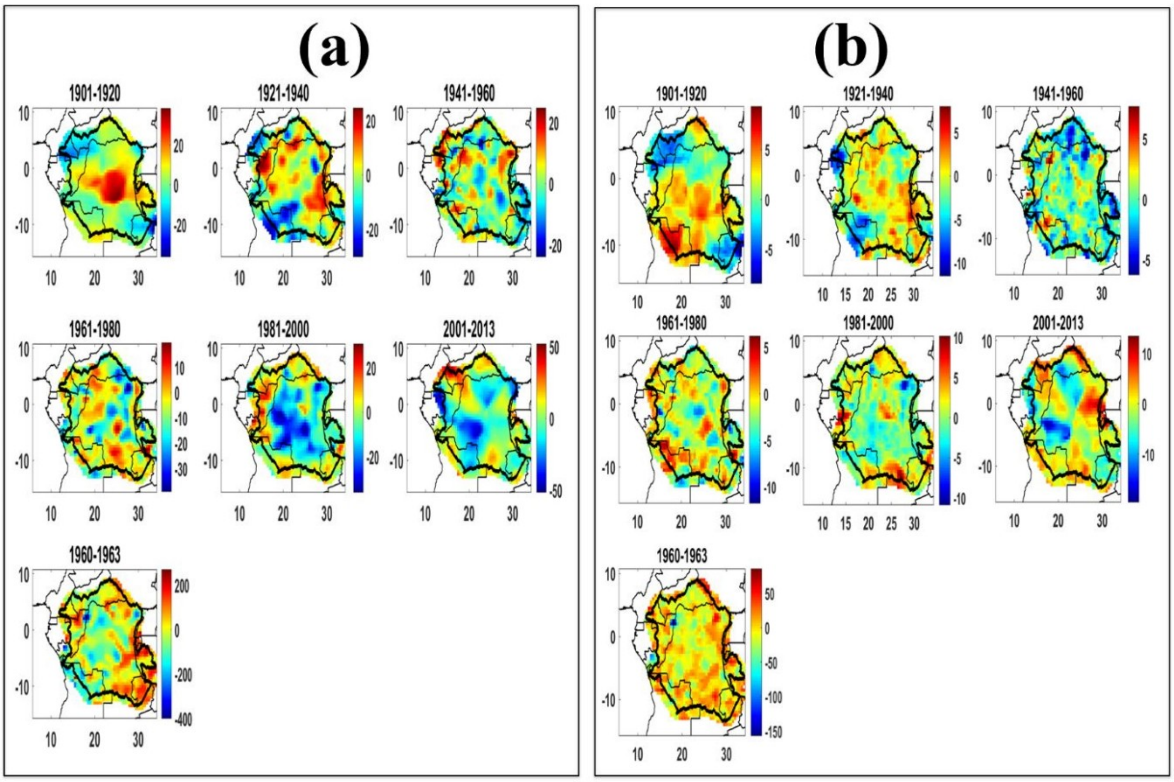

Figure 7: Spatial distribution of trends (mm/yr) in (a) annual and (b) maximum annual rainfall (mm) over the Congo basin. Estimated rainfall trends are based on 20 years interval except for the 1960-1963 and 2001-2013 periods.

