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Multidecadal changes in hydrological droughts across Sub-Saharan Africa

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A R T I C L E I N F O

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Streamflow
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Trend
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A B S T R A C T

Study Region: Sub-Saharan Africa, a region highly vulnerable to climate variability, faces significant challenges from hydrological droughts due to their widespread socio-economic and environmental impacts.
Study Focus: This study investigates the spatiotemporal evolution of hydrological droughts and their links to meteorological droughts across Sub-Saharan Africa. Using the African Database of Hydrometric Indices (ADHI), we analyze streamflow data from 1466 gauging stations spanning 1951–2018 to detect trends in drought characteristics.
New Hydrological Insight: A major shift in hydrological drought patterns occurred in the 1980s, with increased drought duration and severity during 1951–1980, followed by a general decrease from 1981 onward. Spatially, southern Africa experienced more frequent but shorter and less severe droughts, whereas central and eastern regions saw fewer but more intense and prolonged events. These spatial contrasts reflect differences in climate and basin characteristics. Although meteorological drought indices (SPI, SPEI) broadly align with hydrological drought trends, local factors introduce important variability. These findings enhance our understanding of drought dynamics in the region, with implications for water management, food security, and climate adaptation strategies.

1. Introduction

Climate change is possibly intensifying the hydrological cycle, accelerating the frequency and magnifying the severity of hydroclimatic extremes (Seneviratne et al., 2021). Among hydroclimatic extreme events, drought has the greatest temporal and spatial extent, and it is extremely difficult to quantify and characterize (Wilhite and Pulwarty, 2017). Drought is one of the most damaging natural hazards in terms of human casualties, economic costs, societal conflicts, and ecological impacts (Gautier et al., 2016; Tian et al., 2018).

There are several drought definitions (Wilhite and Glantz, 1985) but drought generally refers to below-normal water availability

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with respect to long-term climatological conditions (Tallaksen and Van Lanen, 2004; Tallaksen, Van Lanen, 2004; IPCC, 2023). The impacts of droughts are usually associated with soil moisture and hydrological deficits because crops, ecosystems and human water uses depend on water from catchment storages (Forzieri et al., 2014; Blauhut et al., 2015; Van Loon, 2015). Among the different drought types, hydrological drought is gaining global relevance as a consequence of the human increased water demands (Tallaksen and Van Lanen, 2004; Tallaksen, Van Lanen, 2004). Hydrological drought affects the quality of aquatic and riparian habitats, as well as water quality, and it causes serious problems for urban and industrial water supplies, irrigated agriculture, riverine transport, and hydropower production (Van Loon, 2015). Hydrological drought events are strongly complex since they are triggered by meteorological factors, local catchment characteristics, and human management (Van Loon, 2015; Odongo et al., 2023). In the context of climate change and growing human exposure to water scarcity due to population and water use increases, these negative impacts constitute a major challenge, and as future climate scenarios indicate, they are expected to worsen (Prudhomme et al., 2014; Seneviratne et al., 2021; Tramblay et al., 2020).

Africa is one of the regions of the world that is most affected by droughts (Haile et al., 2019). Africa has regularly experienced severe droughts, resulting in the death of hundreds of thousands of people and contributing to food insecure conditions in several African countries (Vogt, 2021). The Emergency Events Database (EM-DAT) stresses among others the outstanding effects of recent drought events in Africa, notably: the 2010–2011 drought in East Africa (Horn of Africa), the 1999–2002 and 2005 drought in North Africa, the 2001–2003 and 2015–2018 day-zero droughts in southern Africa, and the persistent droughts in the Sahel during the 1970s and 1980s. These droughts had devastating impacts on the population, agriculture, and ecosystems, causing famines, forced migrations, and conflicts over scarce resources.

In Africa, examples of regional drought studies, typically focus on meteorological drought in southern Africa (Rouault and Richard, 2005; Manatsa et al., 2008; Clarke, 2023; Cornforth, 2013; Mutowo and Chikodzi, 2014; Nhamo et al., 2019; Mazibuko et al., 2021), western Africa (Giannini et al., 2008; Govaerts and Lattanzio, 2008; Lebel, Ali, 2009; Kasei et al., 2010; Lodoun et al., 2013, Ayugi et al., 2022), eastern Africa (Syroka and Nucifora, 2010, Anderson et al., 2012, Dutra et al., 2014, AghaKouchak et al., 2015, Gebremeskel et al., 2018) and northwestern Africa (Touchan et al., 2011, Bouras et al., 2020). A few studies deal with drought on the continental scale over Africa (Masih et al., 2014; Peng et al., 2020; Ekolu et al., 2022). In addition, despite the recognized importance of studying droughts in Africa (Shiferaw et al., 2014; Sidibe et al., 2018), very few studies hitherto investigated the spatiotemporal variability and trends of hydrological drought (Ekolu et al., 2022). One of the key challenges of understanding trends and variability in hydrological drought in Africa is data limitations. Securing a high-quality, long-term, fine-temporal resolution dataset with extended spatial coverage is a challenge. This situation becomes more complicated when considering the notion that the vast territory shows extremely complex hydrological variability, with diverse land use and water management practices, as well as significant socioeconomic imbalances (Mahe et al., 2013; Gudmundsson et al., 2019; Dixon et al., 2020).

Recently, the African Database of Hydrometric Indices (ADHI) has been developed, representing the first pan-African hydrological database (Tramblay et al., 2021). The ADHI aggregates data from more than 1500 hydrometric stations throughout Africa, creating a comprehensive dataset of river discharge characteristics. This database addresses the continent's low density of hydrometric stations and provides valuable hydrological information for scientific research. This new hydrological database allows for a comprehensive assessment of the spatiotemporal characteristics of hydrological droughts in Sub-Saharan Africa. This assessment can provide valuable insights for drought forecasting and water resource management.

This study employed the ADHI database to analyze hydrological droughts in Sub-Saharan Africa over the past seven decades (1951–2018). Specifically, we aimed to determine the characteristics and trends in hydrological droughts and explore their connections with climate variability in Sub-Sahara region.

2. Material and methods

The objectives set out in the present study are achieved through a workflow based on data obtained from various information sources (Fig. 1). In the first part of this section, the main geographical features of the study area are described, in the second part of this section, the different sources of the data used are described, and in the third part, the methodology carried out is explained.

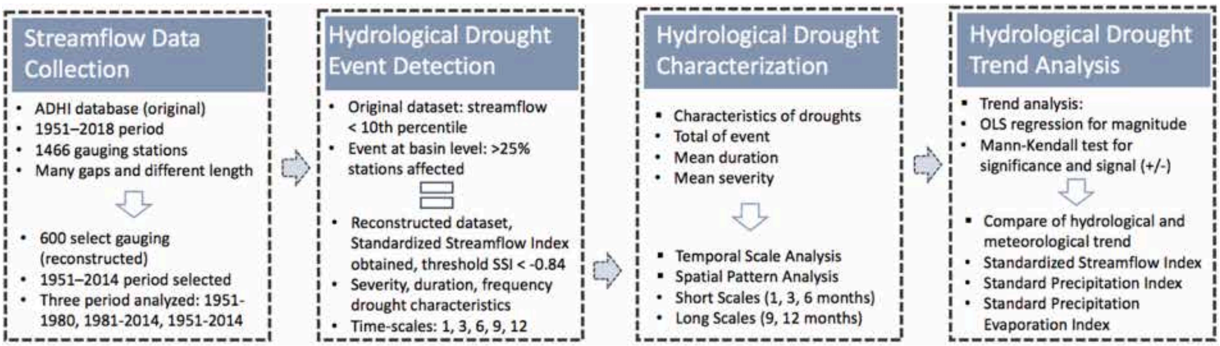

Fig. 1. Flow-chart of the material and methods.

