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Research papers

Long-term variability in hydrological droughts and floods in sub-Saharan Africa: New perspectives from a 65-year daily streamflow dataset

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ABSTRACT

Understanding hydrological variability is of crucial importance for water resource management in sub-Saharan Africa (SSA). While existing studies typically focus on individual river basins, and suffer from incomplete records, this study provides a new perspective of trends and variability in hydrological flood and drought characteristics (frequency, duration, and intensity) across the entire SSA. This is achieved by: i) creating a 65-year long, complete daily streamflow dataset consisting of over 600 gauging stations; ii) quantifying changes in flood and drought characteristics between 1950 and 2014; iii) evaluating how decadal variability influences historical trends. Results of daily streamflow reconstructions using random forests provide satisfactory performance over most of SSA, except for parts of southern Africa. Using change-point and trend analyses, we identify-three periods that characterise historical variations affecting hydrological extremes in western and central Africa, and some parts of southern Africa: i) the 1950s–60s and after the 1980s–90s, when floods (droughts) tend to be more (less) intense, more (less) frequent and more (less) persistent; and ii) the 1970s–80s, when floods (droughts) are less (more) intense, less (more) frequent and less (more) persistent. Finally, we reveal significant decadal variations in all flood and drought characteristics, which explain aperiodic increasing and decreasing trends. This stresses the importance of considering multiple time-periods when analysing recent trends, as previous assessments may have been unrepresentative of long-term changes.

1. Introduction

Climate change is increasingly manifested by global increases in the frequency and magnitude of hydrological extremes (i.e., floods and droughts), with severe impacts on economies, livelihoods, and the environment (Jonkman, 2005; Di Baldassarre et al., 2010; Winsemius et al., 2016; Zhang et al., 2019). This is particularly important in sub-Saharan Africa (SSA), where historical trends and variability in hydrological extremes have led to devastating consequences (Di Baldassarre et al., 2010; Shiferaw et al., 2014). For example, in SSA over the 20th and 21st centuries, drought alone has resulted in more than 800,000 deaths and 2 billion USD in economic damages according to the Centre for Research on the Epidemiology of Disasters (Masih et al., 2014). Similarly, flood events have had an overwhelming impact on lives and economies (Bates et al., 2008; Di Baldassarre et al., 2010; Winsemius et al., 2018; Lumbroso, 2020), and these impacts have been steadily increasing over the last 70 years (Tramblay et al. 2020a).

Over the second half of the 20th century, several studies report increasing trends in flood magnitude in western Africa (Descroix et al., 2013, 2018; Nka et al., 2015; Aich et al., 2016; Do et al. 2017; Wilcox et al., 2018; Tramblay et al. 2020a), eastern Africa (Bernard et al., 2013; Degefu et al., 2019; Tramblay, et al., 2020a), and southern Africa (Do et al. 2017; Tramblay et al. 2020a). These studies, however, are too often restricted to the catchment scale, limiting interpretations of the relative

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role of climate change from those of catchment properties (e.g., groundwater support, land-use change, and human consumption (Kingston et al., 2020). This has been identified as one of the main challenges for the hydrological community over the coming decades (Blöschl et al., 2019). Meanwhile, little is known about historical trends in hydrological drought in SSA (e.g., Paturel et al., 1998, Servat et al., 1998, Tramblauer et al., 2014). Over this region, most studies have indeed focused on meteorological drought (e.g., Masih et al., 2014; Malherbe et al., 2016; Lweendo et al., 2017; Onyutha, 2017; Degefu et al., 2019; Gebremeskel Haile et al., 2019), which does not necessarily translate into hydrological droughts (Van Loon & Van Lanen, 2012; Van Lanen et al., 2016). In addition, most studies on hydrological extremes in SSA focus on one characteristic, i.e., maximum and minimum flow. Yet the frequency, duration, and intensity of floods and droughts are equally vital metrics for effective water management because they determine the type of mitigation strategy that is most effective (Bond et al., 2008; Yang & Liu, 2020). Similarly, most studies focus on either floods or droughts, but not both, despite a need for water management strategies, plans and policies to consider both extremes (Di Baldassarre et al., 2010; Rangecroft et al., 2016; Brunner et al., 2021).

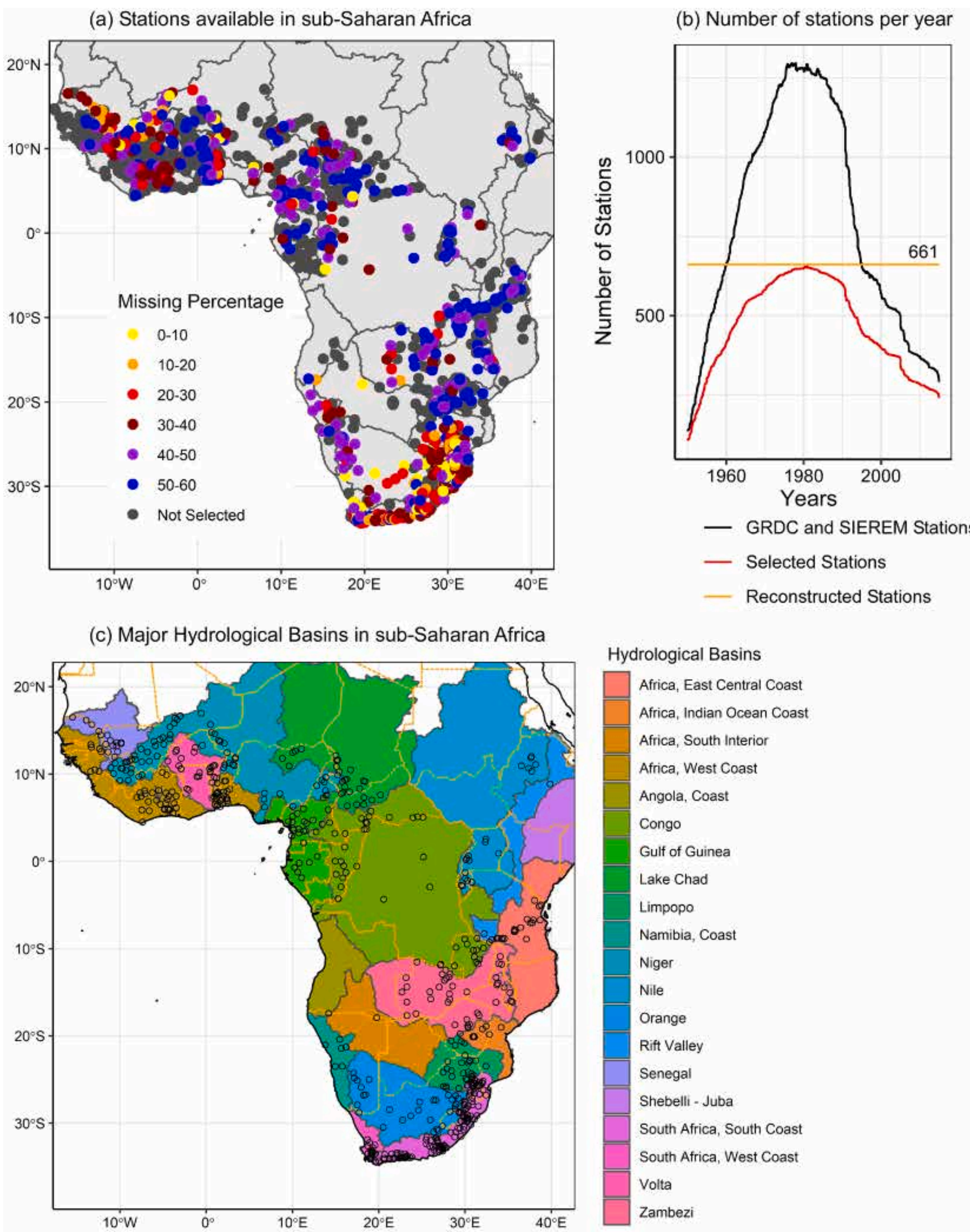

Fig. 1. The compiled daily streamflow database over the major hydrological basins of SSA. a) Spatial distribution of streamflow gauge stations from the SIEREM and GRDC databases. Grey dots highlight stations that were rejected, while colour shading indicates the location of selected stations along with the missing percentage of data between 1950 and 2014. b) Number of stations available each year in the period 1950–2014, selected for analysis (black line = total number of stations from the SIEREM and GRDC that are available for SSA, red line = total number of stations selected for the study, orange line = total number of reconstructed stations, n = 661). c) Major hydrological basins in SSA (Source. FAO-GeoNetWork. Accessed in November 2021) and the compiled hydrological database. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Data scarcity, however, remains a considerable challenge impacting the study of hydrological extremes across SSA (Mahe et al., 2013; Do et al., 2017; Dixon et al., 2020; Tramblay et al., 2020a-b), and limiting such efforts. Global datasets used to study hydrological extremes, such as the Global Runoff Data Centre (GRDC) dataset, are relatively short, with several gaps in their record for the African continent (Dixon et al., 2020). In addition, these datasets are not always quality-controlled, especially over SSA (Hannah et al., 2011; Tencaliec et al., 2015; Giustarini et al., 2016). Recently, by combining the GRDC dataset with the data collected and analysed over the last 70 years by the French Institute for Research and Development (IRD), Tramblay et al. (2020b) compiled the first daily African Database of Hydrometric Indices (ADHI), spanning the entire continent between 1950 and 2018. Subsequently, the ADHI was used to further understand continental trends in annual maximum flow (Tramblay et al. 2020a). However, the ADHI dataset presents numerous and random gaps with varying lengths over most regions in SSA, which could limit the accurate detection of trends and variability (Slater & Villarini, 2017).

