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RESEARCH ARTICLE

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Drought variability, changes and hot spots across the African continent during the historical period (1928–2017)

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Abstract

The spatiotemporal variability of meteorological droughts, its changes and hot spots location across Africa are analysed for the period spanning 1928–2017 using the Standardized Precipitation Index (SPI) applied to the precipitation products from the Climatic Research Unit (CRU), University of Delaware (UDEL) and Global Precipitation Climatology Centre (GPCC). Spatially, an analysis based on rotational empirical orthogonal function identifies five regions of similar drought variability, namely the Sahel, East Africa, East Southern Africa, West Southern Africa and the Gulf of Guinea. Temporally, the most common periods of drought occurrence are the 1970s, the 1980s and, to a lesser extent, the 1990s. Changes in drought characteristics for the intermediate past (1958–1987) and recent past (1988–2017) compared to the far past (1928–1957) indicate robust increases of drought duration, frequency and severity in the Sahel, and to a lower extent in the Gulf of Guinea, some areas of Central Africa, part of Southern Africa and over Madagascar. These changes are stronger (weaker) along the Sahel during the intermediate past (recent past) and stronger (weaker) over Central and Southern Africa and Madagascar during the recent past (intermediate past). As a consequence, drought hot spots, mostly driven by severity during the regions' wet season, are identified in areas confined in the Sahel during the intermediate past and in regions mainly over Central and Southern Africa and Madagascar during the recent past. Our results are useful for drought disaster risk management across Africa and provide a valuable reference for future drought analysis under global warming conditions.

KEYWORDS

drought characteristics, drought hot spots, drought variability, SPI

1 | INTRODUCTION

Droughts are among the most complex recurrent climatic phenomena that have disastrous consequences on natural environments and socio-economic systems across the world (Portela et al., 2015; Van Loon, 2015; Wilhite & Pulwarty, 2017). Negative impacts on society and the environment include mortality, desertification, prolonged aridity, food shortages, health issues and mass migration, all more marked in the least developed countries. Of primary concern is the projection that Africa is likely to experience the worst impacts of climate change, with droughts and water scarcity becoming more severe and frequent (Gan et al., 2016; Gizaw & Gan, 2017; Sylla et al., 2018; Trisos et al., 2022). Some of these changes are already observed in areas of Africa (Nicholson et al., 2018; Nicholson & Entekhabi, 1986) such as West Africa and the Horn of Africa (Haile et al., 2020; Nicholson, 2017; Ranasinghe et al., 2021; Seneviratne et al., 2021; Sylla et al., 2016).

In order to reduce the risk related to drought events and to mitigate their adverse impacts, a good drought management planning is necessary and requires a comprehensive understanding of historical droughts (Vicente-Serrano et al., 2012). For example, a spatial analysis of past and recent drought events, their duration, frequency and severity can improve quantification of their impacts and the readiness of countries where they occur. In addition, analysis of past droughts can help to better assess the vulnerability of different development sectors such as water resources, agriculture and energy.

Quantification and understanding of drought characteristics, both spatially and temporally, rely on the use of drought indicators (Guo et al., 2019; Spinoni et al., 2014; Zargar et al., 2011), which can identify meteorological, agricultural, hydrological, socioeconomic and ecological droughts depending on the approach and the input variables used (Ranasinghe et al., 2021; Wilhite, 2006; Zargar et al., 2011). Among these, the standardized precipitation index (SPI) is recommended by World Meteorological Organization (WMO) as a standard drought-monitoring index and has been widely used for operational purposes and for climate change research across various domains (Dutra et al., 2013; Gidey et al., 2018; Hao & AghaKouchak, 2013; Mishra & Singh, 2010; Spinoni et al., 2014).

Several studies have investigated droughts in different regions of Africa. In West Africa, an important decline of about 40% in annual total precipitation during 1968–1990 relative to 1931–1960 has been reported (Dai, 2011). This has motivated numerous studies focusing in particular on the Sahelian droughts (Ali & Lebel, 2009; Diasso & Abiodun, 2017; Kasei et al., 2010; Lebel & Ali, 2009; Lodoun et al., 2013; Traore & Fontane, 2007; Zeng, 2003). In East Africa, Yang and Huntingford (2018) found a precipitation reduction of 40% during August, September and October (ASO) of 2016 compared to the mean ASO rainfall for the period 1981–2015. In fact, historical drought analysis revealed that the region ranks among the most exposed to drought across the world, with a high potential for increased drought risk linked to water and food shortages (Funk et al., 2014, 2015; Masih et al., 2014; Zeleke et al., 2017). South Africa is also subject to the occurrence of droughts (Araujo et al., 2016; Masih et al., 2014; Meque & Abiodun, 2015; Ujeneza & Abiodun, 2015), and in northwestern Africa, a number of moderate to severe droughts during the 20th century have been found (Ouassou et al., 2007; Touchan et al., 2008, 2011).

While past droughts have been investigated in these regions, little attention has been given to Central Africa (Hua et al., 2016) and North Africa (Ouassou et al., 2007; Touchan et al., 2008, 2011). In addition, only a few studies considered more than one region of Africa (Calow et al., 2010; Herweijer & Seager, 2008; Naumann et al., 2012; Rojas et al., 2011; Tadesse et al., 2008) and a comprehensive historical drought study covering the whole African continent is not available. Even though some studies have been carried out at the global level (Spinoni et al., 2014, 2019), analysis of the nature and severity of historical droughts remains largely unexplored over the whole African continent. As a matter of fact, the recently released Intergovernmental Panel on Climate Change (IPCC) in its chapter 12 of the Working Group 1 categorizes observed information on drought changes in Africa in the medium to low confidence category due to limited evidence and agreement (Ranasinghe et al., 2021). This study is thus designed to address some of these gaps.

Our main objective is to comprehensively analyse spatiotemporal characteristics and changes of drought events throughout Africa during the historical period (1928–2017) using the Standardized Precipitation Index (SPI) and three observational records. In particular, we aim to (1) detect modes of drought variability by applying a rotated empirical orthogonal function (REOF) to the SPI values; (2) quantify recent changes in drought characteristics (e.g., maximum drought duration, frequency and severity) and (3) identify drought hot spots and how seasonal variability contributes to determining drought hot spots. The results of this study are thus intended to provide a key valuable scientific reference for drought risk planning and preparedness across Africa, while a comprehensive assessment of the physical mechanisms leading to drought occurrence is beyond the scope of the present paper and needs specific analysis to be reported in future work.

2 | MATERIALS AND METHODS

2.1 | Data description

For our study, we use gridded precipitation datasets as they provide spatially and temporally continuous data compared to classic gauge observations that are location specific (Cheng et al., 2015; Thavorntam et al., 2015). However, we stress that gridded datasets are produced through interpolation from gauge observations, and are thus characterized by some uncertainties in regions with sparse gauge coverage. This is the main reason why three observation products are used in this present study.

The first one is the latest version of the Climatic Research Unit monthly precipitation data (CRU TS4.04; Harris et al., 2020). This choice is based on the fact that, first, the CRU dataset relies on a large number of ground-based stations with good quality control and homogeneity check (Harris et al., 2020) and, second, the $0.5^\circ \times 0.5^\circ$ monthly spatiotemporal resolution and long-term availability of data are adequate for robust computation of the SPI, which requires at least 30 years of precipitation data (Burroughs & Burroughs, 2003).

A consideration that can impact our analysis is the fluctuation in the number of stations used for generating the observed gridded datasets (e.g., of CRU; Harris et al., 2014). However, previous studies (i.e., Schroeer et al., 2018) have shown that the effect of the number of stations is stronger at fine temporal scales and for extreme precipitation analysis rather than for the monthly scale adopted in our study. In addition, there is a general agreement that the overall variability is generally well characterized in the CRU data (Herrera et al., 2019; Shi et al., 2017). Finally, recent studies (Akinsanola & Ogunjobi, 2017; Guenang et al., 2019; Kalisa et al., 2020; Ongoma et al., 2018; Peng et al., 2020) have suggested that the CRU dataset is an appropriate and satisfactory set of data for climatological studies in Africa.

To ensure the reliability of our findings and conduct a comprehensive historical drought analysis, we have incorporated two additional gridded precipitation datasets alongside the CRU dataset. The University of Delaware precipitation dataset (UDEL V5.01; Willmott, 2000) provides global gridded information at a spatial resolution of $0.5^\circ \times 0.5^\circ$, derived from diverse global gauge measurements, including the Global Historical Climatology Network and Global Synoptic Climatology Network archive. Additionally, following the suggestions made by Dai and Zhao (2016) regarding the potential superiority of the Global Precipitation Climatology Centre (GPCC) dataset for specific analyses compared to the CRU and UDEL datasets, we have integrated the GPCC dataset, provided by NOAA ESRL (National Oceanic and Atmospheric Administration Earth System Research Laboratory) at a spatial resolution of $0.5^\circ \times 0.5^\circ$. GPCC spans the period 1891–2020 and is reconstructed from gauge observations from numerous stations. This inclusion ensures the evaluation of precipitation trends and variability with enhanced reliability (Dilinuer et al., 2021; Schneider et al., 2017; Song et al., 2022). Dai and Zhao (2016) also highlighted limitations in the CRU data coverage since the 1990s, emphasizing the significance of including alternative datasets like GPCC to address potential data gaps and enhance the robustness and comprehensiveness of our historical drought assessment.