2.1. Study area

Africa exhibits remarkable geographical, climatic, and hydrological diversity. Its latitudinal extent gives rise to a wide range of climate zones, including equatorial rainforests, savannas, arid deserts, and temperate mountainous regions. The continent's topography is highly heterogeneous, covering 32 million km^2, with large lowland basins such as the Congo and Chad, vast plateaus dominating the south and east, and major mountain systems such as the Atlas Mountains in the northwest and the Ethiopian Highlands in the east. Elevations range from depressions below sea level, such as the Danakil Depression, to peaks over 5000 m, such as Mount Kilimanjaro and the Rwenzori Mountains (Fig. 2a). Africa's river network is dominated by large river basins including the Nile, Congo, Niger, Zambezi, and Orange, which play a fundamental role in water resource availability and the region's socioeconomic development. However, the spatial distribution of rivers and their flow regimes are closely linked to the continent's climatic variability and geographical contrasts (Fig. 2b).

Precipitation in Africa is strongly influenced by latitude, altitude, and atmospheric circulation, particularly by the seasonal

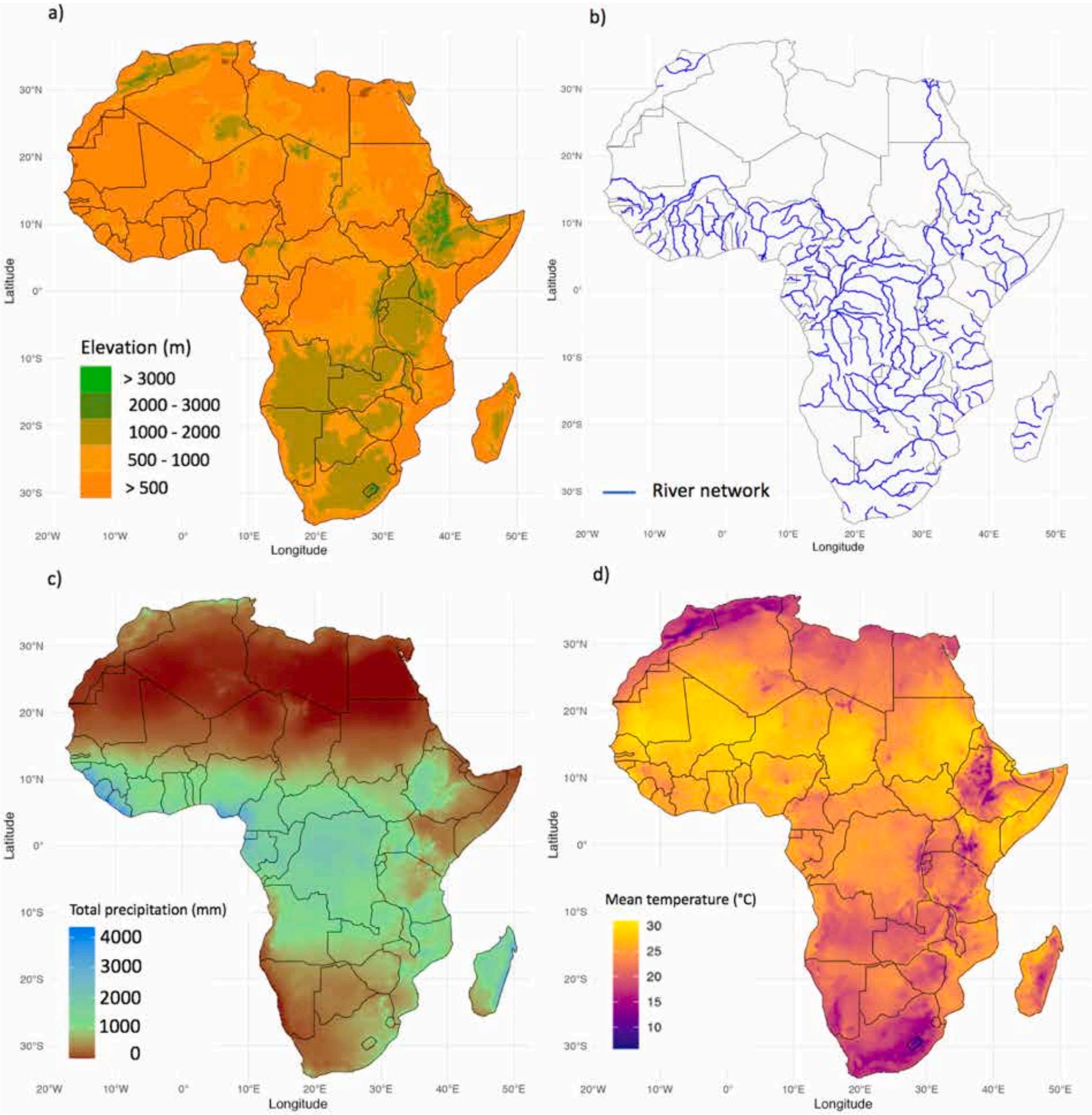

Fig. 2. a) Elevation in Africa. Source: Hollister and Shah (2017); b) Fluvial red in Africa. Source: Kelso, Patterson, (2023); c) Total annual precipitation in Africa. Source: Fick, Hijmans, (2017); Mean temperature in Africa. Source: Fick, Hijmans, (2017).

movement of the Intertropical Convergence Zone (ITCZ). Equatorial regions, such as the Congo Basin, receive over 2000 mm of rainfall annually, while arid zones like the Sahara Desert, and the Namib and Kalahari deserts, receive less than 250 mm per year (Fig. 2c). Seasonal rainfall variability is especially pronounced in regions such as the Sahel and southern Africa, where precipitation is concentrated in short wet seasons. Regarding air temperature, the continent also presents a marked spatial gradient. Average annual temperatures exceed 30 °C in desert areas, while in high-altitude regions, such as the Ethiopian Highlands, they can fall below 10 °C (Fig. 2d).

In Africa, meteorological drought types show marked spatial variability, shaped by regional climate patterns. In the northern part of the continent, particularly in the desert and semi-arid areas of the Sahara, prolonged droughts prevail, characterized by low precipitation throughout the year. In the Sahel, in western Africa, droughts are both seasonal and interannual, strongly influenced by climate variability. In contrast, Central Africa, with its predominantly equatorial climate, experiences occasional droughts, generally associated with anomalies in precipitation patterns. The Horn of Africa is one of the most vulnerable regions on the continent, where droughts are recurrent and long-lasting, reflecting the high irregularity of seasonal rainfall. In Southern Africa, droughts tend to be seasonal or interannual and are influenced by climate teleconnections. Finally, in Eastern Africa, particularly in the highland areas, droughts are seasonal and intermittent, closely tied to monsoon variability and regional atmospheric circulation.