Therefore, this paper aims at characterizing patterns of trends and variability in the frequency, duration, and intensity of both flood and drought events, for the first time, across SSA. This is accomplished by presenting a new reconstructed gap-free daily streamflow dataset, enabling us to examine 65 complete years of data. This long-term record, free of gaps, is indeed crucial to separate the influence of interannual to decadal variations on potential trends (Hannaford et al. 2013; Dieppois et al., 2016; Sidibe et al. 2018). The paper is organized as follows. In Section 2, we present the study area, datasets, and methods used. In Section 3, we evaluate the performance of the gap-filling methods used to generate a robust and complete streamflow dataset for SSA. Then, we examine changes (abrupt and gradual) and variability in streamflow. In Section 4, we summarize our main results and discuss their wider implications.

2. Methods AND DATA

2.1. Data

Daily streamflow data are collected from a large database of daily river discharge data, obtained from the "Système d'Informations Environnementales sur les Ressources en Eaux et leur Modélisation" (SIEREM: http://www.hydrosciences.fr/sierem/; Boyer et al., 2006) and GRDC (https://portal.grdc.bafg.de/) databases. From these databases, we collected 1764 stations with a minimum of 10 years of data from 1950 to 2018 across SSA (Fig. 1a-b). Geographic data for the major basins and river networks in the SSA are also extracted from the GRDC database. Previous studies have restricted the selection of stations to those with no more than 50 % of missing data (e.g., Sidibe et al., 2018; Arriagada et al., 2021). Here, from the original 1764 daily streamflow gauges, we first selected stations with a maximum of 60 % missing data (totalling 720 stations) to ensure adequate spatial coverage (Fig. 1a), and then evaluated the data quality in the remaining stations i.e., checking for the presence of thresholding in the maximum streamflow due to gauge rating curve exceedances, and the presence of anomalous data especially in southern Africa as noted in previous studies (e.g., Valimba et al., 2005; Trambauer et al., 2014; Chawanda et al., 2020), to retain 661 stations. Using all stations with a maximum of 60 % missing data also ensures that the gap-filling procedure is informed with sufficient data to identify robust statistical relationships (cf. Section 2.2).

As illustrated in Fig. 1a, the density of the compiled database is particularly large over western and southern Africa. Southern African stations also have the lowest percentage of missing data over the study period (Fig. 1a). However, the Congo River, the largest basin in Africa andsecond-largest river in the world, is very poorly covered by gauging stations with long time series, although it represents about half of the freshwater flowing into the Atlantic Ocean from Africa (Alsdorf et al., 2016). Time coverage of daily streamflow data is more limited in the 1950s–60s, which is the beginning of the hydrological networks in many countries, and the post-1990s (Fig. 1b). Furthermore, to simplify, analysis and interpretation of trends and variability are stratified according to 19 major hydrological basins (Fig. 1c).

2.2. Creating a complete daily streamflow dataset for SSA

To reconstruct a complete daily streamflow dataset between 1950 and 2014, we use a random forest (RF) algorithm. RF is a machine learning technique that relies on classification and regression algorithms to learn from a set of variables to predict another variable (Breiman, 2001). RF algorithms have already been used successfully for reconstructing complete daily to monthly streamflow datasets in western Africa (Sidibe et al. 2018) and South America (Arriagada et al. 2021). Tyralis et al. (2021) highlight that the RF reconstructing and forecasting skills are stronger than those of multiple linear regressions and neural networks. Specifically, a new variant of the original RF, known as "missranger" (MR; Wright & Ziegler, 2018), is chosen for this study. The MR algorithm was designed to overcome some of the limitations of the original RF, which does not scale well with increasing data (Wright & Ziegler, 2018). Additionally, the MR algorithm is faster and less computationally demanding than the original RF (Wright & Ziegler, 2018).

Cross-validation of the results of the reconstruction is performed by running 1000 simulations, randomly generating artificial gaps of six years for each station. Reconstructions from the MR algorithm are then evaluated against the original data using the Kling-Gupta efficiency (KGE; Kling et al., 2012) and the Nash–Sutcliffe efficiency (NSE; Nash & Sutcliffe, 1970). When all modelled values are equal to the mean of observations, KGE and NSE are equal to -0.41 and 0, respectively (Knoben et al., 2019). The best model performance is given by KGE and NSE equal to 1. Thus, in the present study, all stations showing an NSE less than 0 or KGE $<$ -0.41 in the cross-validation results are considered unacceptable. In addition, to provide a more comprehensive assessment of the goodness of fit, we quantify the number of stations showing good performances (i.e., NSE and KGE greater than 0.5; Knoben et al. 2019).

2.3. Hydrological extreme indicators

We examine the duration, intensity, and frequency of both hydrological droughts and floods in SSA. As the nature and development of floods and hydrological drought events are different, their detection and characterization are too. The following two sub-sections discuss the methodology we employ to characterize them.

2.3.1. Flood event characterization

Although flood peaks play a crucial role, the peak alone may not properly depict a flood nor its impact (Blöschl et al., 2013). Aspects like the frequency, intensity, and duration of an event are vital characteristics of flood typology to be considered (Diederen et al., 2019; Fischer et al., 2019; Tarasova et al., 2019). Such characteristics can be estimated through event separation methods (Fischer et al., 2019).

Here, we use a peak-over-threshold (POT) approach that relies on a baseflow separation method to determine the start and end of flood events (Mangini et al. 2018; Oppel & Mewes, 2020). As in Mangini et al. (2018), the start of each flood event is determined when the flow starts to increase suddenly, while the end of the event is determined when the plot of log-transformed flow versus time becomes straight. To achieve this, the baseflow is estimated using the Chapman digital filter (Chapman, 1999), and the recession constant is determined for each station using the approach by Thomas et al. (2013). The start and end of each event are defined using a 3-day centred moving average. Following recommendations from Mangini et al. (2018), recessions with durations lower than 10 days are not considered. The direct runoff is then computed as the difference between the baseflow and streamflow (Mangini et al., 2018; Tarasova et al., 2018; Giani et al., 2021). Finally, we compute the annual frequency of events and maximum flood duration. Meanwhile, flood intensity is estimated from the ratio between the volume and duration of flood events. Note that we also tested different thresholds, such as 2, 4, 5, and 8 events per year, but this did not significantly impact our results (not shown).

2.3.2. Drought event characterization

Understanding hydrological drought processes and impacts require one to examine drought characteristics like timing duration, severity or intensity, and extent (Tallaksen & Lanen, 2004; Mishra & Singh, 2010; Van Loon, 2015; Oikonomou et al., 2020). This can be accomplished using fixed or variable thresholds. Here we use a variable threshold because it considers the seasonality of drought (Van Loon et al., 2015, 2019; Kozek & Tomaszewski, 2019; Sutanto & Van Lanen, 2020; Tomaszewski & Kozek, 2021).

For each month, the flow duration curves are computed, and the 80th percentile is calculated, before being smoothed using a centred average of 30 days (Van Loon, 2015). Then, mutually dependent droughts are pooled based on the inter-event time method (Fleig et al., 2006). Here, for all catchments, an inter-event period of 10 days is used, as recommended by Tallaksen et al. (1997) and Fleig et al. (2006). In our study, according to previous studies (e.g., Van Loon & Van Lanen, 2012; Kozek & Tomaszewski, 2019; Van Loon et al., 2019; Sutanto & Van Lanen, 2020; Tomaszewski & Kozek, 2021), we used a duration limit of 15 days for minor droughts. As shorter drought duration could have also been used (e.g., Fleig et al., 2006), we also tested shorter duration droughts, such as 5 and 10 days, but this did not significantly impact our results (not shown).

From this procedure, we estimate the annual frequency of drought events and maximum drought duration. Annual maximum drought intensity is estimated by dividing the volume deficit by the drought duration.

2.4. Detecting historical changes and trends in hydrological extremes

2.4.1. Step changes detection

To investigate potential long-term changes in the different characteristics of flood and drought, we first perform a change-point analysis. Several change point tests are normally used to detect abrupt changes in streamflow time series. Here, we use an algorithm for a non-parametric multiple change point analysis that uses dynamic programming and pruning, based on the Kolmogorov-Smirnov statistics, known as the change point procedure via pruned objectives (CP3O; Zhang et al. 2017). For any type of distribution within a given dataset, this method detects the number of change points and their locations simultaneously. This is particularly important for hydrological extremes, whose distributions depart from the normal distribution.

2.4.2. Trend analysis

We then investigate the presence of trends in the flood and drought characteristics. We examine how the historical baseline trends (1950–2014) compared to those identified in a recent period defined by the step changes. For the duration and intensity of events, we use the Mann-Kendall (MK) statistical test (Mann, 1945; Kendall, 1975), which is a non-parametric and rank-based method that has been extensively used for detecting trends in hydrological variables (Kundzewicz & Radziejewski, 2006; Wang et al., 2020). As the MK test can only be used when the data are independent and is not robust against serial correlation, we use a modified MK trend test with iterative pre-whitening of the series (Zhang et al., 2000; Zhang & Zwiers, 2004), as recommended in (Bürger, 2017). To detect changes in the time series of discrete events, i.e., flood and drought frequency, we use Poisson regression to quantify the trend statistical significance (e.g., Vormoor et al. 2016; Mangini et al., 2018b; Hodgkins et al., 2019).

2.4.3. Trend versus long-term and decadal variability

Trend analysis strongly depends on the start and end dates chosen to compute them because long-term and decadal variations are very likely to influence the trend magnitude over specific decades (Chen & Grasby, 2009; Hannaford et al., 2013; Onyutha, 2016; Sidibe et al., 2018). To assess the contribution of long-term trends and decadal variations, we use a multi-temporal trend analysis, where trends are analysed recursively for every segment of 10 to 65 years within the time series. Here, over each segment of the multi-temporal trend analysis, the rate of change is estimated using the Theil-Sen approach, which is less sensitive to outliers than linear regression methods (Theil, 1950; Sen, 1968). To assess the significance of trends for the intensity and duration, we use the MK test (cf. Section 2.4.2). For the frequency of events, we use a significance test based on Poisson regression (cf. Section 2.4.2). Further details about how the multi-temporal trend analysis is constructed and interpreted are available in Supplementary Material (Fig. S1). To facilitate comparisons between regions, this test is applied to regionally average duration, intensity, and frequency of events.