By utilizing the CRU, UDEL and GPCC datasets collectively, we effectively address inherent uncertainties in observed precipitation products, leading to a more robust analysis. The consistent features present across all three datasets further strengthen the robustness of our conclusions. This comprehensive approach allows us to conduct a thorough examination of historical drought patterns from 1928 to 2017, offering valuable insights into long-term climatic trends.

Nonetheless, it is crucial to acknowledge the limitations associated with gridded datasets, particularly during the early 20th century (i.e., pre-1950s), where data availability may be limited. Prior studies have recognized that such limitations can lead to underestimates of spatial variabilities in precipitation within gridded datasets (Becker et al., 2013; Nasrollahi et al., 2015; Vittal et al., 2013). Despite these potential challenges, the incorporation of multiple datasets and careful consideration of previous research findings allow us to account for and mitigate these issues, ensuring a more comprehensive and well-informed assessment of historical droughts within the context of our study.

2.2 | Methods

2.2.1 | Standardized precipitation index

Of the various drought indices that exist, the most used ones are the Palmer Drought Severity Index (PDSI; Palmer, 1965), the Standardized Precipitation Index (SPI; McKee, 1995; McKee et al., 1993) and the Standardized Precipitation-Evapotranspiration Index (SPEI; Vicente-Serrano et al., 2010). The PDSI requires numerous parameters that are not available in Africa for the study period. By taking into account the effects of temperature, SPEI represents a simple climatic water balance and is a good indicator for agricultural drought. However, its calculation requires potential evapotranspiration (PET) and there are multiple formulations of PET that lead to different estimations (Dewes et al., 2017; Sylla et al., 2018; Trenberth et al., 2014; Yuan & Quiring, 2014). In addition, Spinoni et al. (2014) stressed that SPEI has difficulties discriminating between a heat wave and a meteorological drought that adds various levels of uncertainties to the SPEI results. In this paper, as we are interested in meteorological drought, we thus chose SPI, based on precipitation only, as a drought index.

The SPI is recommended by the WMO for monitoring drought conditions based on accumulated precipitation (Svoboda et al., 2012). Past studies (Guttman, 1998; McKee, 1995; McKee et al., 1993) have demonstrated a good performance by the SPI in representing precipitation anomalies and drought characteristics. This index has been used for different applications including climate research for different regions and seasons. Such studies include over Europe (e.g., Cammalleri et al., 2022; Lloyd-Hughes & Saunders, 2002; Spinoni et al., 2014), Asia (e.g., Aadhar & Mishra, 2017; Sharma et al., 2021; Zhai et al., 2010), Northern America (e.g., Agnew, 2000; Sung & Stagge, 2022), South America (e.g., Sgroi et al., 2021; Zanvettor & Ravelo, 2000), Australia (e.g., Mpelasoka et al., 2008; Yildirim & Rahman, 2022) and Africa (e.g., Gader et al., 2022; Naumann et al., 2012; Ntale & Gan, 2003).

In order to derive the SPI, a parametric cumulative distribution function (CDF) is used to fit the homogenized precipitation time series. This is performed separately for each month and grid point. Then, the fitted distribution function is transformed into a normalized distribution with a mean of zero and a standard deviation of one (McKee et al., 1993; McKee, 1995). Here we use the Gamma distribution to represent the CDF of the precipitation time series (Husak et al., 2007; Lloyd-Hughes & Saunders, 2002; McKee, 1995; McKee et al., 1993) because it has the advantage of being zero-bounded and positively skewed (Thom, 1958; Wilks, 2002). The maximum-likelihood estimation method is employed to calculate the gamma distribution parameters considering the entire historical period (1928–2017), making thus the SPI computation more robust, as suggested by Wu et al. (2005) and Spinoni et al. (2020). In fact, selecting a shorter time period, likely marked by occasional and mild droughts, could impact the SPI calculation, causing an overestimation of droughts in different periods (Spinoni et al., 2014).

For an appropriate application of the SPI in a continent-wide analysis with areas defined by distinct seasonal precipitation distributions, a medium accumulation period (12 months) is chosen when computing the drought indicator (i.e., SPI-12) and is applied to the CRU, UDEL and GPCC precipitation time series as done in Spinoni et al. (2014). The underlying reason is that a medium accumulation is better suited for detecting different precipitation regimes over a large domain such as Africa. Shorter (SPI-3, SPI-6) or longer accumulations (SPI-24, SPI-48) are likely sensitive to extremes and can possibly omit relevant drought episodes. In addition, very arid areas (the Sahara, the Namib and eastern Somalia deserts) that are physically not meaningful for drought analysis are excluded from the SPI calculation (see Figure 1). Hence, the potential effects of low-precipitation seasons and dry climates on the SPI representation are avoided as suggested by Spinoni et al. (2014) in a global analysis and Wu et al. (2007) over the contiguous United States.

The SPI-12 method described above is thus applied to monthly CRU, UDEL and GPCC precipitations. Following McKee (1995) and McKee et al. (1993), the wet/drought conditions are characterized as moderate, severe or extreme depending on the SPI value (see Table 1).

2.2.2 | Principal component analysis

Principal component analysis (PCA) is applied to the SPI-12 time series of CRU, UDEL and GPCC to identify

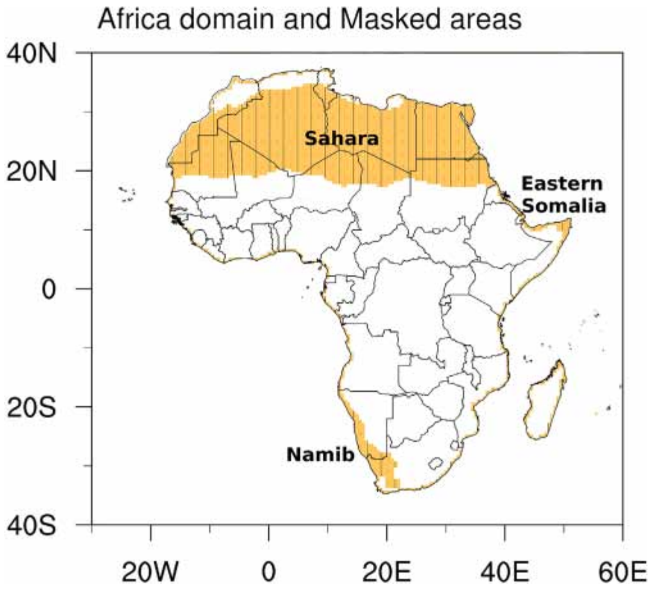

FIGURE 1 The Africa domain and masked areas (Sahara, Namib and eastern Somalia deserts)

subregions with similar SPI variability and thus drought modes, focusing specifically on SPI values lower than −1. PCA is an efficient dimensionality reduction method to derive structural information and patterns with similar variance features. It can be based on empirical orthogonal function (EOF) or rotated empirical orthogonal function (REOF) analysis. The PCA makes use of a few linearly uncorrelated principal components (PCs) by computing the eigenvalues and eigenvectors of the corresponding covariance matrix (Raziei et al., 2009). The concept of "loadings," defined as the normalized eigenvectors, is used to represent the correlation between the original data and the time series of component scores.

Because of its orthogonality constraint, the EOF analysis has a tendency to produce complex spatial structures and causes difficulty in their physical explanations (Hannachi et al., 2007). This limitation can be partly alleviated by the Rotated EOF analysis (REOF) which, in addition, can further optimize the variance quantification of squared correlations between the rotated principal components (RPCs) and the corresponding variables, thus simplifying the spatial patterns with similar temporal variations (Janowiak, 1988; Lian & Chen, 2012; Nikiema et al., 2017; Zhao et al., 2012). There are several types of REOF schemes (Richman, 1986). In this study, the Varimax rotation method (Richman, 1986; von Storch & Zwiers, 2002) is applied to the PCA as in an early analysis over Africa (Janowiak, 1988) and more recently over West Africa (Nikiema et al., 2017). Therefore, for each REOF loading showing the spatial pattern of a mode of variability, there is a corresponding time series (i.e., RPC) displaying the temporal variation of the mode.

It is worth mentioning that the Varimax REOF approach tends to produce a set of subdomain coherent regions that are largely independent of time, which means the results may miss large-scale teleconnection drivers of SPI-12 in the CRU, UDEL and GPCC datasets.