2.2. Dataset description

We utilized the streamflow data from the ADHI database (Tramblay et al., 2021), comprising the mean monthly streamflow data of

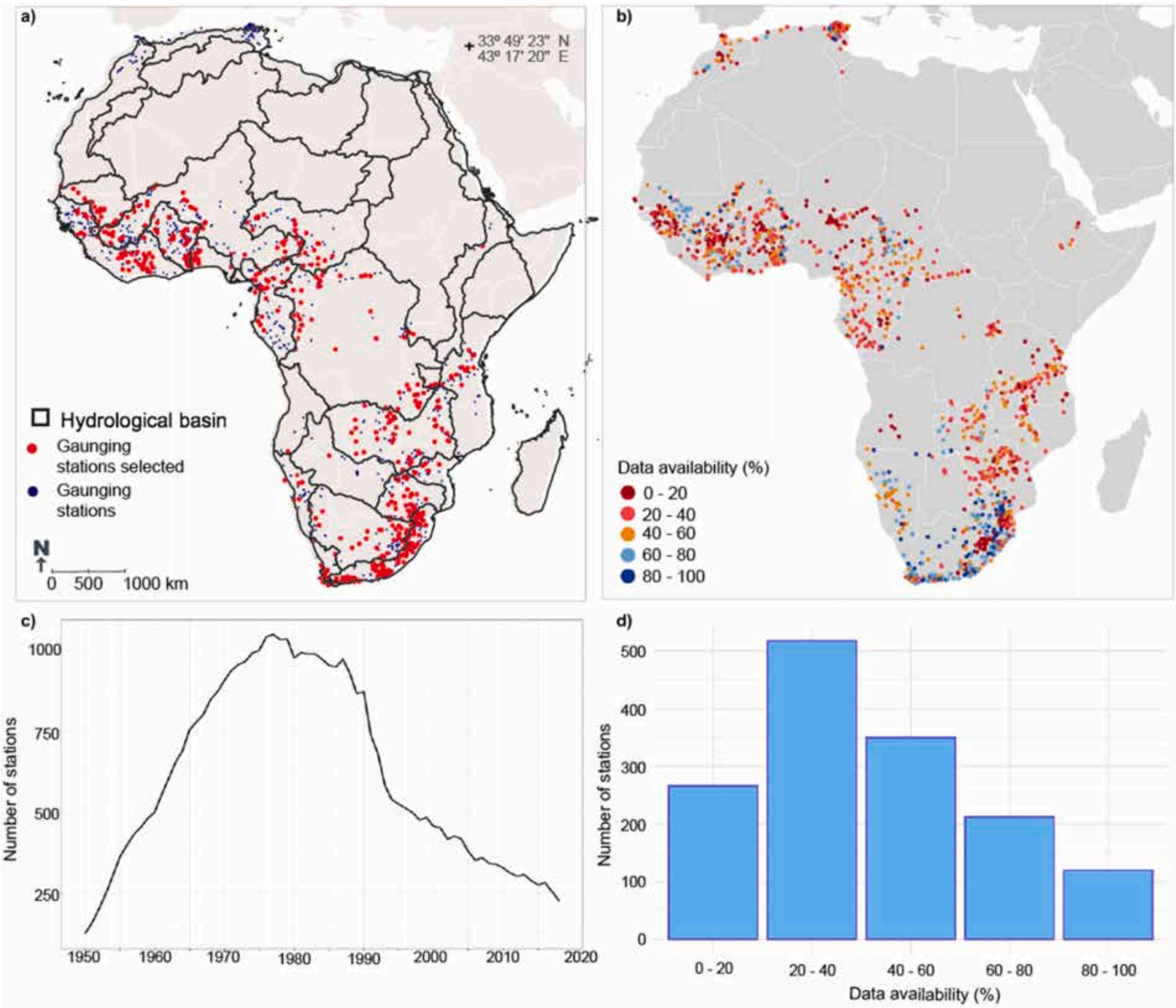

Fig. 3. a) Spatial distribution of the 1466 gauging stations of the original series (1951–2018 period) and spatial distribution of the 22 hydrological basins in Africa (level 3), based on Lehner and Grill (2013). b) Spatial distribution of 1466 gauging stations by percentage of data availability. c) Number of gauging stations available per year. d) Number of gauging stations by percentage of data availability.

1466 gauging stations in Africa spanning from 1951 to 2018. The ADHI database was created by combining the "Système d'Informations Environnementales sur les Ressources en Eaux et leur Modélisation" (SIEREM) database and the Global Runoff Data Center (GRDC) dataset. The ADHI dataset includes series with highly variable time lengths, many of which even have large time gaps, which makes it difficult to carry out a robust trend study. Consequently, we employed a complete streamflow dataset spanning from 1951 to 2014 derived from the temporal reconstruction of 1466 gauging stations within the ADHI dataset using a random forest (RF) algorithm, as developed by Ekolu et al. (2022). The highest density of stations is in Western and Central Africa, around the Great Lakes region in East Africa and southern Africa. In contrast, North, Central, and East Africa regions are less represented (Fig. 3a).

Additionally, the percentage of available data throughout the time series varies across the continent. Stations with the longest temporal records are located in the south and northwest Africa (Fig. 3b). In this regard, West and South Africa present the longest record length of the gauging stations (> 60 % data availability). Furthermore, most gauging stations contain half of the records of the entire study period (20–60 %), and around 100 stations have more than 80 % of the complete time series (Fig. 3d). From a temporal perspective, the number of stations increased over time until the 1970s, when it maintained some stability. In the 1990s, the number of available gauging stations began to decrease, and in recent years this decrease has become very pronounced. The 1990s were a period of significant changes in Africa, encompassing political, social, and economic aspects. These socio-economic changes had repercussions on the maintenance of measurement stations throughout the territory (Gubler et al., 2017).

In addition to hydrological data, we extracted different monthly climate information for each drainage catchment. In particular, we used precipitation from the Global Precipitation Climatology Center (GPCC) dataset (Schneider et al., 2014) and the atmospheric evaporative demand (AED) from the Climatic Research Unit (CRU, version 4; Harris et al., 2020). The drainage catchments were obtained from the HydroBASINS dataset (level 3), developed in the HydroSHEDS project (Lehner and Grill, 2013). This database established a hierarchical coding framework to define and standardize the description of drainage units throughout the African continent. Distinct identification codes were allocated to the drainage units according to their geographical position and classification tier within the hierarchy. The hierarchical classification organized the 1007 catchments on the African mainland into 274 subbasins, 119 basins, 32 subregions, 12 regions, and 5 systems, encompassing islands.

2.3. Methods

We first assess the temporal evolution of hydrological drought events from a regional perspective, focusing on 22 major hydrographic basins of Africa (Fig. 3a), using the original ADHI time series spanning the period between 1950 and 2018. A drought event was defined as monthly streamflow falling below the threshold level of the 10th percentile for the study period. We determined that a basin registers a drought event when it is detected in more than 25 % of the gauging stations within that basin.

Secondly, a detailed study of the characteristics of hydrological drought events was conducted, based on 600 complete gauging stations from Ekolu et al. (2022). We calculated a hydrological drought index, which allows comparability between the streamflow series independently of the different streamflow magnitude. The Standardized Streamflow Index (SSI) generates a monthly standardized time series characterized by an average equal to zero and a standard deviation equal to one (Vicente-Serrano et al., 2012). The SSI is flexible, selecting the most suitable probability distribution to fit the streamflow data for each gauging station and month.

Following the same approach as for streamflow data, we calculated the Standardized Precipitation Index (SPI, McKee et al., 1993), based on monthly precipitation, and the Standardized Precipitation-Evapotranspiration Index (SPEI, Vicente-Serrano et al., 2010b), based on data for precipitation and atmospheric evaporative demand (AED). These indices were calculated for the drainage basin upstream of each analyzed gauging station.