Finally, we examine how strong decadal variations in flood and drought characteristics are over SSA. Decadal variations ($\geq$9 years) in the frequency, duration, and intensity of flood and drought events have thus been extracted using maximum overlap discrete wavelet transform (MODWT; Percival & Walden, 2000; Quilty & Adamowski, 2018; Sidibe et al., 2019). To do so, we use a least asymmetric (LA 8) wavelet filter, as recommended for the decomposition of turbulent signals (Cornish et al., 2006; Roushangar & Alizadeh, 2019). We then calculate the percentage of explained variance by comparing the variance of decadal variations to the total variance of the time series (i.e., the variance of non-filtered time series). The significance of decadal variations has been estimated by quantifying the probability that decadal variance exceeds the variance that would be detected at the same timescale in random noise. We thus use 1000 Monte-Carlo simulations of a signal presenting the same autoregressive (1) coefficient at lag-1 (AR[1]), mean, and standard deviation.(Sidibe et al., 2018; Dieppois et al., 2019).

3. Results

3.1. Performances of daily streamflow reconstructions

The RF algorithm is applied to all stations with less than 60 % missing data (661 streamflow gauges). Note, however, that the results are overall similar using all stations with less than 50 % missing data, but the RF gap-filling performance decreases when including stations with more than 70–90 % of missing data (not shown). For all stations, cross-validated KGE is greater than -0.4, but NSE is less than 0 for 45 stations out of the 661 stations (i.e., 7 %; Fig. 2a-b). Thus, based on the KGE and NSE, 616 daily streamflow gauges (i.e., 93 %) are reconstructed with acceptable results (cf. Section 2.2). In addition, over 72 % of stations are reconstructed with good performances according to the KGE and NSE (i.e., KGE and NSE $>$ 0.5).

Cross-validated NSE and KGE results are greater over western Africa, with an average performance higher than 0.9 (Fig. 2a-b) due to the high density of stations available for this region. Similarly, the performance of the RF algorithm is very high across the two major basins of central Africa (Lake Chad and Congo), where the mean KGE and NSE values are greater than 0.9 (Fig. 2a-b). These results are therefore consistent with previous studies reconstructing daily streamflow over the Volta basin using direct sampling (Dembélé et al. 2019). Likewise, these daily reconstructions provide similar performances to the monthly reconstructions of western and central African streamflow provided by Sidibe et al. (2018), using RF and multivariate imputations by chained equations. Across eastern Africa, the performances are generally good, but appear lower in the Nile basin (KGE and NSE of 0.85 and 0.71, respectively; Fig. 2a-b). Across southern Africa, the performances show large differences between several catchments in the region. Greater performances are observed in the Zambezi River and the South Africa

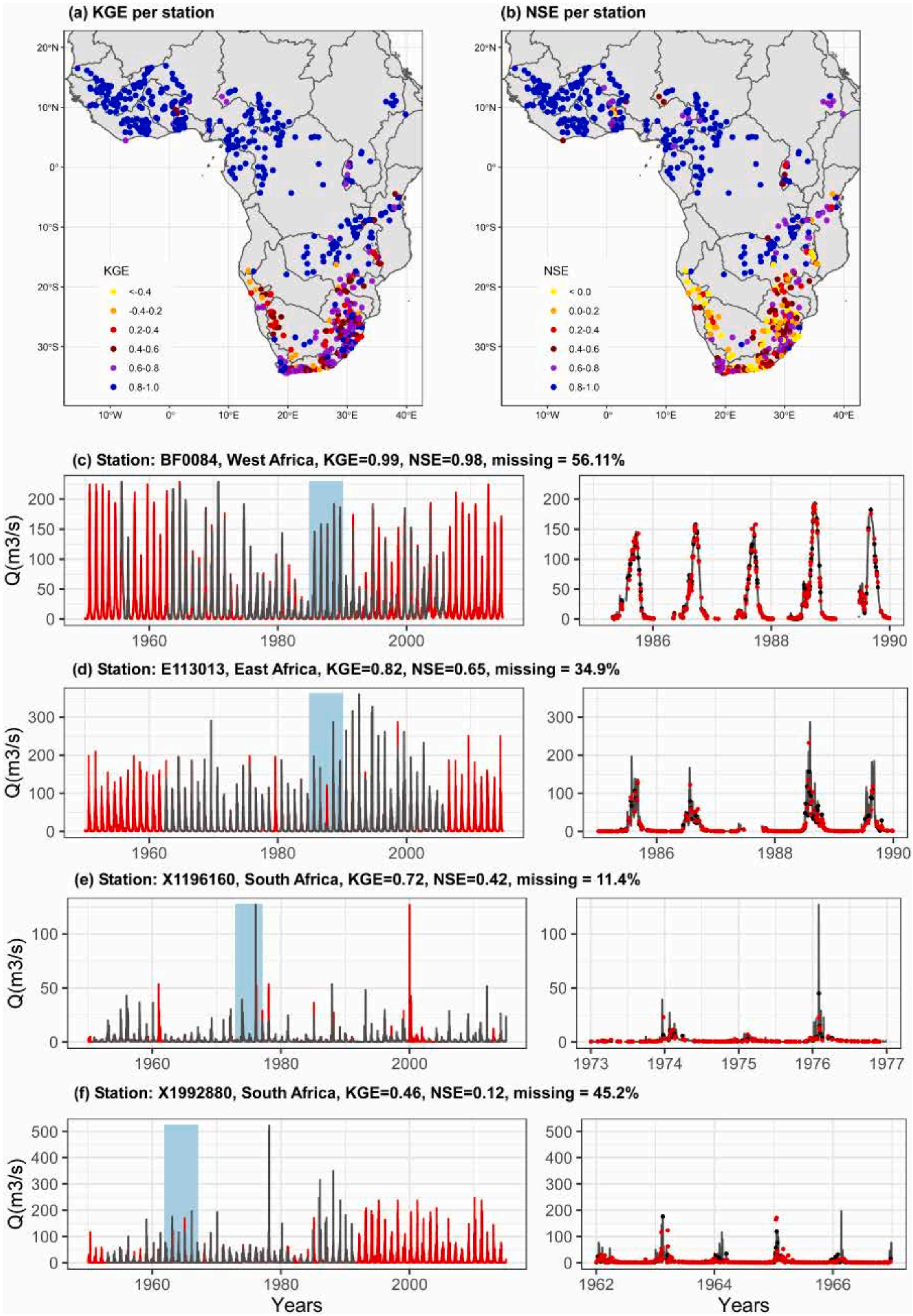

Fig. 2. Performance of RF-based reconstruction over SSA. a) Spatial distribution of the cross-validated KGE Model performance evaluated using the KGE. b) Same as a) but using NSE. c- f) Comparison between best-performing (c-d) and least performing (e-f) cross-validated reconstructions (red lines) and the original daily streamflow time series (grey lines) for a sample of station hydrographs. The panels to the right of (c) to (f) are samples outlined in blue from the 65 years. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

West Coast basins, where 63 % of stations show NSE greater than 0.6 (Fig. 2a-b). Results are generally lower over the Orange River, Limpopo River and the Namibia coastal basin, with a mean KGE and NSE of 0.58 and 0.33, respectively (Fig. 2-b). Nevertheless, over some parts of southern Africa, our results show greater performances than previous studies modelling historical monthly streamflow (Chawanda et al., 2020). We note that the presence of changed flows due to human influence (i.e., river regulation, dams, irrigation) in southern Africa is the likely reason for the weakened model performance. For instance, Brunner (2021) found that reservoir regulation impacts regional hazards by reducing spatial flood connectedness, which could significantly reduce the performance of RF reconstructions.

Overall, the RF algorithm reproduces quite well the observed streamflow hydrographs (Fig. 2c-f). As illustrated in Fig. 2c-f, both the