TABLE 1 Classification of drought categories from SPI Drought Index

Drought severity levels	SPI value
Extremely wet	SPI ≥ 2.0
Severely wet	1.5 ≤ SPI < 2.0
Moderately wet	1.0 ≤ SPI < 1.5
Near normal	−1.0 < SPI < 1.0
Moderate drought	−1.5 < SPI ≤ −1.0
Severe drought	−2.0 < SPI ≤ −1.5
Extreme drought	SPI ≤ −2

2.2.3 | Drought characteristics

Once the SPI-12 time series are computed for the CRU, UDEL and GPCC datasets at each grid point for the entire period 1928–2017, we subdivide this time series into three climatological (i.e., 30 years) subperiods: 1928–1957 (far past), 1958–1987 (intermediate past) and 1988–2017 (recent past). The decision to break the record into three 30-year periods is motivated by our objective of investigating changes in drought metrics at the climatological time scale. In fact, choosing the entire 1928–2017 period for SPI-12 computation in drought characterization minimizes potential biases introduced by statistical distributions based on shorter periods, such as the three selected past periods, as emphasized in Spinoni et al. (2014, 2015). Through this approach, we enable a robust analysis of drought variability within a long-term climatological context, facilitating the identification of meaningful patterns and changes in drought characteristics across the three subperiods.

For this, we adopt a drought episode definition which is slightly different than in Spinoni et al. (2014), whereby a drought episode starts when the SPI falls below −1 and ends when the SPI returns above −1 for at least two consecutive months. This choice is based on the fact that we consider SPI values in Table 1 between −1 and 0 as being near normal conditions. Changes in drought characteristics between the different 30-year periods are thus examined using the metrics defined below:

- Maximum Drought Duration (MDD) represents the longest series of consecutive drought months (i.e., months with SPI lower than −1) in a given period. It provides information on the duration of the most prolonged drought episodes. By expressing MDD in months per decade, we can assess how the length of these drought events has evolved over time. MDD helps identify periods when Africa experienced prolonged drought conditions, enabling to understand the temporal patterns and to foresee the potential impact on various sectors.
- Drought Frequency (DF) measures the total number of drought months (i.e., months with SPI lower than −1) in all drought episodes for a given period. It quantifies the frequency at which drought conditions occur throughout the region. Expressed in months per decade, DF helps us understand the occurrence and recurrence of drought events. Higher DF values indicate more frequent drought episodes, highlighting regions or periods that experience recurrent droughts.
- Drought Severity (DS) provides a measure of the cumulative severity of drought events within a given period. It is calculated as the sum, in absolute values, of all SPI values lower than −1 in all drought episodes. This dimensionless parameter allows to assess the overall severity of drought conditions across Africa. Higher DS values indicate more severe and widespread drought impacts.

For each of these, yearly values are summed up and then climatologically averaged over the entire periods.

Change between the intermediate (recent) and the far past are computed by differencing between 1958–1987 (1988–2017) and 1928–1957. In order to compare these two changes, the difference between the recent (i.e., 1988–2017) and the intermediate past (i.e., 1958–1987) is also performed. Finally, significant changes are detected using a two-tailed Student's *t* test at the 95% confidence level, consistent with standard statistical practices.

2.2.4 | Hot spots identification

To finally provide an overview of areas most susceptible to drought, drought hot spots are identified for each subperiod based on drought severity time series computed from the SPI using CRU, UDEL and GPCC observations. A drought hot spot is defined as a region of contiguous grid points where drought severity is much higher compared to the adjacent regions. Specifically, the following procedure is adopted to identify drought hot spots:

- First, we identify the domain 99th percentile of drought severity by considering all SPI values in all drought episodes, at all grid points (i.e., the whole Africa domain except grid of the dry regions indicated in section 2.2.1) and for the entire period (i.e., 1928–2017).
- Second, we calculate for CRU, UDEL and GPCC, for each grid point and each subperiod (i.e., far past, intermediate past and recent past) the total drought extreme severity (TDES) by summing up all values above the domain 99th percentile.
- Third, we identify as drought hot spots the regions where the maximum values of TDES are found.

For the following section, features present in CRU, UDEL and GPCC in the drought variability analysis, the changes in drought characteristics as well as the identification of hot spots are considered robust.

3 | RESULTS

3.1 | Drought variability

The geographical distribution of the first five loadings (i.e., those with the largest fraction of variance explained) is shown in Figure 2 for CRU, UDEL and GPCC, whereas the loadings time series are shown in Figure 3. Ten more modes of SPI variability were identified over different regions of Africa but with lower explained variance (see Figures S1–S4, Supporting Information). These 15 modes together explain 63%, 55% and 52% of the total variance for the CRU, UDEL and GPCC observations, respectively. Here we analyse the first 5 modes only as they characterize the main spatial coherences of the SPI variability over relatively large portions of the continent. The loading patterns are designated as REOFs and their associated time series as RPCs.

The observed first five REOFs explain more than 39%, 33% and 31% of the total variance for CRU, UDEL and GPCC, respectively, and are in the same range as those obtained in Janowiak (1988) across the whole Africa. In particular, the first mode explains 15.71%, 12.83% and 11.25% of the total variance for CRU, UDEL and GPCC, respectively, and corresponds to a large strip of maximum negative values extending from East to West Africa along the Sahel region (Figure 2a–c). This pattern is therefore defined as the Sahel mode.

The second and third modes explain 7.29% and 6.47% of the total variance for CRU, 5.78% and 5.44% for UDEL, and 6.10% and 6.15% for GPCC. They indicate homogeneous negative patterns over East Africa (REOF2; i.e., Figure 2d–f) and East Southern Africa (REOF3; i.e., Figure 2g–i). For the East Southern Africa

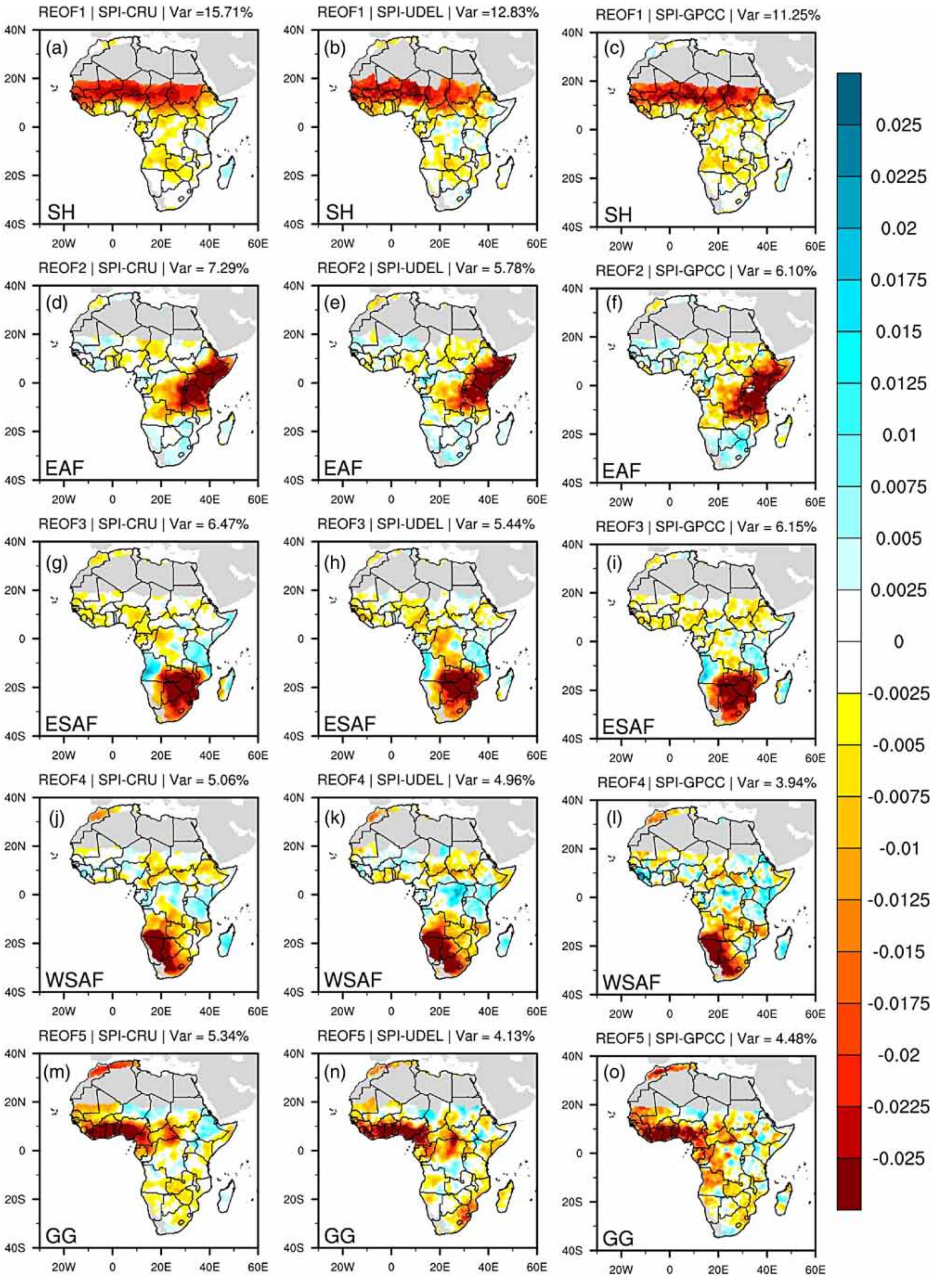

FIGURE 2 Legend on next page.

mode, the pattern covers countries such as Zambia, Zimbabwe, Botswana and South Mozambique, while for the East Africa mode, it is mainly located in southern Ethiopia, Somalia, Kenya, Uganda and northern Tanzania. Finally the fourth and fifth modes, which explain 5.06% and 5.34% (for CRU), 4.96% and 4.13% (for UDEL), and 3.94% and 4.48% (for GPCC) of the total variance, respectively, show maximum negative values in West Southern Africa and over the Gulf of Guinea. These five modes of SPI variability identify coherent features of similar nature, indicating that each of these regions is either overall dry or overall wet depending on the temporal variability (i.e., RPCs).