To characterize hydrological and meteorological drought events at the catchment scale, we used a criterion based on the run theory (Yevjevich, 1967; Fleig et al., 2006), in which the hydrological drought events were defined based on a threshold of −0.84, which corresponds to the strongest drought severity expected over a return period of 5 years (Lorenzo-Lacruz et al., 2013). The characteristics of hydrological drought events (severity, duration, and frequency) were quantified for the spells that showed a value below the selected threshold (Van Loon, 2015). Specifically, the drought frequency was defined as the number of events recorded over the study period. The drought duration of an event refers to the number of months from onset ($SSI < -0.84$) to termination ($SSI >= -0.84$). Drought severity was defined as the integrated values between the value of the SSI at drought onset and termination during the event duration. Additionally, the characteristics of droughts were analyzed at different time-scales to verify if the spatial patterns of hydrological droughts vary as a function of temporal scale: i.e., short (1, 3, 6 months) vs. long timescales (9 and 12 months).

The study of hydrological drought trends is conducted through the analysis of magnitude of change and significance. Additionally, the trend of meteorological drought is obtained from SPI and SPEI. In all cases, the trend was analyzed using the 1 month time-scale (SSI-1, SPI-1 and SPEI-1). The magnitude of change in the annual duration, frequency, and severity of hydrological drought events was analyzed, over the three different study periods (1951–2014, 1951–1980 and 1981–2014), using the Ordinary Least Squares regression method (Moberg, Brattström, 2011). The statistical significance of these changes was tested using the modified Mann-Kendall test (Hamed, Ramachandra Rao, 1998), which allows for consideration of autocorrelation by returning the corrected probability values after accounting for temporal pseudo-replication (Kiktev et al., 2003, Alexander et al., 2006). The results of the analysis were grouped into three main categories of trends: non-significant, significant at $p < 0.05$, and significant at $p < 0.01$. Finally, we calculated the percentage of gauging stations with positive/negative trends in the characteristics of hydrological drought events. The same analysis was applied to the drought events obtained from meteorological drought indices (SPI and SPEI) and the trends of all metrics were compared spatially and temporally.

3. Results

3.1. Characteristics of hydrological drought events

As expected, the number of hydrological drought events decreases as the temporal scale of analysis increases, while the duration and severity of these droughts increase (Fig. 4). Most hydrological drought events occur on a short temporal scale (1, 3, 6 months), whereas only a few drought events extend over longer timescales (9, 12 months). Additionally, the events recorded at longer temporal scales have a greater duration and severity than events detected at shorter temporal scales.

Spatial patterns of hydrological drought characteristics are displayed in Fig. 5. In South Africa, a higher number of events are recorded, but these drought events are shorter and less severe on average than in other regions. In central and eastern Africa, there are fewer events, but they are longer and more intense. Finally, in West Africa, there is a greater number of events, which are short but in general more intense.

3.2. Hydrological drought dynamic

Each year and month over the entire study period, we estimated the number of hydrological basins where more than 25 % of the stations recorded drought conditions (Fig. 6). The spatial extension of hydrological droughts increased from the 1950s to the 1990s, with a maximum in 1983–1984, and, from the 1990s to 2014, hydrological drought conditions decreased (Fig. 6). In the 1980s and 1990s, there was a period of widespread hydrological droughts in a high percentage of African basins.

The trends in the characteristics of hydrological drought events were analyzed using the SSI-1 (Fig. 7). This choice is based on the optimization of the number of events, which is higher considering shorter time scales. We have applied the analysis in three periods, 1951–2014, 1951–1980, and 1981–2014 to assess independent trends over the two periods suggested by Fig. 6 based on the raw streamflow series. Thus, the analysis based on the gap-filled time series confirms the occurrence of two different periods in the evolution of hydrological droughts (Fig. 7). Considering the whole period of analysis, the boxplots that represent the magnitude of change in the duration and magnitude of drought events is almost around zero, but this is the result of a very different behaviour observed over the 1951–1980 and 1981–2014 subperiods. The trend analysis clearly shows an increase in the duration and severity of drought events between 1951 and 1980, while it shows a decrease between 1981 and 2014. We applied a Wilcoxon test to estimate the significance (at $p < 0.05$) of the median differences between the two subperiods, and the test confirms a general change point in the duration and severity of hydrological droughts in the 1980s.

Moreover, we found that this pattern is spatially coherent since the strong differences in trends between the two subperiods are observed in most gauging stations (Fig. 8). The hydrological drought trend analysis for the 1951–2014 period shows high variability, without a clear spatial pattern. Nevertheless, in the two subperiods, a more homogeneous pattern is identified. Between 1951 and 1980, positive trends predominate and are found in 68 % (39 % significant) and 61 % (57 % significant) of gauging stations in the duration and severity of hydrological droughts, respectively. Meanwhile, during the same period, negative trends are found in 32 % (14 % significant) and 39 % (33 % significative) of gauging stations in the duration and magnitude of hydrological droughts, respectively. On the contrary, between 1981 and 2014, negative trends predominate and are found in 80 % (47 % significative) and 76 % (72 % significative) of gauging stations in the duration and severity of hydrological droughts. During the same period, positive trends are found in 20 % (8 % significative) and 24 % (19 % significative) of gauging stations in the duration and magnitude of hydrological droughts.

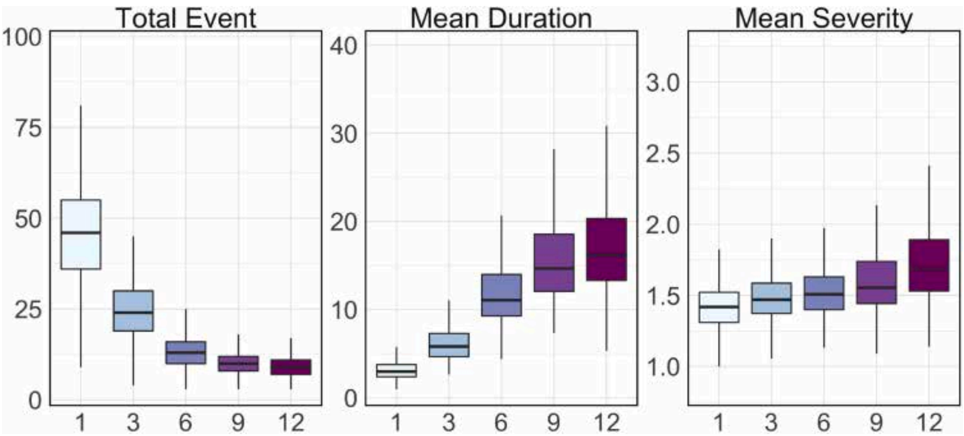

Fig. 4. Boxplots showing hydrological drought characteristics: (a) total event, (b) mean duration, and (c) mean severity, based on different SSI temporal scales (light to dark blue shading: 1, 3, 6, 9 and 12 months) in the 1951–2014 period.

Fig. 5. Spatial distribution of hydrological drought characteristics (left to right columns: total event, mean duration and mean severity) based on different SSI time scales (top to bottom row: SSI-1, 3, 6, 9, 12) in the 1951–2014 period.