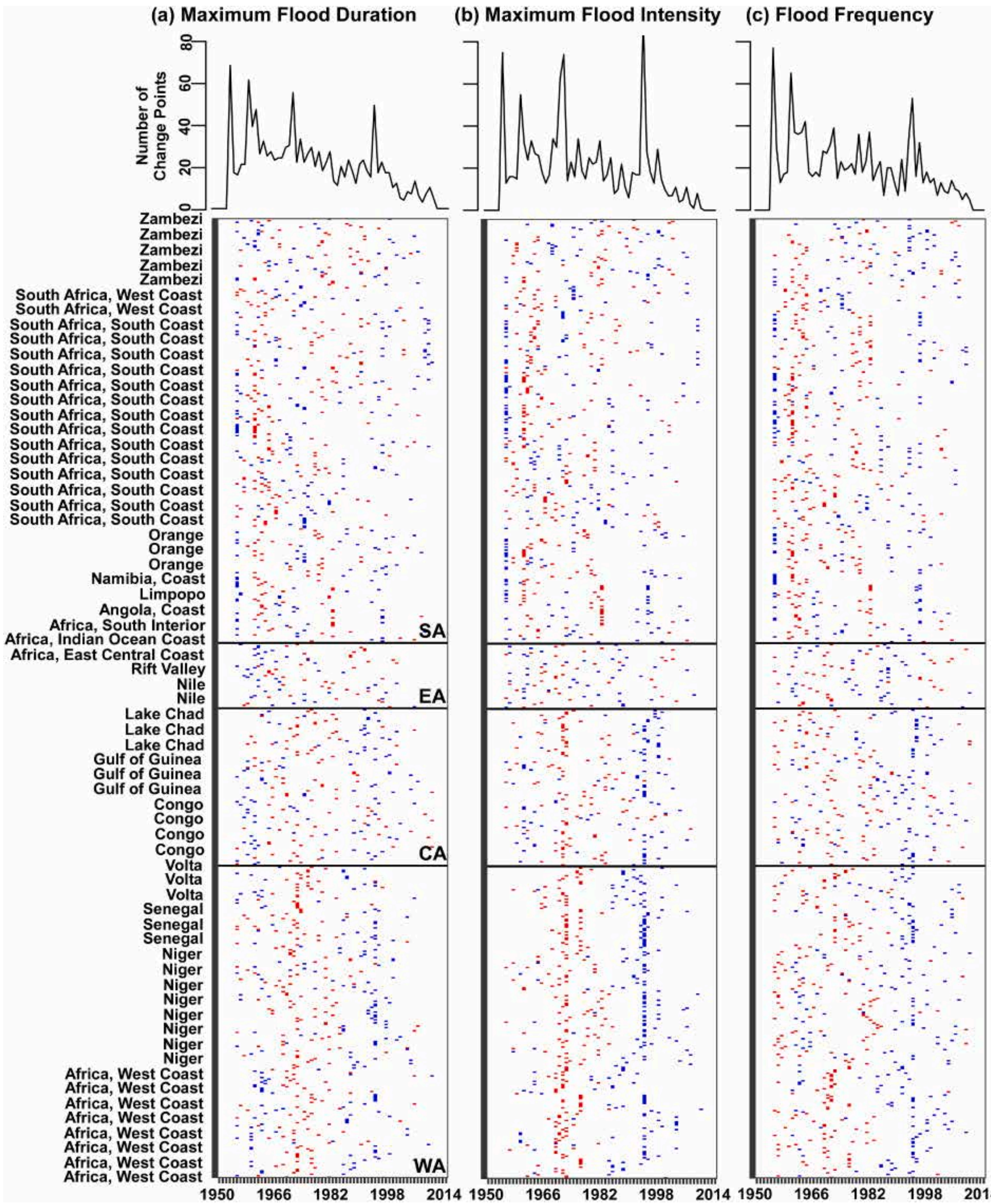

Fig. 3. Temporal location of step-changes in flood event characteristics over SSA. Positive and negative shifts in the mean flood characteristics (intensity, duration, frequency) are displayed in blue and red, respectively. a) Annual frequency (top) and regional distribution (bottom) of step-changes in annual maximum flood duration across the 616 reconstructed time series. b-c) Same as a) but for annual maximum flood intensity and annual flood frequency. Step changes are identified using the C3PO method (Zhang et al. 2017). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

high-flow and low-flow characteristics, such as the timing, duration, and shape, are generally well represented even in regions where cross-validation results are lower (Fig. 2c-f). Nevertheless, in some regions of southern Africa where streamflow is more intermittent and highly seasonal, the RF algorithm shows some limitations in reconstructing peak flows (Fig. 2f).

3.2. Historical step-changes in flood and drought event characteristics

Statistical analysis of multiple change-points has been carried out for the annual maximum duration, maximum intensity, and frequency of flood and drought events between 1950 and 2014 using the CP3O approach (Zhang et al., 2017).

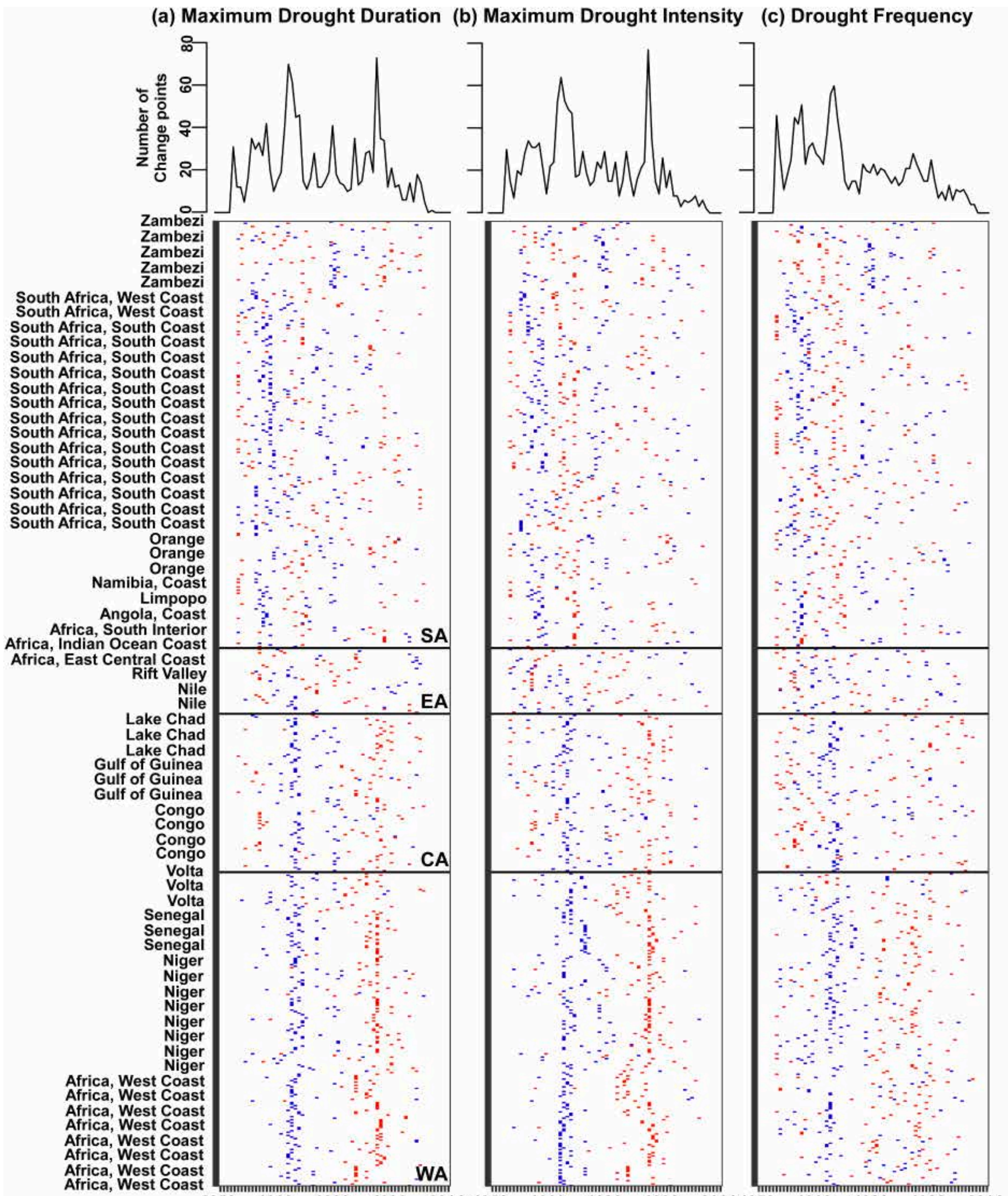

Fig. 4. Temporal location of step-changes drought event characteristics over SSA. Positive and negative shifts in the mean drought characteristics (intensity, duration, frequency) are displayed in blue and red, respectively. a) Annual frequency (top) and regional distribution (bottom) of step-changes in annual maximum drought duration across the 616 reconstructed time series. b-c) Same as a) but for annual maximum drought intensity and annual drought frequency. Step-changes are identified using the C3PO method (Zhang et al. 2017). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.2.1. Step-changes in flood event characteristics

Spatial distribution and time-location of the first and second step-changes of flood event characteristics are summarized in Fig. 3.

Across SSA, similar change points are observed in flood duration, intensity, and frequency. Compared to the rest of SSA, temporal changes in the flood characteristics are significantly more consistent in western and central Africa. In these regions, we detect two change-points, one in the late 1960s-70s and another in the 1980s-90s (Fig. 3a-c). These two regional change-points result in three distinct flood regimes in western and central Africa: i) until the late 1960s, we note more frequent, more intense, and longer duration flood events; ii) between the late 1960s-70s and the 1980s-90s, flood events are less frequent, less intense and tend to be shorter; iii) in the post-1990s, longer duration flood events become more frequent, more intense. This is thus consistent with previous studies analysing temporal changes in rainfall and average flow (*e.g.*, Lebel & Ali, 2009; Nicholson, 2013; Sidibe et al., 2018), which, according to our study, may have affected all flood characteristics. We note, however, that the high-level of similarity in the detection of change-points over the post-1990s in western and central Africa may be exacerbated due to the gap-filling procedure, as this time-period is less densely covered (Fig. 1b).

In eastern and southern Africa, the change points analysis reveals different patterns. While eastern Africa seems to be affected by very large spatial variability, southern Africa shows two regionally coherent change points in 1955 and the early 1960s (Fig. 3a-c). Before 1955 and after the early 1960s, most of southern Africa experienced less frequent, less intense, and shorter duration floods than between 1955 and the early 1960s. In addition, several southern African stations show change-points in the 1960s-70s and 1980–90s, consistently with changes reported in western and central Africa (Fig. 3a-c). Nevertheless, we note that changes in mean characteristics of flood events are less coherent at the regional scale over the second half of the timeseries, especially in southern Africa (Fig. 3a-c). This could be due to anthropogenic influence, such as reservoir construction, diversion of water from some basins and extensive water abstraction in parts of southern Africa (Brunner, 2021). However, some studies of southern rainfall variability reported an increased variability, which could potentially impact the detection of change points after the mid-1960s (e.g., Dieppois et al. 2016; Malherbe et al. 2016).

3.2.2. Step-changes in drought event characteristics

Spatial distribution and time-location of the first and second step-changes of drought events are summarized in Fig. 4.

Drought duration, intensity, and frequency show similar change points. Over most of western and central Africa, the change-point patterns are temporally consistent. The results show two change points, one in the late 1960s-70s and another in the 1980s-90s (Fig. 4a-c), resulting in three distinct drought regimes: i) until the late 1960s, we note less frequent, less intense, and shorter duration drought events; ii) between the late 1960s-70s and the 1990s, drought events are more frequent, more intense and tend to last longer; iii) in the post-1990s, shorter duration droughts are less frequent and less intense.