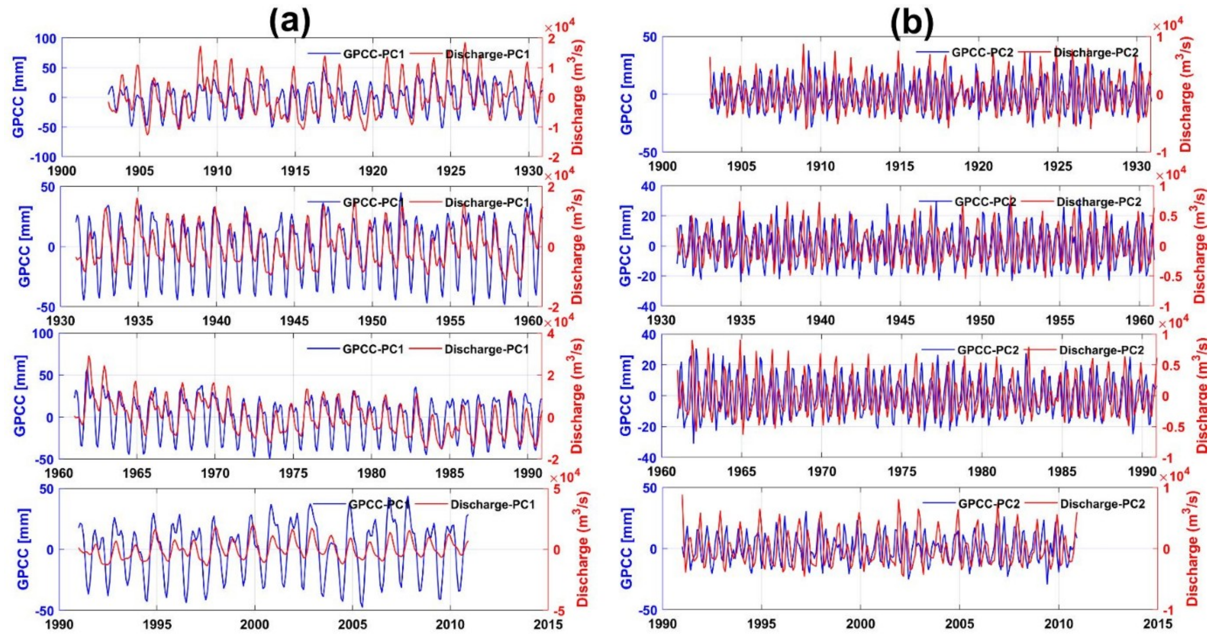

Figure 8: Dominant modes of river discharge time series of the Congo river between 1903 and 2010. The leading
modes (i.e., the annual variations and multi-annual variations) of river discharge are compared with those of precipitation. The time series of river discharge are the reconstructed expansion coefficients.

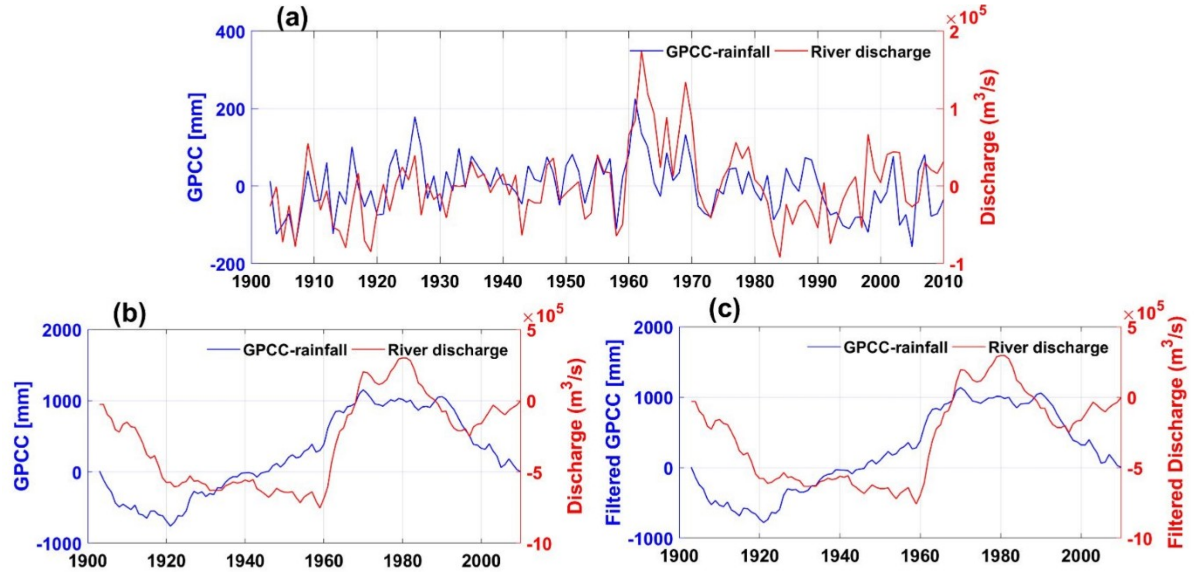

Figure 9: Inter-annual variations and cumulative departures of rainfall and discharge. (a) The temporal variations of rainfall and discharge anomalies, (b) the cumulative departures of rainfall and discharge, and (c) the cumulative departures of rainfall and discharge after applying the local least-squares polynomial approximation-based filter of Savitzky and Golay (1964) to smoothen out the effects of low frequency noise.