3.3. Comparison between the variability of meteorological and hydrological droughts in Sub-Saharan Africa

Here, we analyzed the trends in the duration and severity of drought events based on the SSI, SPI and SPEI using a 1-month integration timescale. The analysis considers the whole study period (1951–2014), and two subperiods, 1951–1980 and 1981–2014

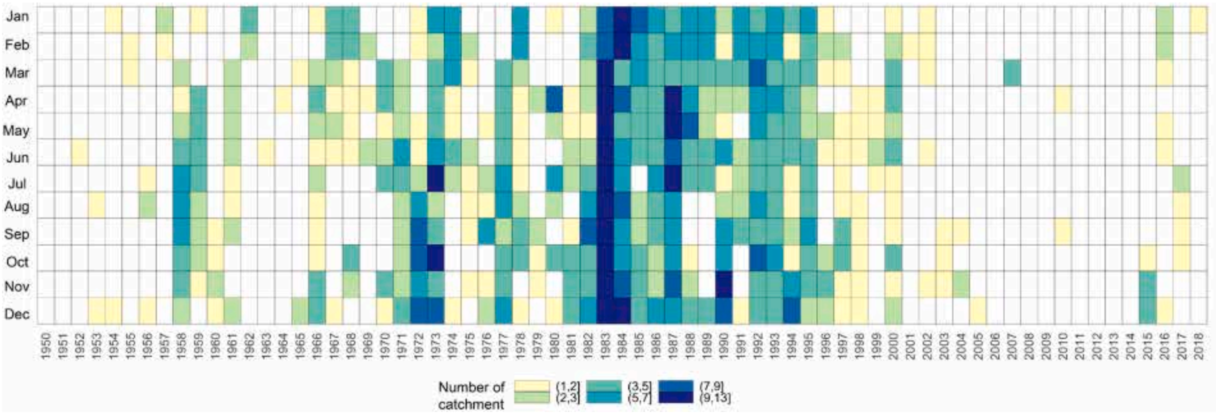

Fig. 6. Number of hydrological catchments with more than 25 % of gauging stations with hydrological drought conditions in the original series between 1951 and 2018.

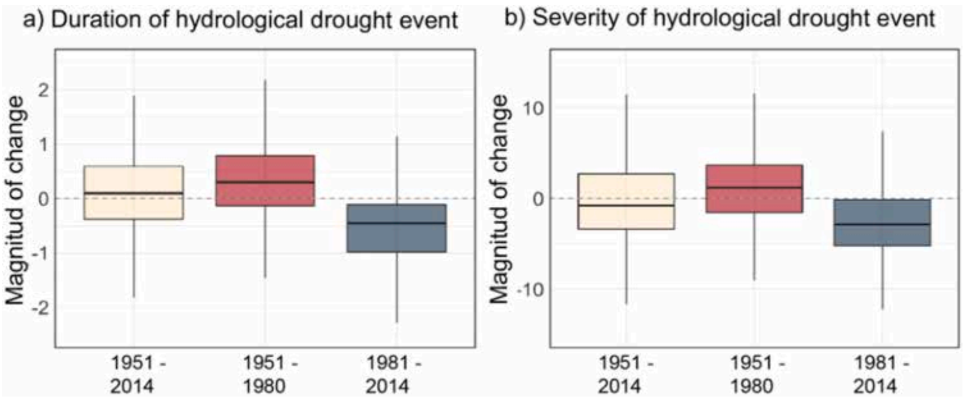

Fig. 7. Boxplots showing duration (a) and severity (b) hydrological drought trend for all periods (1951–2014), first period (1951–1980) and second period (1981–2014).

(Fig. 9). The SPEI shows an increase in the duration and severity of drought events over the two subperiods (1951–1980 and 1981–2014). On the contrary, but consistent with the behaviour of hydrological droughts, the SPI shows different behaviour, characterized by an increase in the duration and severity of drought events during the 1951–1980 subperiod and a decline in the 1981–2014 subperiod.

In Fig. 10, the different spatial pattern obtained between the SPEI and SPI is examined at the continental scale for the three periods. We find high spatial diversity and important differences between trends observed in the SPI and SPEI over the whole study period and the two subperiods. Over the whole period, we detect a general reduction of the severity and duration of meteorological droughts based on the SPI over most basins of Sub-Saharan Africa, but the opposite pattern is found using the SPEI. These differences are reinforced over the two subperiods, particularly over the most recent one in which most of the basins show a decline in the severity of the drought events based on the SPI but an increase based on the SPEI.

Then, we analyze the spatial differences in the magnitude of the change between the SSI and SPI, and the SSI and SPEI during the 1951–1980 and 1981–2014 subperiods. In general, the greatest differences occur between SSI and SPEI in the northwest of Sub-Saharan Africa, with a negative sign, which means the hydrological drought is more pronounced than the recorded meteorological drought (Fig. 11).

4. Discussion

4.1. Characteristics of hydrological drought events

As the temporal scale of analysis increases, hydrological droughts become less frequent but tend to last longer and be more severe. Most events are observed over shorter timescales (1–6 months), with only a few extending to longer periods such as 9 or 12 months. These results are consistent with drought characteristics of other regions (Hayes et al., 1999; Domínguez-Castro et al., 2019).

Hydrological drought characteristics vary across regions. In South Africa, droughts occur more frequently but tend to be shorter

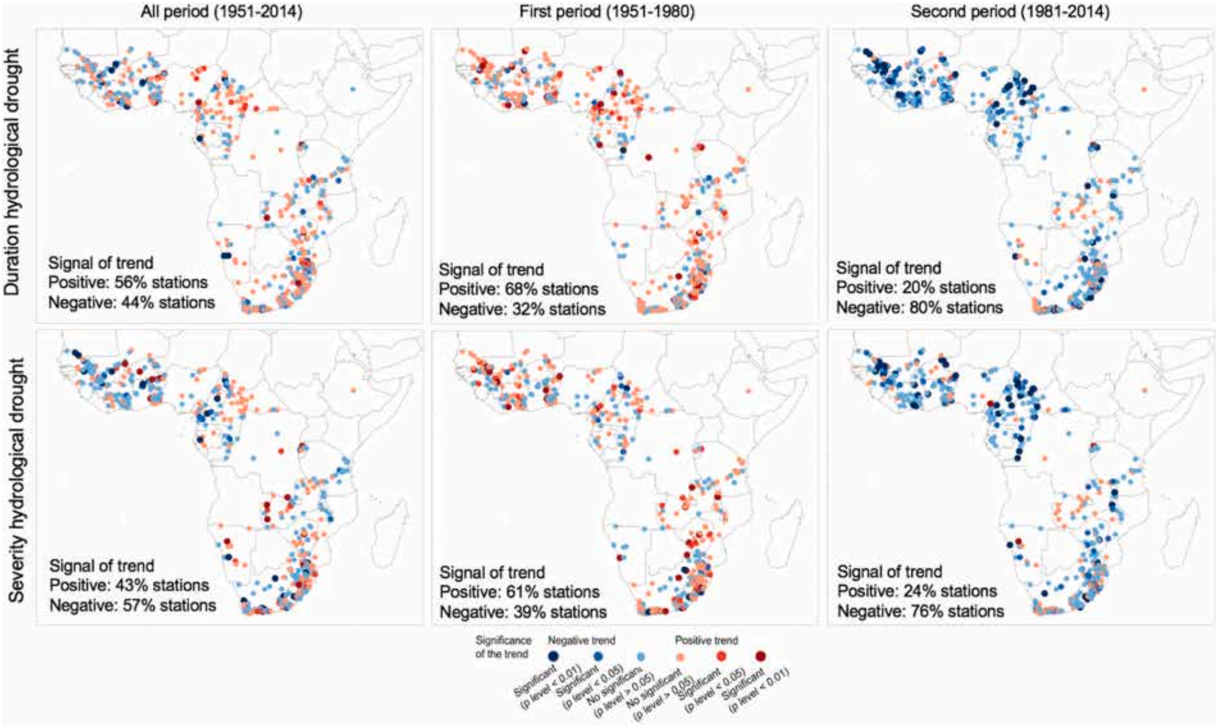

Fig. 8. Spatial distribution of trends (significance at $p < 0.05$, $p < 0.01$) in the duration (up) and severity (bottom) of hydrological drought (SSI-1) for three periods: 1951–2014 (left), 1951–1980 (middle), 1981–2014 (right).

and less severe. Central and eastern Africa experience fewer events, though they are typically longer and more intense. In contrast, West Africa shows a high frequency of events that are generally short but more intense. However, it should be noted that there are no clear boundaries between regions, and these features gradually change over space. No previous studies analyzed the spatial distribution of the hydrological drought characteristics in Africa but, according to Van Loon and Laaha (2015) and Brunner and Stahl (2023), spatial differences in the frequency, duration and severity of hydrological drought events are common because of differences in the physiography and climatic characteristics of the basins.