The corresponding RPCs representing the temporal variability of the spatial patterns are presented in Figure 3 for CRU, UDEL and GPCC. RPC1 for CRU, UDEL and GPCC (i.e., Figure 3a–c), corresponding to the Sahel mode, exhibits robust wet conditions before the 1960s and marked drought events from the late 1960s onward, with maxima in the 1970s and 1980s (see Figure 3a–c). This behaviour has been highlighted in several studies (Dai, 2011; Giannini et al., 2008; Lebel & Ali, 2009; Mishra & Singh, 2010; Ndehedehe et al., 2020; Zeng, 2003). In fact, REOF1 is a low-frequency multidecadal drought mode affecting the Sahel attributed primarily to a southward shift of the warmest sea surface temperatures (SSTs) patterns in the Atlantic and warming in the Indian Ocean combined to changes in land surface properties (Chaney et al., 2014; Dai, 2011; Doblas-Reyes et al, 2021; Giannini et al., 2008; Lebel & Ali, 2009; Mishra & Singh, 2010; Ndehedehe et al., 2020). Some authors also suggested that an anthropogenic component could have a role at play via greenhouse and aerosol forcings (Ackerley et al., 2011; Biasutti & Giannini, 2006; Held et al., 2005).

RPC2 (i.e., Figure 3d–f) and RPC3 (Figure 3g–i) show strong variability for CRU, UDEL and GPCC, indicating that the East Africa and East Southern Africa regions experienced alternating wet and drought periods. This indicates mostly an interannual (from 1 to 5 years) control on SPI-12 in these regions. For example for the East Africa mode, the 1960s are the wettest years while the 1940s, 1980s and 1990s are the driest periods, as also found in Nicholson et al. (2018) and Kalisa et al. (2020). Most of these drought events in East Africa have been attributed to variations in Ocean Pacific SSTs, that is, the role of the El Niño–Southern Oscillation (ENSO) on interannual East Africa rainfall variability. Studies (e.g., Diro et al., 2011; Hastenrath et al., 1993; Parhi et al., 2016) reported that most dry years are associated to La Niña (ENSO's cold phase) events over East Africa. In addition to the role of ENSO, a negative Indian Ocean Dipole (IOD) prominently plays a key function in recent droughts observed in the region as suggested in some recent studies (e.g., Kebacho, 2022; Nicholson, 2015; Wenhaji Ndomeni et al., 2018). Furthermore, anthropogenic component is also considered as an additional factor causing the underlined drought episodes (AghaKouchak et al., 2015; Schubert et al., 2016; Van Loon et al., 2016; Zeng, 2003). For East Southern Africa, noticeably different drought periods are identified, with very consistent patterns between CRU, UDEL and GPCC data (Table S2). The most prominent droughts occur within three specific periods: the first spanning the late 1960s until the late 1970s, the second from the early 1980s to the late 1990s, and the last starting around 2015. In fact, an increase in the spatial extent of drought over the region since the 1970s has been documented by Rouault and Richard (2005), attributing this to a strengthening of ENSO–southern African rainfall relationship.

For the West Southern Africa mode (i.e., RPC4; Figure 3j–l), the most notable drought events occurred in the early 1930s, mid-1940s and from the early 1980s to the late 1990s, interrupted by periods of wet conditions in the late 1960s and the mid-1970s. These events are captured in CRU, UDEL and GPCC. El Niño–Southern Oscillation (ENSO) was the main driver of droughts during this period, while regional oceanic and atmospheric temperature anomalies (e.g., the Southwest Indian Ocean) also participate in their genesis (Richard et al., 2001; Rouault & Richard, 2005). Another potential cause of the droughts observed in RPC4 is a disruption in the formation and circulation of tropical temperate troughs (TTTs) (Chikoore & Jury, 2021; Vigaud et al., 2009) that are responsible of the important amount of rain falling over the region (Christensen et al., 2007; Vigaud et al., 2009).

Finally, RPC5 (i.e., Figure 3m–o, for CRU, UDEL and GPCC, respectively), corresponding to the Gulf of Guinea mode, displays two distinct and marked periods: one from 1928 to the late 1960s, when positive values are dominant, and another from the early 1970s until 2017,

FIGURE 2 Spatial patterns of the first five modes for the REOF of SPI-12 from CRU (1st column panels), UDEL (2nd column panels) and GPCC (3rd column panels). The percentage of variance explained by each mode is labelled. The different modes of variability are also labelled as SH (Sahel; a, b, c), EAF (East Africa; d, e, f), ESAF (East Southern Africa; g, h, i), WSAF (West Southern Africa; j, k, l) and GG (Gulf of Guinea; m, n, o)

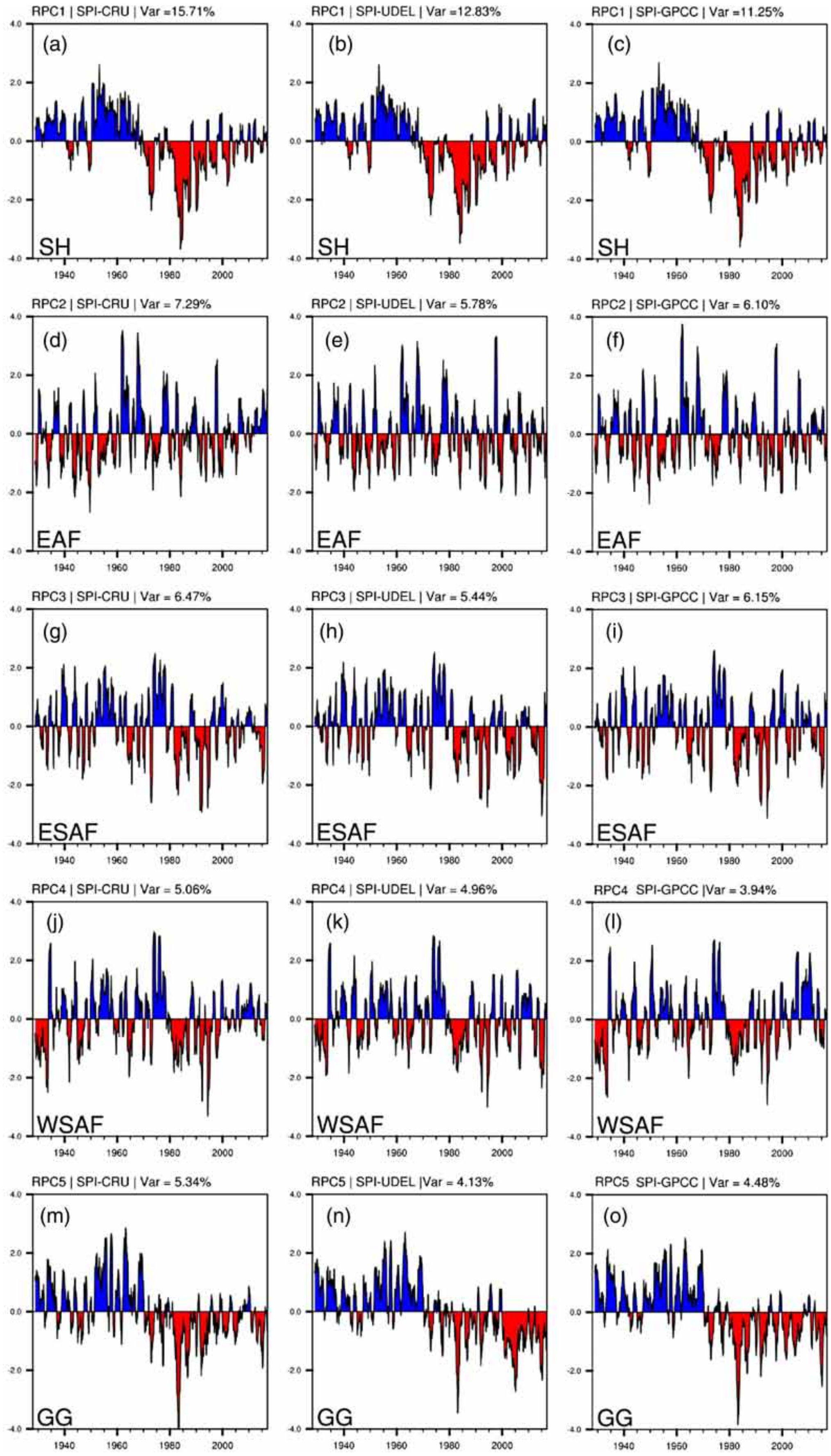

FIGURE 3 Legend on next page.

with negative values. This indicates that the Gulf of Guinea countries experienced wet periods until the late 1960s, when drought conditions started to prevail. This has been linked by some authors to variations in SSTs in the eastern tropical Atlantic Ocean and in the Gulf of Guinea (e.g., Janicot, 1992; Rowell et al., 1995).