Large spatial variability is present in the change-points observed in eastern Africa. Meanwhile, southern Africa shows two regionally coherent change-points, one in 1955 and another in the early 1960s (Fig. 4a-c). First from the start of the study period to 1955, and after the early 1960s to the end of the study period where droughts were more frequent, more intense, and longer duration floods than between 1955 and the early 1960s. In addition, some stations in this region show change points in the 1960s-70s and 1980–90s, with similar patterns of change as in western and central Africa (Fig. 4a-c).

In summary, we identify different regions where temporal changes in drought characteristics are coherent: West and Central Africa, eastern Africa, and southern Africa. We also note that such historical changes in drought characteristics are highly consistent with those reported in flood characteristics but follow opposite trajectories. In addition, temporal and regional changes in flood and drought characteristics appear consistent with historical climate variations in these regions (e.g., Richard et al., 2001; Kizza et al. 2009; Lebel & Ali, 2009; Nicholson, 2013; Dieppois et al., 2016; Dieulin et al., 2019; Onyutha, 2021).

3.3. Historical trends in flood and drought event characteristics

To understand how trends have changed as informed by the change-point analysis, post-1990s trends are compared to the trends of a historical baseline period (1950–2014).

3.3.1. Trends in flood event characteristics

Fig. 5 shows the trend patterns associated with all flood characteristics over the period 1950–2014 and the post-1990s.

Although the regional patterns are generally quite similar in the different flood characteristics, some differences are found regionally. Over the historical baseline period (1950–2014), we find significant and decreasing trends in all flood characteristics in most of southern Africa and the western regions of western Africa (Fig. 5a-c). On the contrary, a large region of equatorial Africa shows consistent positive trends in flood characteristics, especially in flood intensity and frequency, between 1950 and 2014 (Fig. 5a-c). Contrasting trend patterns are found over the eastern part of western and eastern Africa (including the Zambezi River basin), where flood duration tends to become shorter, but more frequent and intense over the historical baseline (Fig. 5a-c).

Looking at the post-1990s period, we find significant positive changes, which are spanning a larger region of western, central, and eastern Africa (especially the western part of the Zambezi River basin) in flood intensity and frequency than in flood duration (Fig. 5d-f). Meanwhile, in all flood characteristics, there are significant negative trends in some parts of equatorial Africa and the south-eastern coast of SSA (Africa east-central and Indian Ocean coasts; Fig. 5d-f). According to the change-point analysis (Fig. 4d-f), non-significant trends are found across most parts of southern Africa (Fig. 5d-f).

We thus note a large variability in flood hazards in SSA, with decreasing/increasing trends over the historical baseline period, switching to increasing/decreasing trends over the post-1990s period, which is fully consistent with the results of Tramblay et al (2020a) obtained with annual maxima sampling. Notably, this variability is associated with an increase in flood duration, intensity, and frequency across most SSA (except southern Africa) in the post-1990s.

3.3.2. Trends in drought event characteristics

Fig. 6 shows the trends linked with all the drought characteristics over the 1950–2014 period and the post-1990s periods.

For the historical baseline period (1950–2014), we find significant increasing trends in all drought characteristics in the southwestern part of southern Africa, western regions of western Africa, Lake Chad, and Blue Nile (Fig. 6a-c). Meanwhile, the eastern part of western Africa, equatorial Africa, and the western part of the Zambezi River basins show decreasing trends, especially in drought duration and intensity, between 1950 and 2014 (Fig. 6a-c). Thus, over these regions, drought events historically tend to become shorter, less intense, but more frequent. This contrasts with the rest of SSA, where the droughts are getting longer, more intense, and more frequent.

Considering the post-1990s period, trends in drought characteristics reverse from those noted over the historical baseline, and we find significant decreasing trends over western Africa, Lake Chad, Zambezi, and western southern Africa for drought characteristics (Fig. 6d-f). Meanwhile, significant increasing trends are found in equatorial Africa (White Nile and the African East Central Coast basins) and the south-eastern coast of SSA (Africa east-central and Indian Ocean coasts; Fig. 6d-f). In addition, in line with step-change analysis (Fig. 4d-f), non-significant trends are found in drought characteristics across most parts of central and the northern region of southern Africa (Fig. 6d-f).

We thus found large variability in hydrological drought over SSA,

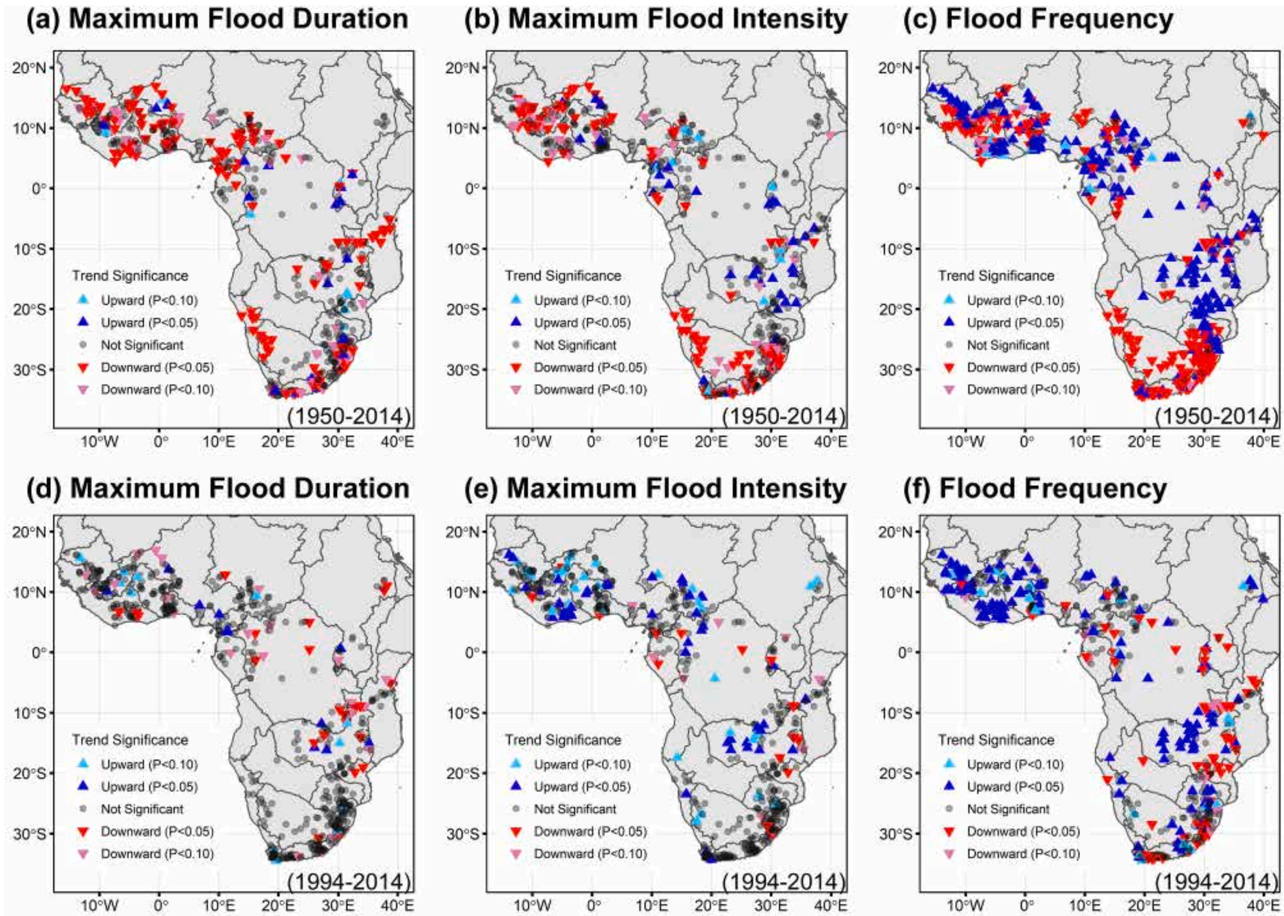

Fig. 5. Historical and post-1990s trends in flood characteristics over SSA. a) Trends in annual maximum flood duration over the historical baseline (1950–2014). b-c) Same as a) but for annual maximum flood intensity and annual flood frequency, respectively. d-f) Same as (a-c) but for the post-1990s period. Statistical significances of trends are assessed using a modified MK-test, accounting for serial correlation. Dark and light blue (red) triangles indicate significantly increasing (decreasing) trends at p = 0.05 and 0.1. Non-significant trends are indicated by dark grey circles. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

with decreasing/increasing trends over the historical baseline period, switching to increasing/decreasing trends over the post-1990s period. In addition, we note coherent variations, with opposite phases, in hydrological floods and droughts.

3.4. Trends versus variability in hydrological extremes

To examine how potential decadal to multidecadal variations affect the detection of regional trends in flood and drought characteristics, we re-evaluated the trends using a multi-temporal approach, testing the trend robustness over each sequence of 10 years or more throughout the entire time series. Further details about how the multi-temporal trend analysis is constructed and interpreted are available in Supplementary Material (Fig. S1).

As illustrated in Figs. 7-8a-c, by considering different starting and ending years, we note that trends computed for each of the flood and drought characteristics in the major hydrological basins in SSA are highly variable both in space and time. Such strong spatio-temporal variability in SSA catchments makes it difficult to discuss the presence of significant long-term trends in all flood and drought characteristics between 1950 and 2014. Most SSA catchments show alternating periods of increasing and decreasing trends in flood and drought duration, intensity, and frequency (Figs. 7-8a-c), suggesting that significant decadal to multidecadal variations could be present in all flood and drought characteristics. Overall, such variations show similar directional and temporal patterns (or timing) in either flood or drought characteristics for most of the catchments, but these changes are generally in opposite directions between the floods and droughts. More importantly, however, such variations are aperiodic (i.e., magnitude changes over time), and this can substantially affect trend detection analysis.