The climate variability that determines the frequency of rainfall episodes strongly determines spatial patterns of drought severity (Domínguez-Castro et al., 2019). In this sense, Masih et al. (2014), based on meteorological drought metrics, showed important differences in the spatial distribution of meteorological droughts in Africa, showing that a higher number of meteorological drought events are commonly recorded in eastern and western Africa and a lesser extent in the interior and north of the continent. It is expected that the spatial differences in the characteristics of meteorological drought events propagate to hydrological droughts, as identified in our study.

4.2. Hydrological drought trend

Throughout the study period, the number of hydrological basins with widespread drought conditions was estimated monthly and annually. The extent of hydrological droughts increased from the 1950s to a peak in the mid-1980s, followed by a general decline through 2014. The 1980s and 1990s were marked by prolonged and widespread droughts affecting a large portion of African basins. These findings align with previous studies on droughts (Ekolu et al., 2022; Ayers et al., 2023; Sidibe et al., 2018).

This pattern is consistent with long-term climate variability since numerous studies in Africa have highlighted the role of decadal to multi-decadal rainfall variability, associated with large-scale climate variations, such as the Atlantic Multidecadal Variability (Mohino et al., 2011; Dieppois et al., 2013, 2014; Zhang et al., 2020; Ekolu et al., 2024) and El Niño-Southern Oscillation (Thomson et al., 2003, Dieppois et al., 2016, 2019; Baudoin et al., 2017; Sidibe et al., 2018; Ekolu et al., 2024). In particular, the 1980s and 1990s were the driest decades in large regions of the continent (Sidibe et al., 2018) with dramatic drought events that caused hundreds of thousands of causalities (FAO, 2022; Vogt, 2021).

When analysing the entire study period (1951–2014), the overall changes in drought duration and severity appear minimal. However, this mask contrasting trends between two distinct subperiods: from 1951 to 1980, both the duration and intensity of drought events increased, whereas from 1981 to 2014, they showed a declining trend. Moreover, we found that this pattern is spatially coherent since the strong differences in trends between the two subperiods are observed in most gauging stations.

We can confirm that, overall, there is not a clear change in the duration and severity of hydrological droughts in Sub-Saharan Africa between 1951 and 2014. Nevertheless, this general conclusion masks a very important variability, with two subperiods characterized

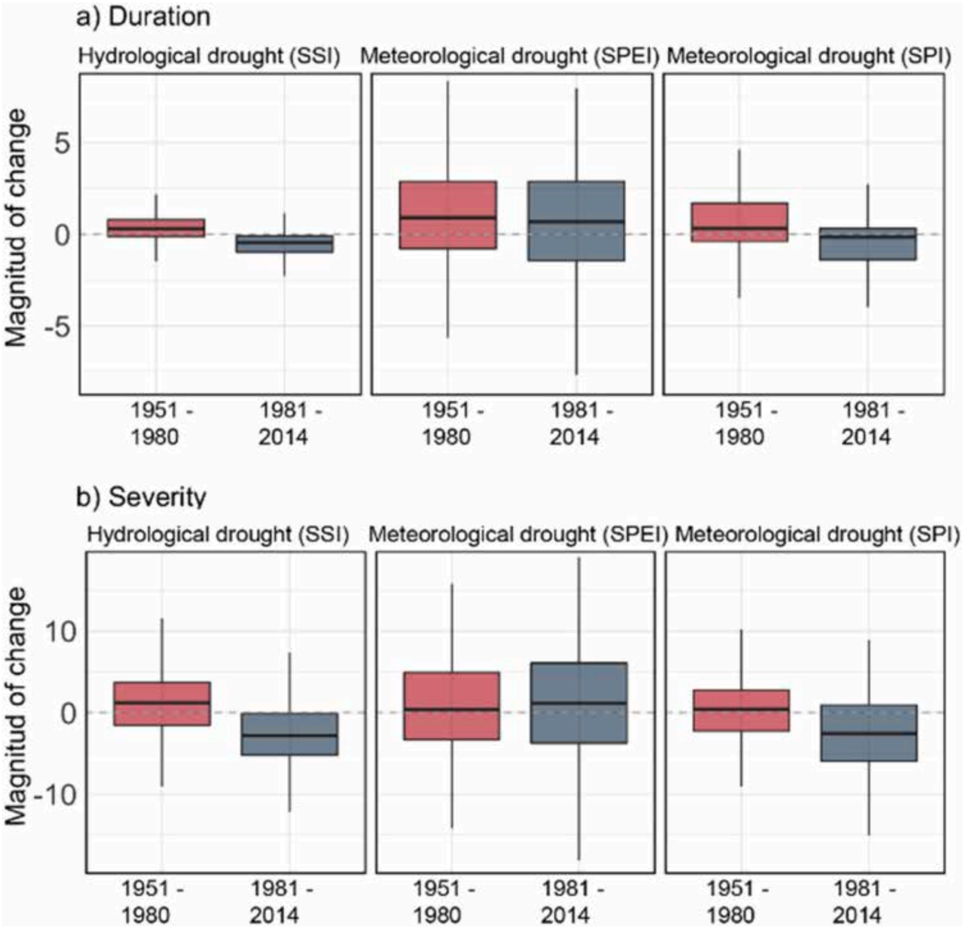

Fig. 9. Boxplots showing the magnitude of trends in the duration and severity of the hydrological (SSI) and meteorological (SPI and SPEI) drought in the time scale 1 for the 1951–1980 and 1981–2014 periods.

by a very different behaviour. Previous studies at the regional scale suggested this change point in the behaviour of hydrological droughts (e.g., Fanta et al., 2001; Sidibe et al., 2018; Ekolu et al., 2022). For example, in southern Africa, a decrease in streamflow had been recorded in the first period (Fanta et al., 2001). Moreover, in western and central Africa, negative and positive change points in streamflow trends were recorded in annual streamflow in the 1970s and 1990s, respectively (Sidibe et al., 2018). Therefore, although some regional differences are found, and could be linked to regional factors (e.g., land cover changes, the presence of reservoirs, aquifer characteristics (Van Loon and Van Lanen, 2012; Van Loon, 2015; Van Loon et al., 2014), our results suggest that the factors explaining the continental-scale change-point in the 1980s could primarily be linked to climate variability. For this reason, in the following section, the connection between the dynamic of hydrological drought and climate variability is analyzed in more details.

4.3. Hydrological drought and its relationship with meteorological drought

The analysis covers the full period (1951–2014) and two subperiods. SPEI indicates a consistent increase in drought duration and severity over time, while SPI shows an increase in the first subperiod followed by a decline in the second, aligning more closely with hydrological drought patterns. Significant spatial variability and notable differences between SPI and SPEI trends are observed, especially in recent decades. Overall, SPI suggests a general reduction in drought severity, whereas SPEI points to worsening conditions. The most marked contrasts between hydrological and meteorological droughts are found in northwest Sub-Saharan Africa, where hydrological droughts appear more intense.