The analysis reveals significant correlations between RPC1 and RPC5, representing the SH and GG regions, respectively, with correlation coefficients of about 0.637, 0.522, and 0.662 across the datasets (Table S1). These strong correlations indicate the substantial impact of the West African Monsoon on rainfall variability in both the SH and GG regions, consistent with findings in Giannini et al. (2008). Moreover, higher correlations are also observed between RPC3 and RPC4, representing the ESAF and WSAF regions, respectively, with correlation coefficients of approximately 0.750, 0.783, and 0.706 in the CRU, UDEL and GPCC datasets for both RPCs (Table S1). These pronounced correlations point out to the pivotal role of the ENSO–southern African rainfall relationship in governing precipitation/drought dynamics in the ESAF and WSAF regions.

In short, the rotated loadings of the SPI-12 for CRU, UDEL and GPCC clearly identify various modes of drought variability across the African continent with the five principal ones being the Sahel, East Africa, East Southern Africa, West Southern Africa and Gulf of Guinea modes. Different episodes of droughts are shown in the corresponding time series during the study period; however, the 1970s, the 1980s and to a lesser extent the 1990s are common periods where droughts have occurred over most of the African continent. How this translates into changes in duration, frequency and severity is investigated below.

3.2 | Changes in drought characteristics

As mentioned, in order to assess how droughts have evolved throughout the past until recent decades, we here divide the whole period into three 30-year subperiods (far past, intermediate past and recent past; see section 2.2.3) and investigate changes in drought characteristics being maximum drought duration (MDD), drought frequency (DF) and drought severity (DS) between these subperiods. However, before analysing such changes, it is useful to examine the corresponding precipitation changes between the periods, which might in fact determine whether conditions conducive to meteorological droughts are likely to occur.

Figure 4 presents changes in annual total precipitation between the far past, the intermediate past, and the recent past for the CRU, UDEL and GPCC observation products. A robust drying tendency in the intermediate past compared to the far past (Figure 4a–c) is observed along the Sahel band from Senegal in West Africa to Sudan in East Africa. In particular, significant precipitation decreases of up to 30% are observed in countries such as Senegal, Mali, Niger and Sudan. Smaller decreases (up to 10%) are found in few areas over Southern Africa (i.e., countries such as Botswana and Zimbabwe), but they are mostly not significant. A nonsignificant wetting tendency is exhibited over southern Ethiopia, Kenya and Somalia, with precipitation increases of up to 30%, spatially more extensive in both CRU and GPCC compared to UDEL.

Negative and positive changes are recorded in the recent past compared to the far past over the Sahel band (mostly up to 20%) and in East Africa (mostly up to 25%), respectively, but with relatively low magnitudes in the three datasets (Figure 4d–f). However, over Central and Southern Africa, some significant precipitation decreases are found in a few areas. These changes are weaker and less extended in both CRU and GPCC compared to UDEL. The UDEL dataset shows a distinct discrepancy in Central Africa, likely attributed to the higher levels of uncertainties observed in that specific region, as demonstrated by Xu et al. (2020). Consequently, during the recent past compared to the intermediate past, precipitation has increased in the Sahel band and has decreased in many other parts of the continent, mainly in southern Central Africa and eastern southern Africa (Figure 4g–i). This suggests that the recent past coincides with a rainfall recovery for the Sahel after the drought episodes of the 1970s and 1980s as found in Sanogo et al. (2015), Sylla et al. (2016), Nicholson et al. (2018) and Ndehedehe et al. (2020). These precipitation changes have strong implications for drought occurrence.

Next, we consider MDD, DF and DS as defined in section 2.2.3 and compute them for the far, intermediate and recent past periods. The climatological maps are presented in Figures S5–S7, while Figures 5–7 present the changes in MDD, DF and DS for the intermediate and

FIGURE 3 The corresponding time series (i.e., RPCs) of the first five modes of SPI-12 REOFs for CRU (1st column panels), UDEL (2nd column panels) and GPCC (3rd column panels). The percentage of variance explained by each mode is labelled. The different modes of variability are also labelled as SH (Sahel; a, b, c), EAF (East Africa; d, e, f), ESAF (East Southern Africa; g, h, i), WSAF (West Southern Africa; j, k, l) and GG (Gulf of Guinea; m, n, o)

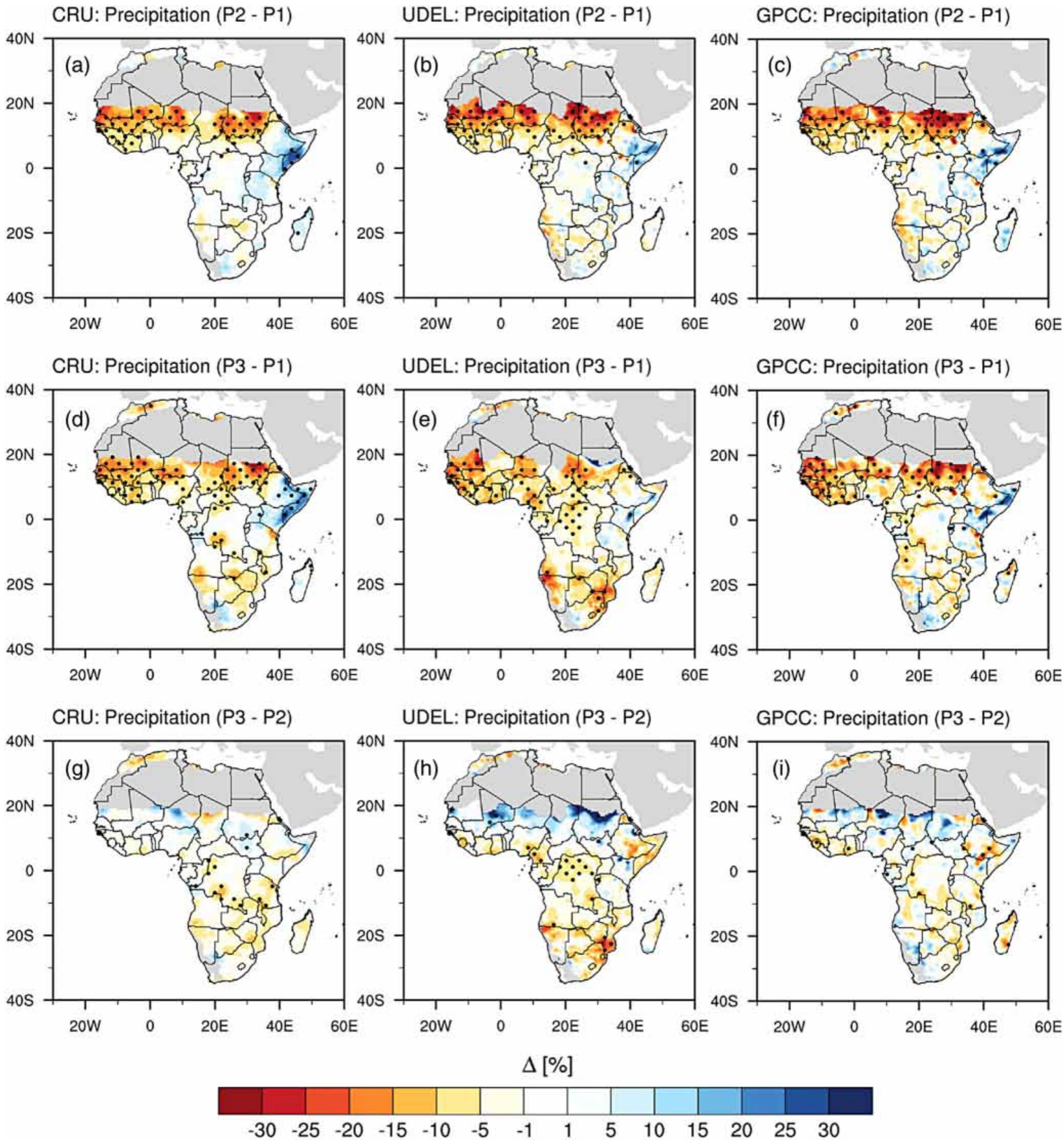

FIGURE 4 Changes in annual total precipitation (in %) considering CRU (1st column panels), UDEL (2nd column panels) and GPCC (3rd column panels) for a, b, c: the intermediate past (P2: 1958–1987) compared to the far past (P1: 1928–1957); d, e, f: recent past (P3: 1988–2017) compared to the far past (P1: 1928–1957); g, h, i: recent past (P3: 1988–2017) compared to the intermediate past (P2: 1958–1987). Stippling indicates grid points with changes that are significant (95% significance level using the *t* test)

recent past with respect to the far past and between the recent past and the intermediate past.