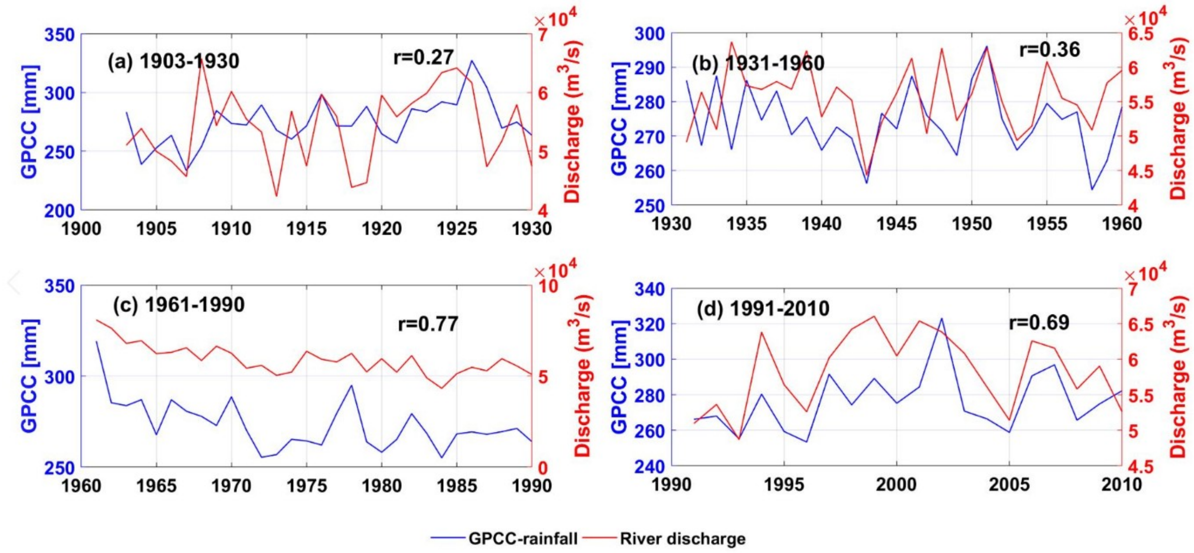

Figure 10: Temporal relationship between rainfall and discharge during the 1903-2010. This relationship is based on (a-d) maximum rainfall and discharge during different climatological windows.

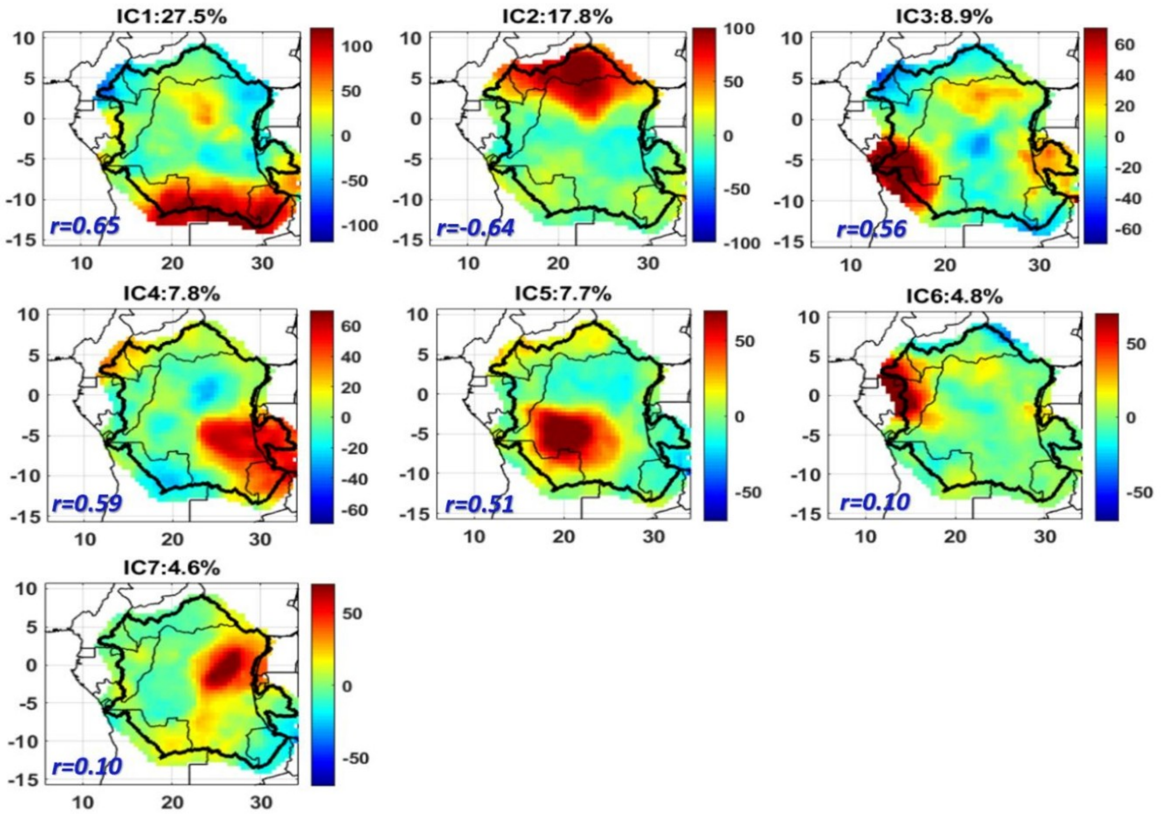

Figure 11: Localised rainfall (mm) over the Congo basin (1991-2010). The independent patterns (i.e., temporal patterns associated with this localized spatial maps) of rainfall from the ICA decomposition were compared with time series of river discharge.

Table 1: Percentages (%) of observed variance explained by leading rainfall and river discharge orthogonal modes during different climatological periods in the last century (1901-2010).

Variable	**Modes**	**1901-1930**	**1931-1960**	**1961-1990**	**1991-2010**
Rainfall	PC-1	59.1	62.3	63.2	60.2
	PC-2	32.8	31.7	31.9	31.0
Discharge	PC-1	69.3	69.6	76.1	75.5
	PC-2	27.4	27.2	21.4	22.8