The analysis connecting trends in hydrological and meteorological droughts thus demonstrates that the change point found in the hydrological drought in the 1980s would mostly correspond to the pattern observed with the meteorological droughts calculated using the SPI. The strong response of hydrological to meteorological droughts has been demonstrated in several drought regions (Van Loon and Laaha, 2015; Barker et al., 2016; Bąk and Kubiak-Wójcicka, 2017), but it is also modulated by soil properties and vegetation characteristics (Odongo et al., 2023).

Precipitation frequency, seasonality, and severity are the main factors governing large scale streamflow variability (Liu et al., 2013;

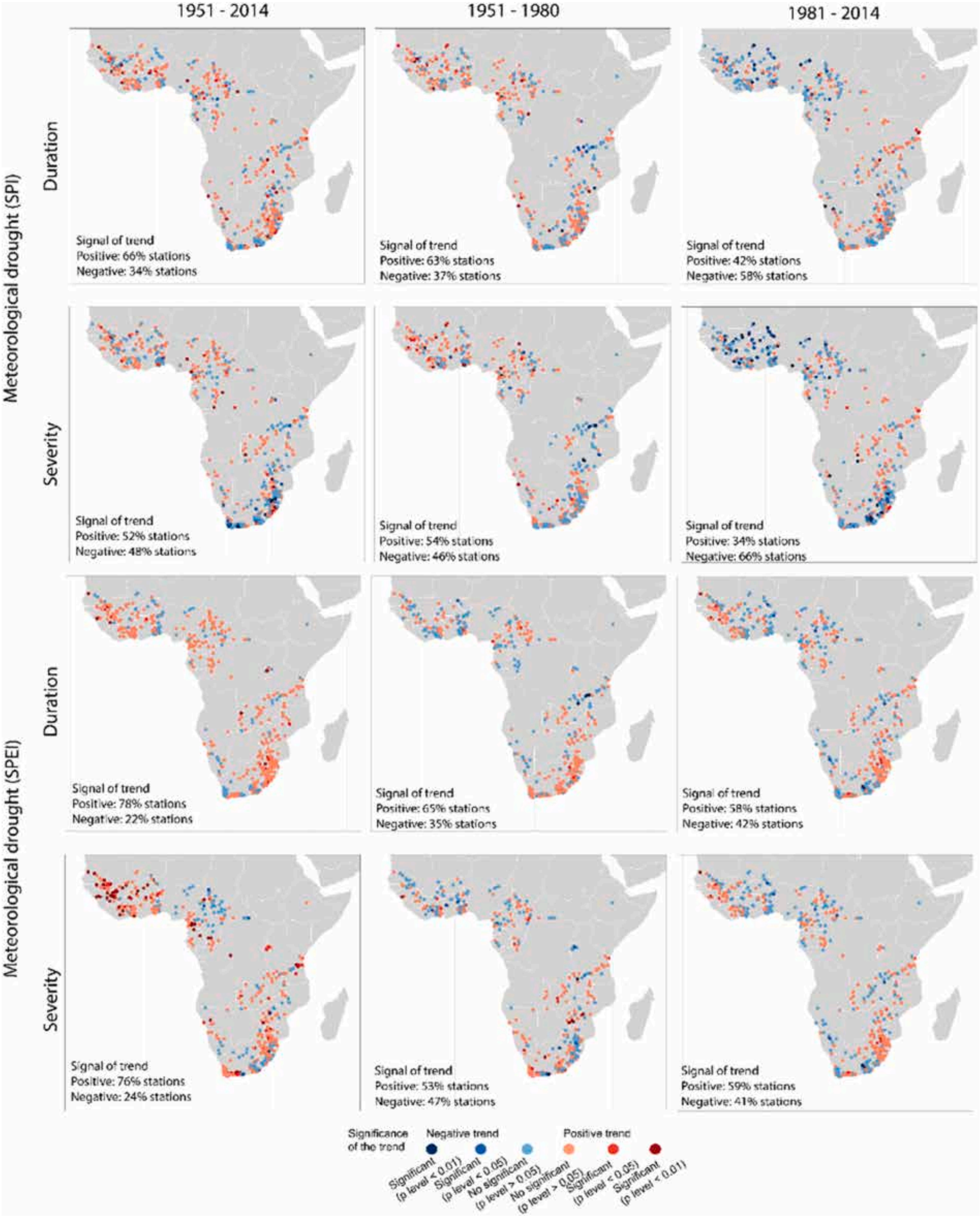

Fig. 10. Spatial distribution of significance of trends (at $p < 0.05$, $p < 0.01$) in the duration (up) and severity (bottom) of meteorological drought based on the 1-month integration timescale and for three periods: 1951–2014 (left), 1951–1980 (middle), 1981–2014 (right).

Kelly et al., 2016), whose mechanisms of response are well explained by earth system models (Scheff et al., 2022). This preponderant role of precipitation would explain why the observed trend in SPEI shows different behaviour. The SPEI is calculated using precipitation and AED (Vicente-Serrano et al., 2010) and is representative of soil or agricultural droughts. Given the strong increase of the