For the intermediate past compared to the far past, both increases and decreases of maximum drought duration occur in many parts of Africa, with the increases being more evident and robust. Specifically, drought events are longer in West Africa and East Sahel in CRU, UDEL and GPCC (Figure 5a–c). This is illustrated by robust and widespread increases of about 25–35 months·decade^{-1} over most countries along the

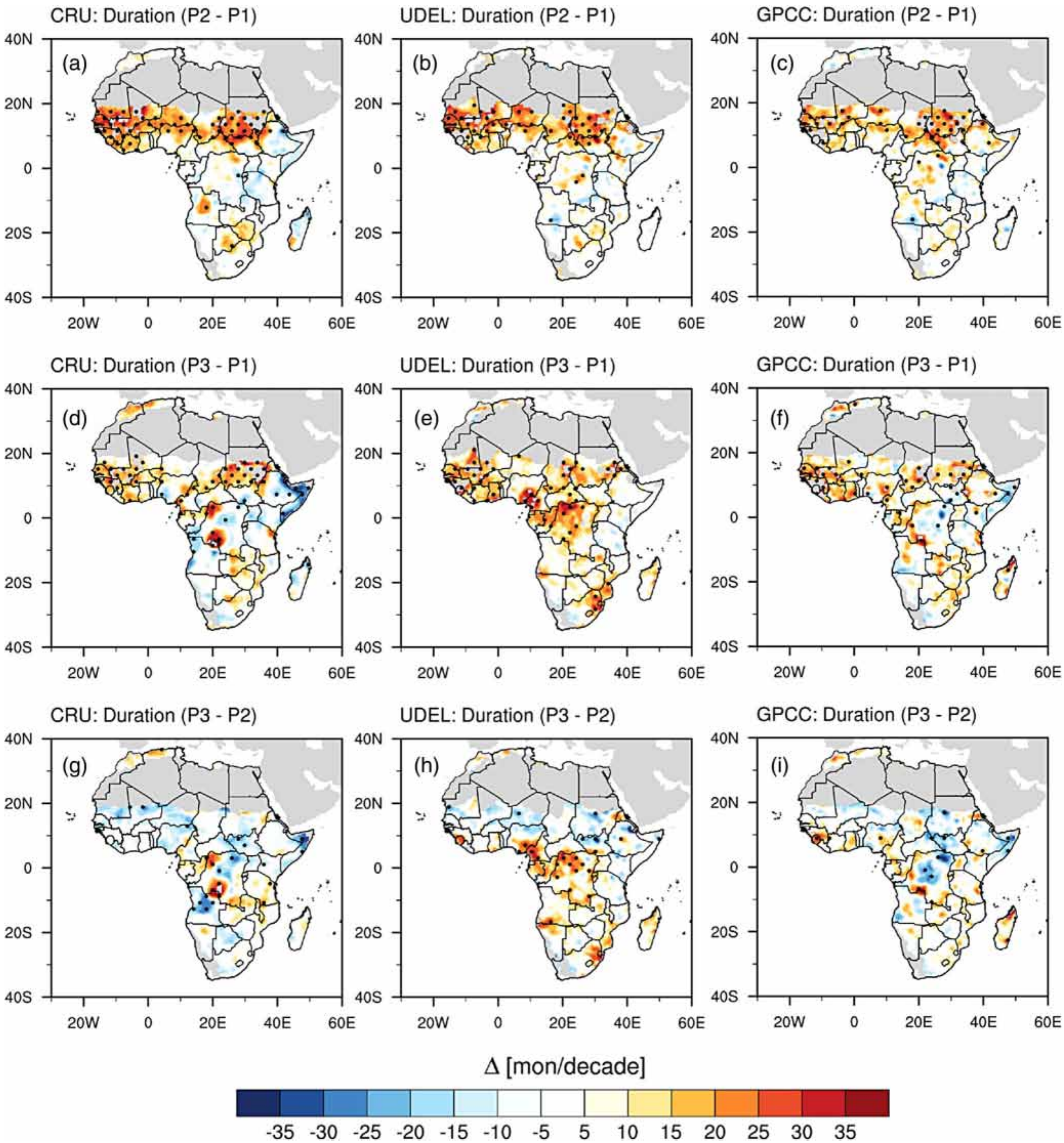

FIGURE 5 Same as Figure 4 but for maximum drought duration (in months·decade^{-1})

Sahel band (i.e., Senegal, Mali, Burkina Faso, Niger, Chad and central Sudan) and the Gulf of Guinea (Cote d'Ivoire, Ghana and Benin). In addition, localized increases of up to 20 months·decade^{-1} are observed in Southern Africa, mainly in Botswana and Zimbabwe, across the three datasets. A few areas in East Africa (central Ethiopia, Somalia, Tanzania) and in the southern part of Central Africa (southern Democratic Republic of Congo [DRC]) experience shorter drought events in the intermediate past compared to the far past.

The recent past exhibits both increases and decreases of drought duration compared to the far past (Figure 5d–f). Robust features of longer maximum drought duration are located in parts of the Sahel (up to 20 months·decade^{-1} in Senegal, southern Mali and southern Sudan), the Gulf of Guinea (up to

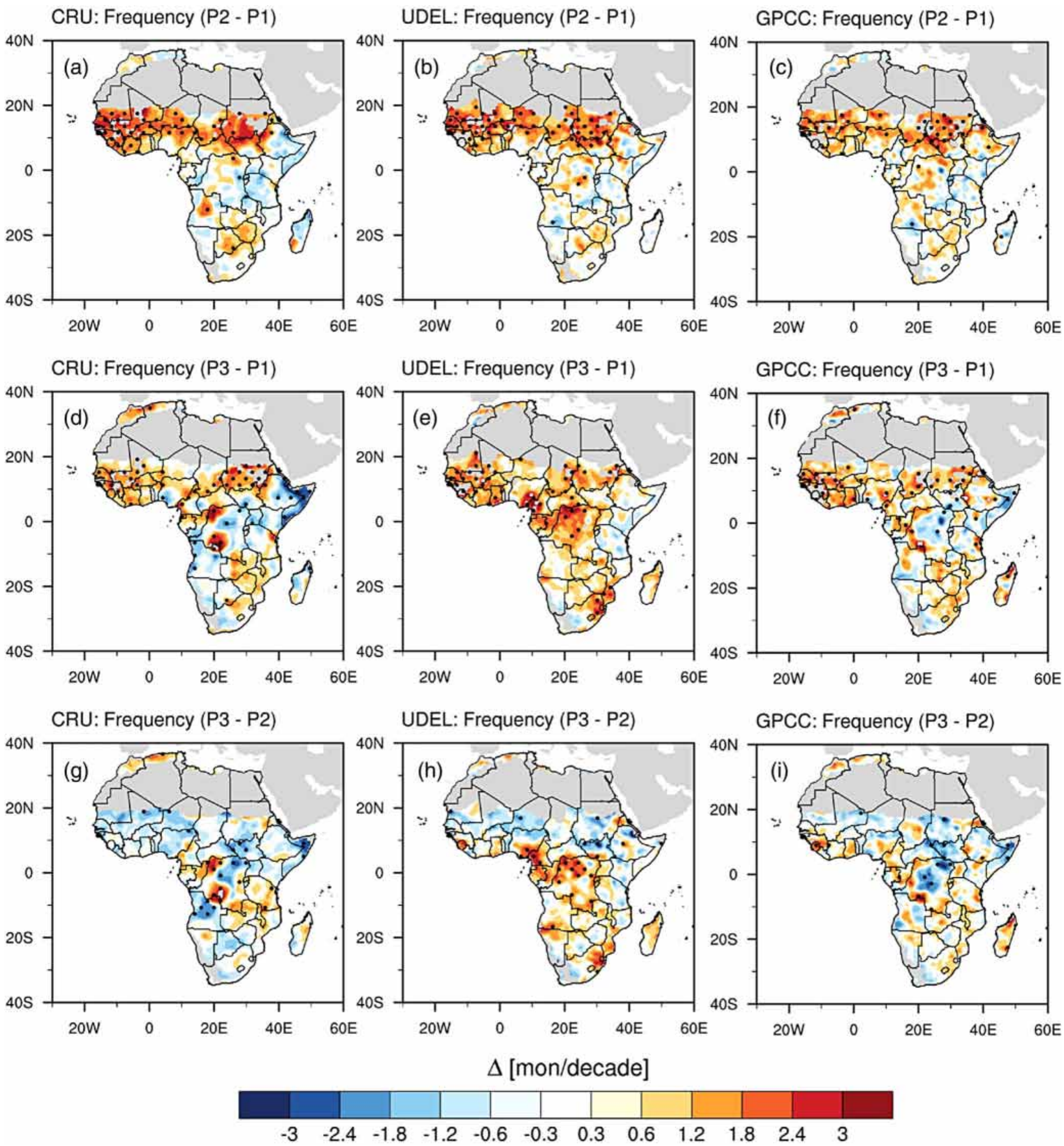

FIGURE 6 Same as Figure 4 but for drought frequency (months·decade^{-1})