Western and central African catchments show some of the strongest trends in flood characteristics, and strong contrasts over time (Fig. 7a-c). For instance, in flood intensity and frequency, we note one period when trends are negative (the 1950s-1970s), followed by one period with positive trends in the post-1980s (Fig. 7b-c). Thus, over these regions, studies analysing trends over a period spanning the last 30 years would tend to show an increase in flood intensity and frequency, while studies using longer records tend to show a decreasing trend. Similarly, including or excluding a couple of years at the start or the end of these time series could drastically change the trend detection and sign. Over western and central Africa, analogous results are found in flood duration; however, while our previous analysis suggested a post-1990s increase in flood duration (Fig. 5d), the multi-temporal trend analysis reveals that this trend is highly unstable over the last 20 years (Fig. 7a). Such temporal instability in trend patterns is particularly pronounced in eastern and southern African catchments (Fig. 7a-c). Such high variability thus could substantially limit the detection of long-term change and trends in flood characteristics over eastern and southern Africa.

Regarding drought characteristics, in western and central Africa, we found very similar, but opposite, trend patterns to flood characteristics. Over these regions, studies analysing trends over a period spanning the last 30 years would tend to show a decrease in drought duration,

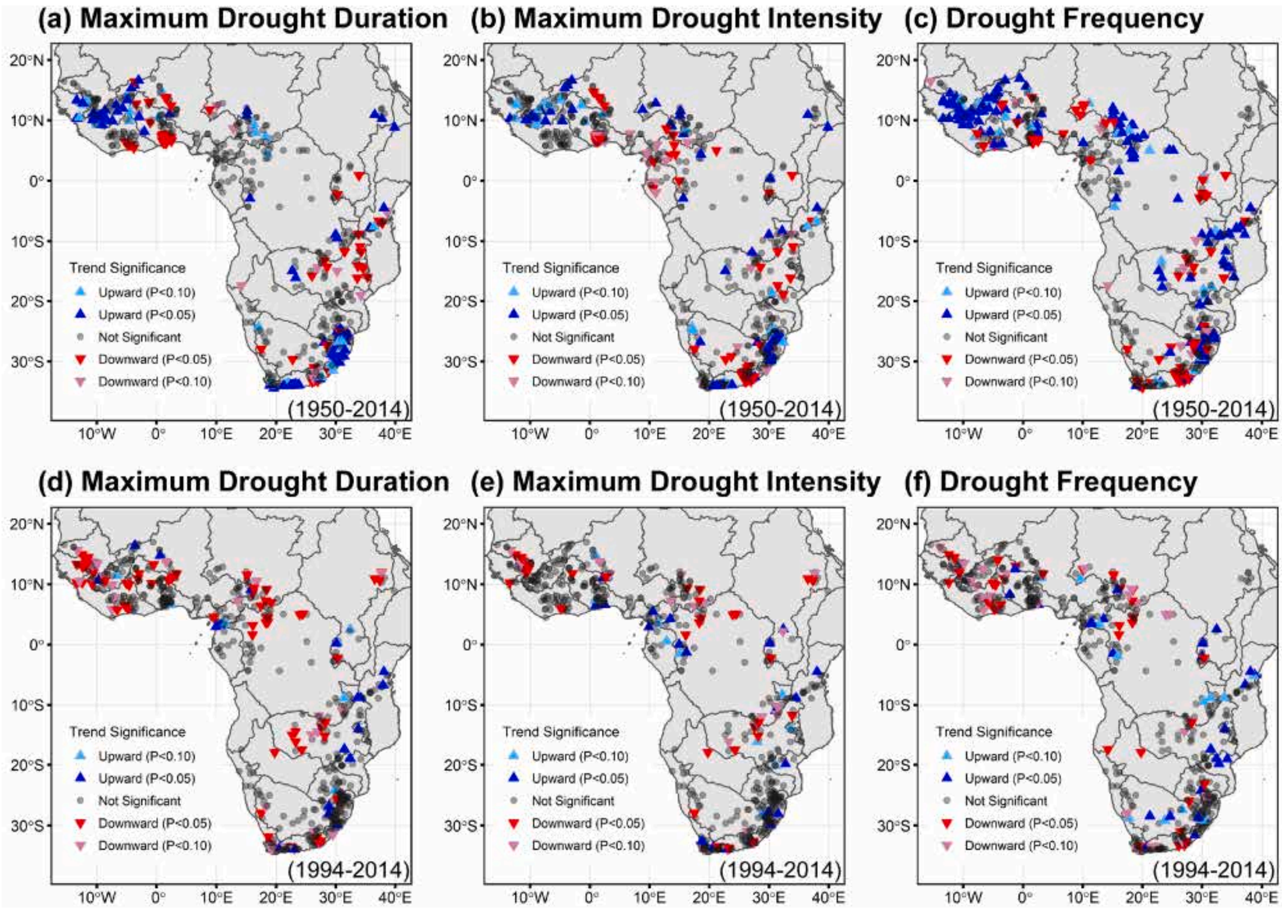

Fig. 6. Historical and post-1990s trends in drought characteristics over SSA. a) Trends in annual maximum drought duration over the historical baseline (1950–2014). b-c) Same as a) but for annual maximum drought intensity and annual drought frequency, respectively. d-f) Same as (a-c) but for the post-1990s period. For the duration and intensity of events, the statistical significance of trends is assessed using a modified MK-test, accounting for serial correlation. For the frequency of events, statistical significance is assessed using Poisson regression. Dark and light blue (red) triangles indicate significantly n increasing (decreasing) trends at p = 0.05 and 0.1. Non-significant trends are indicated by dark grey circles. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

intensity, and frequency (Fig. 8a-c). Like for flood characteristics, this suggests that any long-term trend analysis will be dependent on the length of the records, and especially their starting and ending dates. Nevertheless, unlike in flood duration, we note that previously reported post-1990s trends for shorter droughts are more stable than in flood duration in recent years (Fig. 6d, 8a). Similarly, over eastern and southern Africa, like for flood characteristics, the multi-temporal trend analysis reveals very high variability in drought characteristics from one decade to the next (Fig. 8a-c), highlighting potentially large uncertainty in the detection of long-term change and trends.

3.5. Contribution of decadal variability to hydrological extremes

We then examine the magnitude of decadal to multidecadal variations (greater than10 years) in flood and drought characteristics using MODWT (Fig. 9).

Across SSA, as illustrated in Section 3.4.1, changes and trends in flood characteristics are significantly influenced by decadal variability (Fig. 9a-c). However, the amount of total variance explained by decadal variability is generally lower in flood duration than in flood intensity and frequency throughout the study region (Fig. 9a-c). Overall, the relative amount of decadal variance in all flood characteristics is considerably higher in western Africa as compared to the rest of SSA (Fig. 9a-c). This difference is most apparent in the flood intensity, where decadal variability explains more than 40 % in stations located in the Sahel (and even more than 60 % over the Senegal River basin; Fig. 9b). Meanwhile, decadal variance in flood intensity is generally lower over the coastal regions of western Africa, most equatorial Africa (including the Zambezi), and especially southern Africa (Fig. 9b). The magnitude of decadal variance is however generally stronger in flood frequency and shows similar spatial patterns to those observed for flood intensity (Fig. 9b-c). For example, over western, central, and south-eastern Africa, the amount of variance explained is higher along the coastal regions (20–60 %) than in the intensity and duration of flooding (Fig. 9a-c).

According to Section 3.4.2, drought characteristics across SSA are also found to be significantly influenced by decadal variability (Fig. 9d-f). Comparatively, the amount of variance explained by decadal variability, although generally lower than in floods, is more nuanced (Fig. 9d-f). For instance, drought duration is more influenced by decadal variability than floods over western and central Africa, but not over eastern and southern Africa (Fig. 9d). Generally, the amount of total variance explained by decadal variability is ranging between 20 % and 40 % for most stations and in all drought characteristics (Fig. 9d-f). However, the relative amount of variance is generally greater in western Africa (especially over the Senegal River; greater than40–60 %), and lower along the Gulf of Guinea coastal regions and over southern Africa (less than20 %; Fig. 9d-f).

In summary, both flood and drought characteristics are significantly impacted by decadal and multidecadal variability, and this has major consequences on trend detections over the continent. In addition, we note that decadal variability is generally more important in flood than in drought characteristics across SSA, except in western and central Africa.