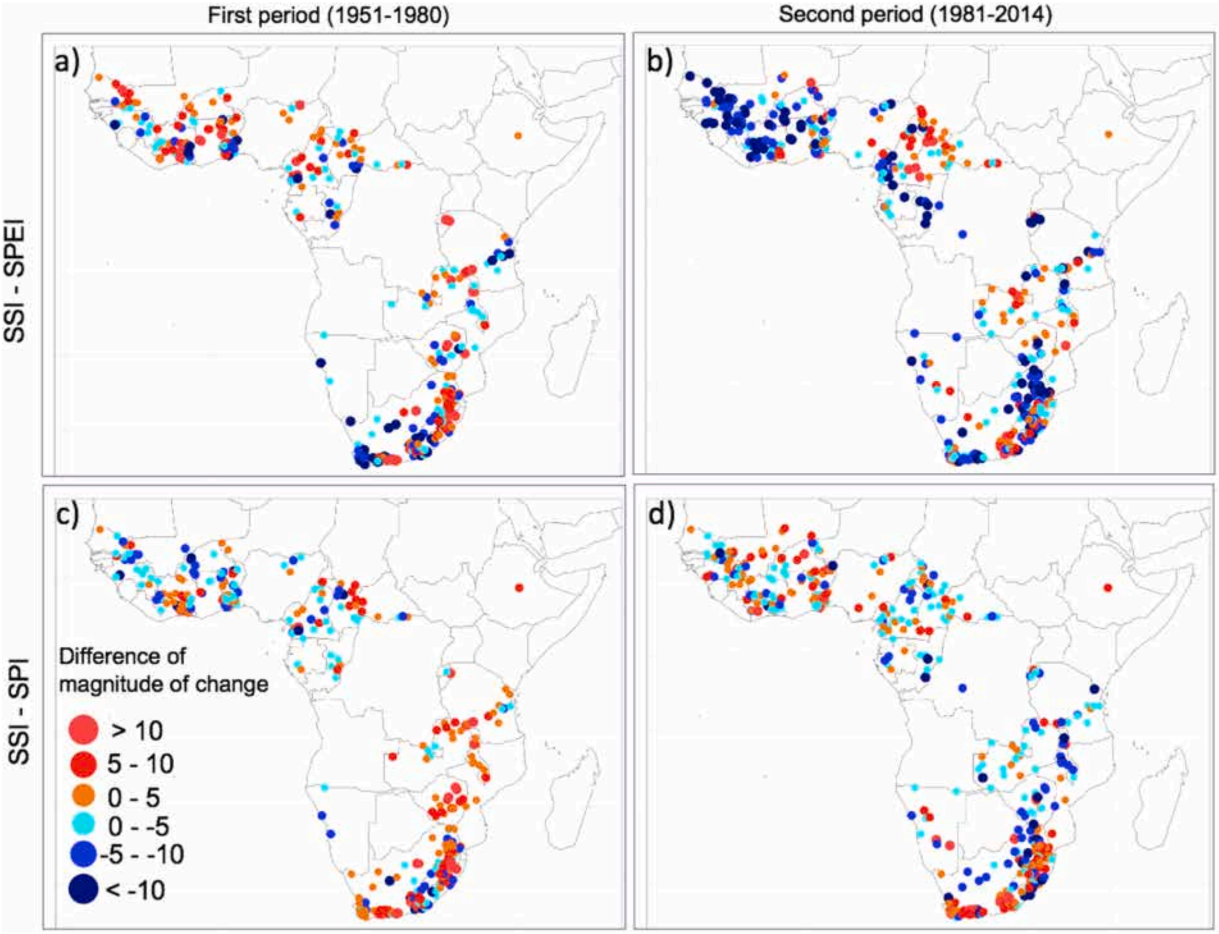

Fig. 11. Differences in the magnitude of change of (a) SSI – SPEI, (c) SSI – SPI in the first period, and (b) SSI – SPI, (d) SSI – SPI in the second period (1980–2014) in the window 1.

observed AED over the last decades in response to global warming (Vicente-Serrano et al., 2020), the SPEI has shown a decline that suggests increased drought severity (Seneviratne et al., 2021; Vicente-Serrano et al., 2022).

Nevertheless, it is necessary to interpret carefully the role of this enhanced drought severity associated with hydrological drought conditions, as shown here, hydrological droughts are not well correlated with SPEI. The role of AED on drought severity is complex and strongly differs between different drought types (Vicente-Serrano et al., 2020). In particular, the influence on agricultural and ecological drought conditions is evident as enhanced AED increases plant water stress conditions, particularly under low soil moisture (Brodribb et al., 2020; Grossiord et al., 2020; Vicente-Serrano et al., 2022).

The correlations between SSI and SPEI, which is an indicator of water balance, may be reduced for various reasons. The first is linked to the mechanisms by which rainfall is transformed into flow, which are strongly influenced by surface conditions and can change over time. For example, in West Africa, it has been shown in various studies that runoff coefficients have increased over time, leading to higher runoff even in the absence of a drastic increase in rainfall (Descroix et al., 2009, Mahé et al., 2013). The second is that many watercourses may be affected by water abstraction, particularly for irrigation or drinking water, and that such abstraction may increase significantly over time as a result of demographic pressure or changes in farming practices (Woltering et al., 2011; Bouimouass et al., 2020; Grill et al., 2019).

Nevertheless, the role of an enhanced AED on hydrological severity is nowadays under debate. In other regions of the world, such as South and North America (Martin, Pederson, 2022), the Mediterranean (Vicente-Serrano et al., 2014) and Australia (Cai and Cowan, 2008), it is suggested a reduction of streamflow associated with enhanced evapotranspiration in response to global warming. Nevertheless, increased AED has a more marginal role in hydrological conditions, particularly in humid regions in which the drought severity is mostly controlled by precipitation variability and change (Tomas-Burguera et al., 2020). This has been suggested at the global scale (Yang, Roderick, 2019) and particularly in Western Europe (Vicente-Serrano et al., 2020).

The differential response of hydrological drought to changes in precipitation and the AED would explain that the dominant dynamic of hydrological drought in Africa is related to the long-term climate variability connected with the Atlantic Multidecadal variability and El Niño Southern oscillation (Onyutha, 2018; Ficchì and Stephens, 2019; Dieppois et al., 2013, 2016, 2019; Ekolu et al., 2022). This close connection with atmospheric dynamics and the general homogeneous response of hydrological droughts to precipitation patterns over the whole continent would open the opportunity to improve the forecasting of meteorological droughts in Africa as investigated by previous studies (Mwangi et al., 2014; Winsemius et al., 2014; Wetterhall et al., 2015) and to move from climate drought forecasting to hydrological drought assessment.

5. Conclusion

This study on hydrological droughts in Sub-Saharan Africa provides a comprehensive analysis of their evolution, characteristics, and connections to meteorological droughts, offering crucial insights into their complex dynamics and implications for water resource management and climate adaptation strategies. The analysis draws on a rich dataset, the ADHI, which integrates streamflow data across 1466 gauging stations from 1951 to 2018. This study shows that, in the study area, most hydrological drought events occur on a short temporal scale and are less severe, whereas only a few drought events extend over longer time scales and are more severe. Spatially, the study identifies distinct patterns in drought occurrence and intensity across Sub-Saharan Africa's diverse hydrographic basins. Southern Africa shows higher frequency but shorter and less severe droughts compared to central and eastern regions, where droughts are less frequent but longer-lasting and more intense. These spatial variations reflect regional differences in climatic conditions and basin characteristics, influencing the hydrological response to precipitation variability.

The trends in hydrological drought characteristics were first analyzed between 1951 and 2018. We found that the 1980s and 1990s were marked by significant hydrological droughts from a spatial perspective, representing a notable change point in the extent of these events. It was observed that the frequency of hydrological drought events decreases as the temporal scale increases, while their duration and severity tend to rise. In Africa, there was a higher incidence of hydrological droughts in the southern and western regions. The study identified two distinct subperiods with opposite trends in drought characteristics. From 1951–1980, there was a positive trend with an increase in the duration and severity of droughts. Meanwhile, from 1981 to 2014, our analysis revealed a predominance of negative trends, characterized notably by a reduction in both duration and severity.

We also examined the interplay between meteorological and hydrological droughts, revealing nuanced relationships. While meteorological droughts (assessed by SPI and SPEI indices) exhibit varied trends, hydrological droughts generally mirror patterns in precipitation, despite some divergence due to local factors, such as land use and water management practices. The analysis connecting the trends between hydrological and meteorological droughts has demonstrated that the change point found in hydrological droughts in the 1980s would primarily be associated with changes in meteorological droughts calculated using the SPI. The relationship between hydrological and meteorological droughts using the SPEI becomes less clear between 1981 and 2014, opening a debate about the effect of recent trends in AED on surface water and streamflow.

In conclusion, the research provides valuable insights into the evolving nature of hydrological droughts in Sub-Saharan Africa, highlighting their temporal trends, spatial variability, and connections to meteorological droughts. The findings underscore the need for robust data and advanced modelling approaches to enhance drought monitoring, prediction, and mitigation strategies in the face of climate change impacts. Addressing these challenges requires interdisciplinary collaboration and targeted interventions to build resilience and ensure sustainable water management across the continent.

CRediT authorship contribution statement

Ahmed El Kenawy: Writing – review & editing, Writing – original draft. **Job Ekolu:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Investigation. **Bastien Dieppois:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Investigation. **Yves Tramblay:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Conceptualization. **Sergio Vicente-Serrano M.:** Writing – review & editing, Writing – original draft, Validation, Investigation. **Dhais Peña-Angulo:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Data curation, Conceptualization.

Declaration of Competing Interest

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

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Data availability

Data will be made available on request.

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