25 months·decade^{-1} in Cote d'Ivoire and Ghana), northwestern Africa (up to 25 months·decade^{-1} in the coastal regions of Morocco and Algeria), Central Africa (more than 35 months·decade^{-1} in DRC and southern Cameroon), East Southern Africa (up to 15–25 months·decade^{-1} in Zambia, Mozambique and eastern part of Southern Africa) and eastern Madagascar (up to 10–15 months·decade^{-1}). Note that the amplitude of increases of drought duration found over the Sahel for the recent past is smaller compared to that of the intermediate past (i.e., Figure 5a–c), as lower duration values are observed in the recent past (see Figures S5). It is worth mentioning that considerable discrepancies are noted in Central and East Africa (mainly in Somalia) in UDEL compared to CRU and GPCC. For instance, CRU and GPCC show shorter drought durations over Somalia and

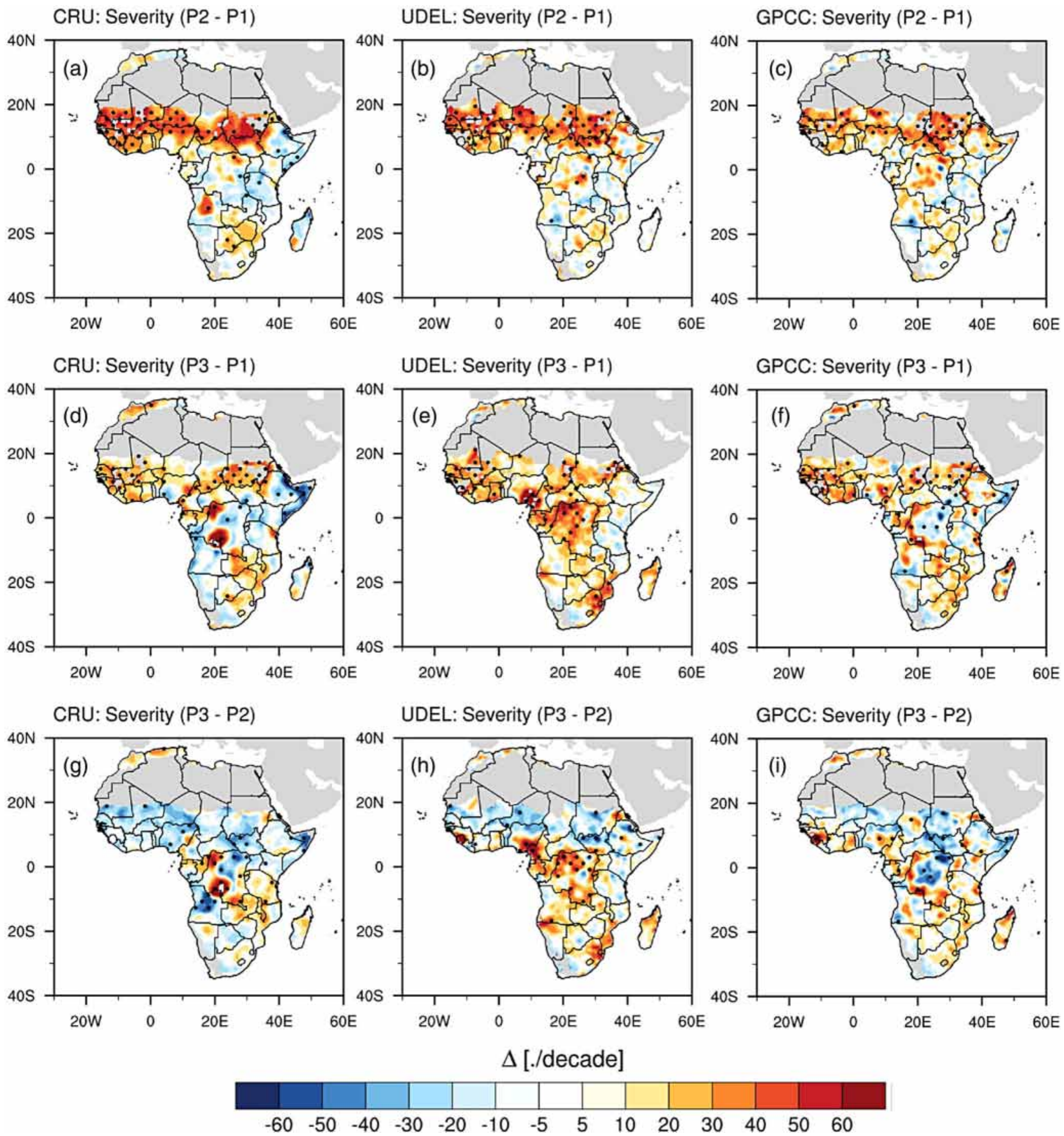

FIGURE 7 Same as Figure 4 but for drought severity (months·decade^{-1})

eastern Ethiopia, with decreases of up to 30 and 25 months·decade^{-1}, respectively, whereas UDEL indicates predominantly negligible changes in these regions.

This drought duration behaviour is confirmed in Figure 5g–i, displaying changes between the recent and intermediate past. In fact, compared to the intermediate past, drought duration has become shorter in the recent past almost everywhere along the Sahel band, and longer over part of Central Africa (northwestern and southeastern DRC), Southern Africa (i.e., in Zambia and northern Namibia) and eastern Madagascar.

The spatial pattern of changes in drought frequency is found to be similar to that of maximum drought duration. For example, changes in the intermediate past compared to the far past (Figure 6a–c) show that the regions with the largest DF increases are primarily the Sahel, with significant increases up to 3 months·decade^{-1} in Senegal, southern Mali and southern Sudan. Other regions such as countries of the Gulf of Guinea (i.e., Cote d'Ivoire and Ghana), Central Africa (i.e., Central Africa country, South Sudan and DRC) and Southern Africa (i.e.,Botswana and Zimbabwe) also exhibit robust changes of up to 1.8 months·decade^{-1}. Conversely, most areas of East Africa are characterized by modest decreases of drought frequency not exceeding 1.8 months·decade^{-1}.

For the recent past relative to the far past (Figure 6d–f), droughts are more recurrent in same Sahel countries, but also in coastal regions of Morocco and Algeria, some regions of Central Africa (i.e., DRC), East Southern Africa and Madagascar. Other regions show different responses across the three datasets. For example,

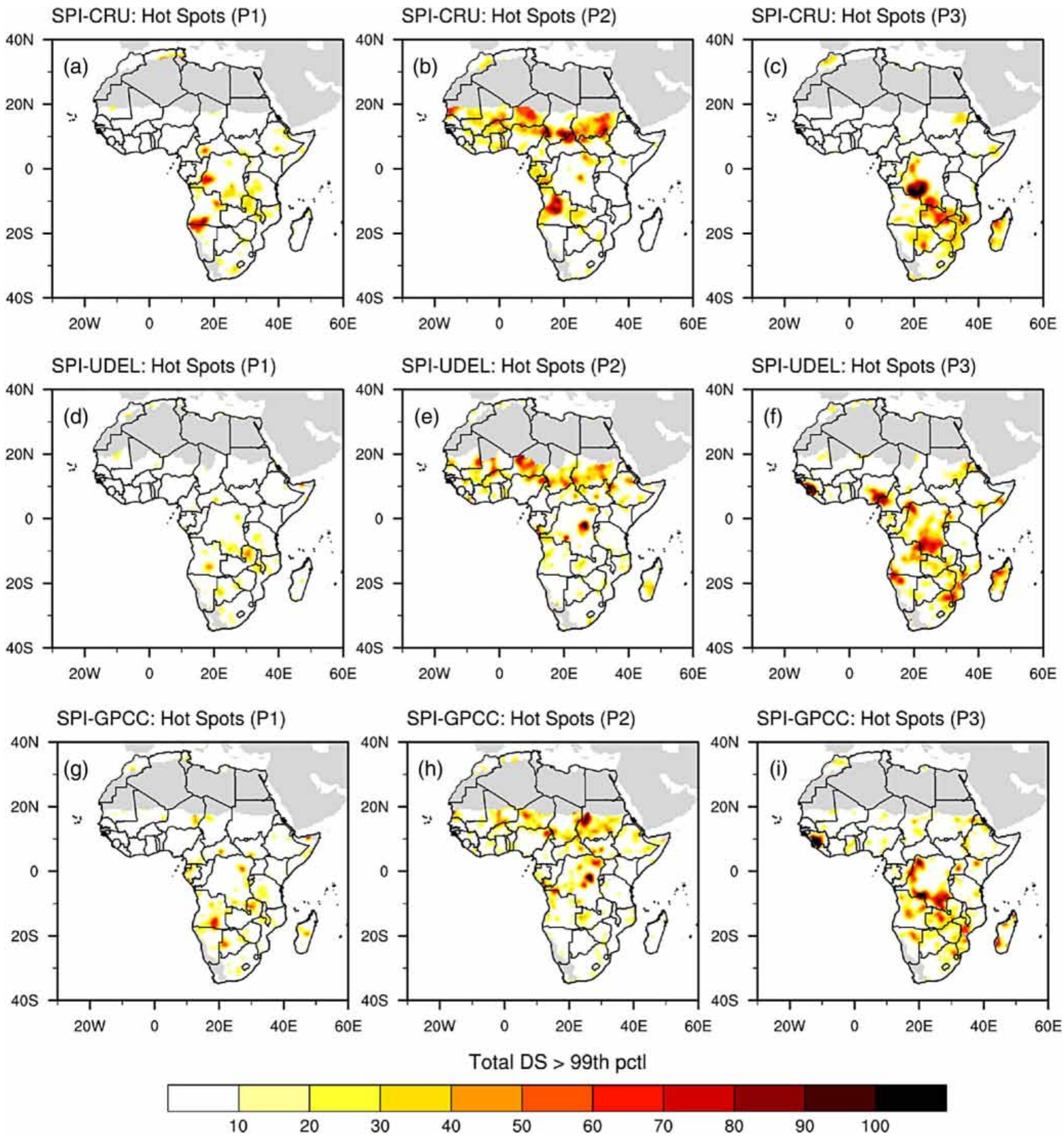

FIGURE 8 Drought hot spots in the subperiods P1 (1928–1957), P2 (1958–1987) and P3 (1988–2017) for CRU (1st row panels), UDEL (2nd row panels) and GPCC (3rd row panels)