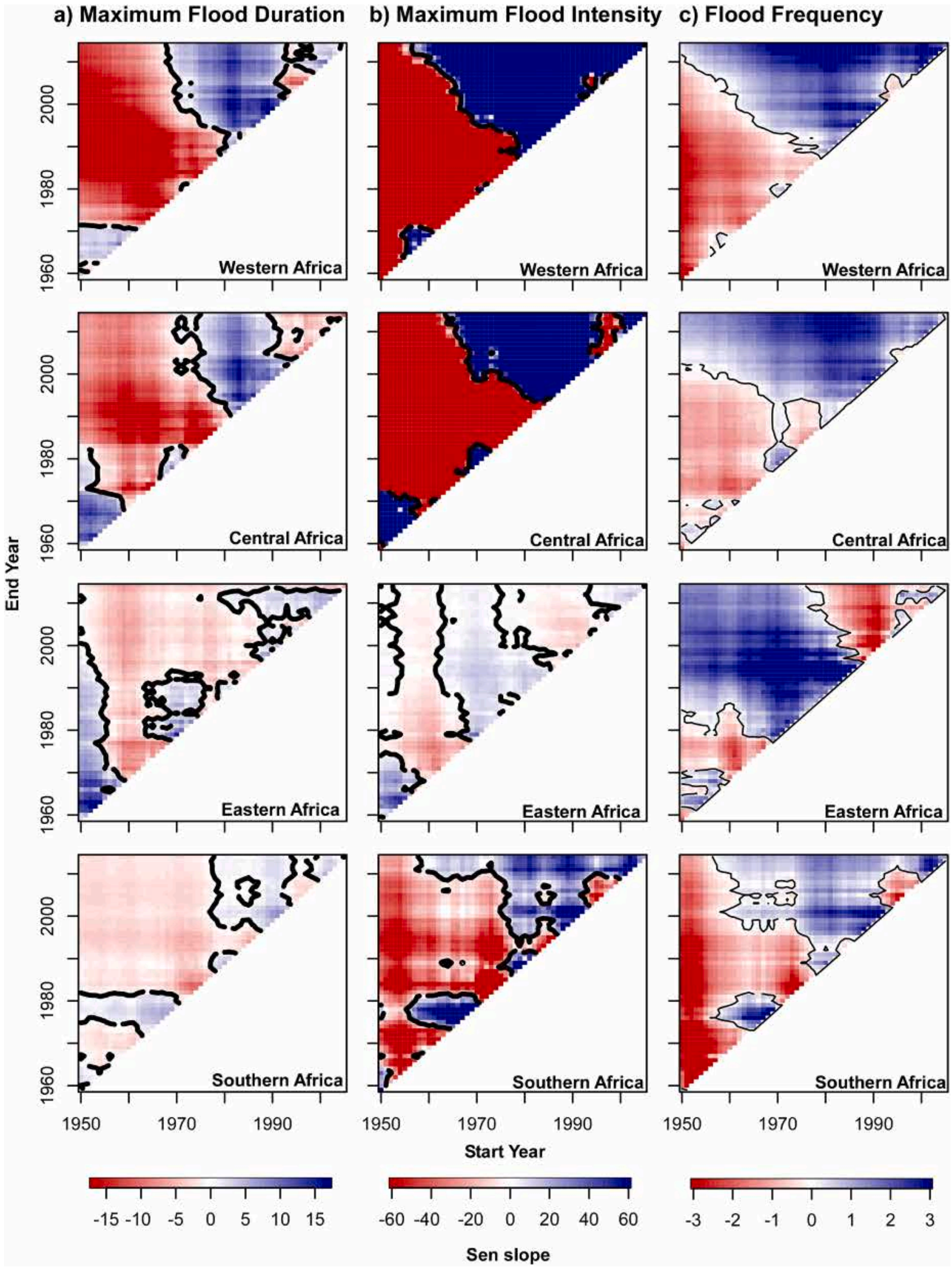

Fig. 7. Multi-temporal trend analysis of all flood characteristics between 1950 and 2014. a) Multi-temporal trend analysis in annual maximum flood duration. b-c) Same as a) but for maximum flood intensity and frequency, respectively. Results are summarized for western (top), central (middle-top), eastern (middle-bottom), and southern Africa (bottom). Start-years are represented on the x-axis, while end-years are displayed on the y-axis. The rate of change of each segment is estimated using Sen's slope. For the duration and intensity of events, the statistical significance of trends is assessed using a modified MK-test, accounting for serial correlation. For the frequency of events, statistical significance is assessed using Poisson regression. Black contours display periods where trends are found statistically significant at p = 0.05. Further details about how the multi-temporal trend analysis is constructed and interpreted are available in Supplementary Material (Fig. S1).

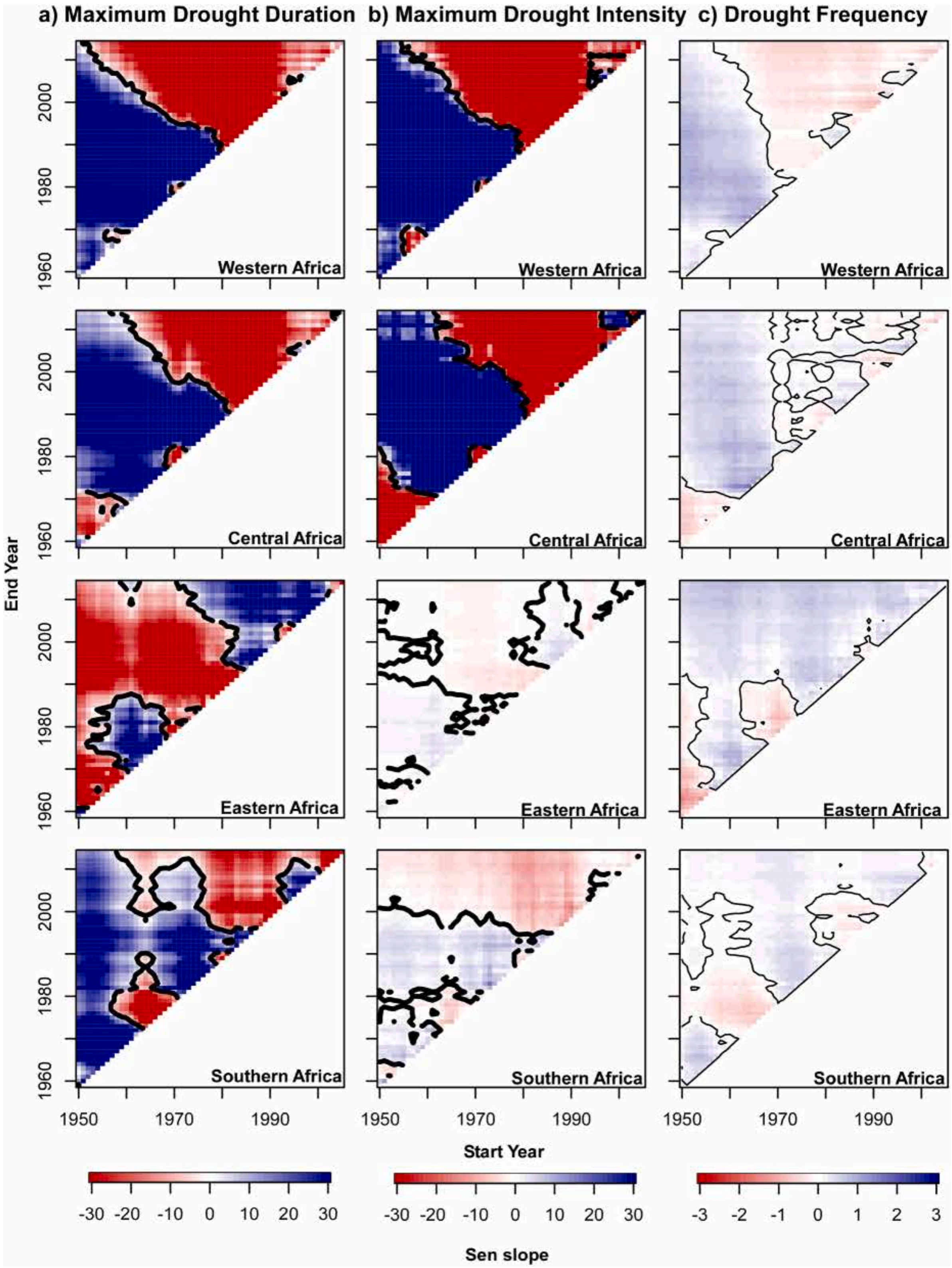

Fig. 8. Multi-temporal trend analysis of all drought characteristics between 1950 and 2014. a) Multi-temporal trend analysis in annual maximum drought duration. b-c) Same as a) but for maximum drought intensity and frequency, respectively. Results are summarized for western (top), central (middle-top), eastern (middle-bottom), and southern Africa (bottom). Start-years are represented on the x-axis, while end-years are displayed on the y-axis. The rate of change of each segment is estimated using Sen's slope. For the duration and intensity of events, the statistical significance of trends is assessed using a modified MK-test, accounting for serial correlation. For the frequency of events, statistical significance is assessed using Poisson regression. Black contours display periods where trends are found statistically significant at p = 0.05. Further details about how the multi-temporal trend analysis is constructed and interpreted are available in Supplementary Material (Fig. S1).

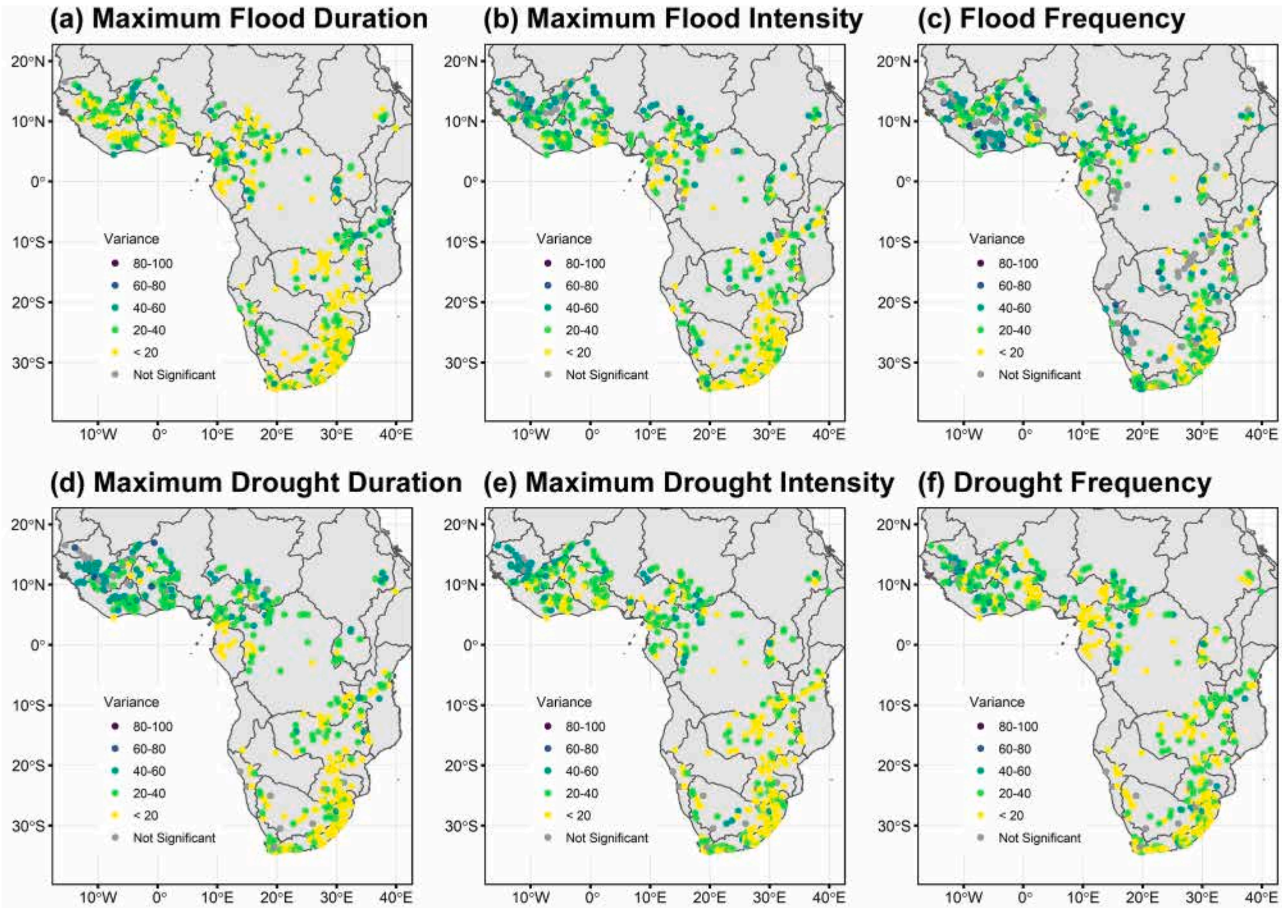

Fig. 9. Magnitude of decadal variations in flood and drought characteristics. (a-c) Percentage of explained variance (yellow to dark blue colour shades) of decadal variations in maximum flood duration, maximum flood intensity, and annual flood frequency, respectively. (d-f) Same as (a-c) but for maximum drought duration, maximum drought intensity, and annual drought frequency. Decadal variations are extracted using MODWT. The percentage of explained variance is estimated from the ratio between decadal variance and total variance (i.e., variance in the non-filtered time series). Statistical significance is estimated by quantifying the probability that decadal variance exceeds the variance that would be detected at the same timescale in a random noise using 1000 Monte-Carlo simulations of a signal presenting the same AR(1) coefficient, mean and standard deviation. Catchments, where decadal variability is found to be non-significant at $p = 0.05$, are displayed in dark grey. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4. Discussion and conclusion

The overall aim of this study is to characterize patterns of trends and variability in the frequency, duration, and intensity of both flood and hydrological drought events across SSA. Although some studies have attempted to characterize past changes in hydrological floods and droughts, mostly based on annual maximum and minimum, in western Africa (Descroix et al., 2013, 2018; Nka et al., 2015; Aich et al., 2016; Do et al. 2017; Wilcox et al., 2018; Tramblay et al. 2020a), eastern Africa (Degefu et al., 2019; Tramblay et al., 2020a), and southern Africa (Do et al. 2017; Tramblay et al. 2020a), these changes are not fully understood beyond the catchment scale. This is largely due to a paucity of hydrological data, therefore emphasizing the need for long-term and complete records to fully interpret large-scale changes in the hydrological regime across SSA (Mahe et al., 2013; Do et al., 2017; Dixon et al., 2020; Tramblay et al., 2020a-b).

Using the RF algorithm, we first reconstructed a new long-term complete daily streamflow dataset across the entire SSA, spanning the period between 1950 and 2014. The quality of the reconstruction was evaluated through cross-validation using the KGE and NSE. Results showed that the performance was satisfactory over the entire subcontinent, with over 72 % and 92 % of the stations showing good and acceptable performances, respectively. The quality of the reconstruction is, however, lower in southern Africa, and this could be due to higher anthropogenic influences, greater and/or more chaotic climate variability over the region. Nevertheless, the quality of the reconstruction of this new daily streamflow dataset shows equivalent performance with previous studies using different techniques and time-steps over western and central Africa (Sidibe et al., 2018; Dembélé et al., 2019), and over southern Africa (Chawanda et al., 2020).

Using the CP3O change-point detection method (Zhang et al. 2017), we identified two change-points, resulting in three hydrological regimes, which primarily affect flood and drought characteristics in western and central Africa: i) the 1950s–60s and after the 1980s–90s, when floods (droughts) tend to be more (less) intense, more (less) frequent and more (less) persistent; and ii) the 1970s–80s, when floods (droughts) are less (more) intense, less (more) frequent and less (more) persistent. We also note similar change points in some parts of southern Africa. However, eastern and southern Africa show much larger spatial variability. These results are consistent with trend patterns in the duration, intensity, and frequency of hydrological extremes, with changing trends over the recent period (post-1990s), as compared to a historical baseline (1950–2014). These results also corroborate previous findings, highlighting increasing frequency and intensity (based on annual maximum) in flood events or disasters after the 1980s–90s over western Africa (Nka et al., 2015; Aich et al., 2016; Li et al., 2016; Fiorillo et al., 2018; Wilcox et al., 2018; Tazen et al., 2019; Tramblay et al., 2020a), the Blue Nile (Conway 2009; Degefu et al., 2019; Tramblay et al., 2020), eastern Africa (Bernard et al., 2013; Tramblay, et al., 2020a), and southern Africa (Do et al. 2017; Tramblay et al. 2020a), and confirm significant variations in flood and drought hazards over the region.

More importantly, using multi-temporal trend analysis and MODWT, we found that analysis of long-term changes and trends in flood and drought characteristics are significantly influenced by aperiodic decadal variability across SSA. As such, considering a fixed, and relatively short, study period will likely lead to misinterpretations of long-term change and trend assessments in hydrological extreme characteristics, reaffirming concerns by previous studies in Europe and western Africa (e.g., Svensson et al., 2006; Chen & Grasby, 2009; Hannaford et al., 2013; Sidibe et al., 2018). For instance, this could explain why previous studies present contrasting results in historical and recent trends over southern Africa (Schäfer et al., 2016), and over Ethiopia (e.g., Melesse et al., 2010; Rientjes et al., 2010; Taye & Willems, 2012; Tesemma et al., 2010; Gebrehiwot et al., 2014; Degefu et al., 2019). We found that the magnitude of such decadal variation in flood and drought characteristics is greater in western Africa, primarily over the Sahelian band, and lower in southern Africa and the Gulf of Guinea. We also note that flood duration and drought intensity are the least impacted by such decadal to multi-decadal variability. Nevertheless, this underlines the need for further understanding the mechanisms and drivers of these decadal variations to improve seamless prediction for flood and drought hazards, at seasonal to decadal scales (Yuan et al., 2015; Kundzewicz et al., 2019; Brunner et al., 2021). While previous hydrological studies indeed highlighted the presence of interannual to decadal variability in hydrological regimes in western, central, and eastern Africa (Taye & Willems, 2012; Nyeko-Ogiramoi et al., 2013; Sidibe, 2019), very few studies discussed the impacts of those decadal variations on hydrological extremes, and their potential causes. This is even though numerous studies in SSA highlighted significant decadal to multi-decadal rainfall variability, which is associated with large-scale climate variations, such as the Atlantic Multidecadal Variation, the other decadal modes of variability in the Pacific Ocean, in the West African Sahel (Mohino et al., 2011; Dieppois et al., 2013; Berntell et al., 2018), eastern Africa (Funk et al., 2014; Nicholson, 2017; Onyutha, 2018; Ummenhofer et al., 2018) and southern Africa (Dieppois et al., 2016, 2019). As highlighted in Ficchì & Stephens (2019), while El Niño-Southern Oscillation often dominates the conversation about the predictability of early warning and preparedness for floods and drought, climate modes of variability in other ocean basins could, at least, be equally important in various regions of SSA.

Although the high level of cross-correlation between SSA catchments suggests that the hydrological droughts and floods are significantly impacted by a large-scale change, the influence of local-scale changes in land use, water management, and rainfall is not negligible. For instance, studies have shown that drought propagation strongly depends on local climate (rainfall seasonality and aridity) and catchment characteristics (Van Loon & Van Lanen, 2012; Van Loon, 2015, Van Loon et al., 2014). Likewise, flood generation is greatly impacted by hydrometeorological processes and catchment properties (Keller et al., 2018; Stein et al., 2020, 2021). Furthermore, stochastic modelling studies have shown that small changes in mean rainfall, or streamflow, combined with strong decadal variability can severely change the rate of occurrence of extreme events (Zhang et al., 2004, Siebert & Ward, 2011). Similarly, in other regions of the world, previous studies demonstrated that reservoir regulation and water abstraction modulate drought and flood frequency, severity and duration (Tijdeman et al. 2018; Brunner, 2021; Van Loon et al., 2022), which may not be negligible in southern Africa (Chawanda et al., 2020). Future studies therefore should thus focus on identifying the relative role of large-scale climate variations, local hydroclimate variations, and anthropogenic influences and their impacts on seasonal to decadal flood and drought prediction systems.

5. Data and materials availability

Not Applicable.

6. Code availability

Not Applicable.

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CRediT authorship contribution statement

Job Ekolu: Conceptualization, Methodology, Data curation, Writing – original draft, Visualization, Investigation, Validation, Writing – review & editing. **Bastien Dieppois:** Conceptualization, Methodology, Data curation, Writing – original draft, Validation, Writing – review & editing. **Moussa Sidibe:** Conceptualization, Methodology, Data curation, Writing – review & editing. **Jonathan M. Eden:** Conceptualization, Methodology, Data curation, Writing – original draft, Validation, Writing – review & editing. **Yves Tramblay:** Conceptualization, Methodology, Data curation, Writing – review & editing. **Gabriele Villarini:** Conceptualization, Methodology, Data curation, Writing – review & editing. **Dhais Peña-Angulo:** Conceptualization, Methodology, Data curation, Writing – review & editing. **Gil Mahé:** Conceptualization, Methodology, Data curation, Writing – review & editing. **Jean-Emmanuel Paturel:** Conceptualization, Methodology, Data curation, Writing – review & editing. **Charles Onyutha:** Conceptualization, Methodology, Data curation, Writing – review & editing. **Marco van de Wiel:** Conceptualization, Methodology, Data curation, Writing – review & editing.

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

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhydrol.2022.128359.

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