changes between the recent past and the intermediate past (Figure 6g–i) indicate fewer occurrences (between 0.6 and 2.5 months·decade^{-1}) over the Sahel, some localized areas of East Africa and portions of West Southern Africa, while areas over Central Africa, parts of Southern Africa and eastern Madagascar show significant increases of drought frequency by about 1.2–2.4 months·decade^{-1}. However, it is important to note that these patterns are not entirely consistent across the three datasets. While CRU and GPCC exhibit quite similar patterns, UDEL shows large differences, especially in Central Africa (Figure 6g–i), as observed for precipitation changes.

Finally, changes in drought severity between the intermediate and far past are shown in Figure 7a–c. The most prominent features are robust increases along the Sahel band in the same areas experiencing more frequent and longer maximum drought duration. In addition, small scale increases of drought severity prevail in the Gulf of Guinea (i.e., Cote d'Ivoire and Ghana), some areas of northern and central DRC and Southern Africa (i.e., Zambia, Zimbabwe and Botswana). Conversely,

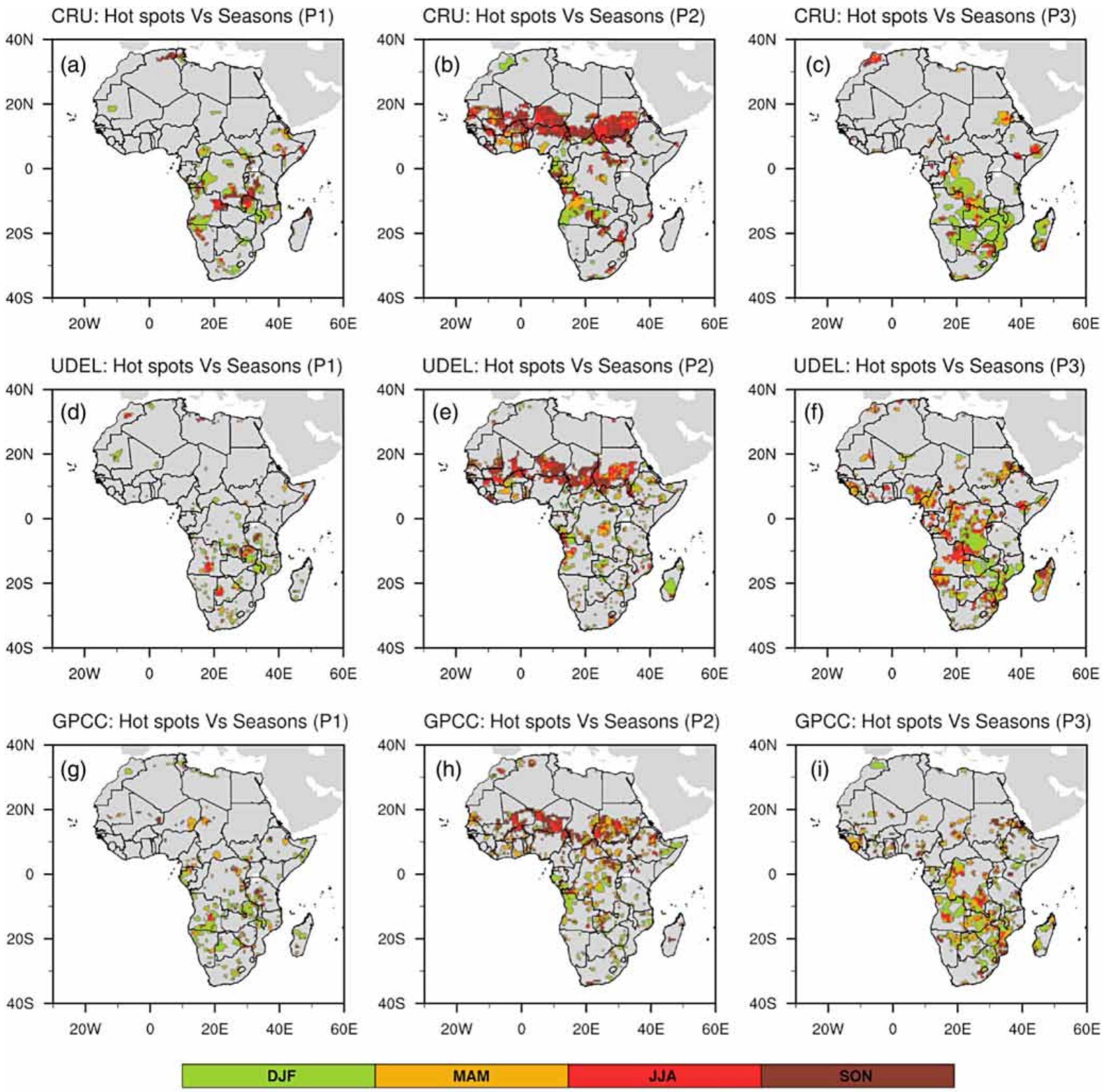

FIGURE 9 Seasonal contributions to drought hot spots in the subperiods P1 (1928–1957), P2 (1958–1987) and P3 (1988–2017) for CRU (1st row panels), UDEL (2nd row panels) and GPCC (3rd row panels)

decreases in drought severity are found in some regions of Central Africa (i.e., southern DRC), East Africa (i.e., Tanzania, central Ethiopia, southern Somalia) and Southern Africa (i.e., southern Angola).

For the recent past (Figure 7d–f), significant increases in severe drought events are regionally consistent with those found for the intermediate past, but with lower magnitudes in the Sahel and larger magnitudes in Central Africa and Southern Africa. Therefore, changes in the recent past compared to the intermediate past (Figure 7g–i) point to less severe droughts over the Sahel, Gulf of Guinea, and East Africa, and more severe droughts over most of Central and Southern Africa and Madagascar. We do again note that results in some regions are uncertain as they display opposite signs of changes depending on which dataset is used (e.g., difference between recent past and far past over Central and south western Africa).

It is thus clear that in recent decades maximum drought duration, frequency and severity have increased over the Sahel, and to a lower extent in the Gulf of Guinea, and some areas of Central Africa, Southern Africa and the eastern Madagascar. These regions mostly coincide with areas where modes of drought variability with larger explained variances are found. However over East Africa, no significant changes were found probably because of the interannual variability of the drought mode found with RPC2.

Our results indicate that on one hand, although droughts have occurred in the recent past in the Sahel, these events were longer, more frequent and more severe during the intermediate past; and, on the other hand, regions in Central and Southern Africa as well as Madagascar have experienced their worst drought episodes in the recent past. These appear thus to be particularly sensitive regions in terms of drought occurrence, and in the next section we apply our methodology described in section 2 to verify whether they are indeed identifiable as drought hot spots.

3.3 | Drought hot spots

Drought hot spots for each subperiod are presented in Figure 8. As discussed in section 2.2.4, the hot spots are identified as areas where the TDES (obtained by summing up all DS exceeding the domain 99th percentile of the whole time series) is larger. According to Figure 8, patterns of drought hot spots are more noticeable in the intermediate and recent pasts than in the far past. For instance, the intermediate past exhibits robust hot spots in regions of the Sahel around central Mali and Niger, the northernmost region of Nigeria, southern Chad and Sudan. In addition, few localized hot spots are found in central and northeastern DRC. For the recent past, robust hot spots are predominant in Central Africa (i.e., northwestern and southern DRC), Southern Africa (i.e., mainly in Zambia, Botswana and Mozambique) and Madagascar.

The seasonal severity contributing the most in determining the hot spots are presented in Figure 9. For example, the Sahel hot spots identified in the intermediate period are mainly due to more severe droughts occurring in June–August (JJA) and September–November (SON). Central and Southern Africa as well as Madagascar hot spots are mostly caused by severe droughts prevailing during December–February (DJF) and to a lower extent March–May (MAM).

Overall, drought hot spots are located along the Sahel band during the intermediate past while during the recent past they move to Central and Southern Africa and Madagascar, with more contributions determined by drought severity during their respective wet seasons. Outside of these regions, there is very little spatial agreement between the CRU, UDEL and GPCC datasets; therefore, conclusions cannot be drawn in these regions.

4 | SUMMARY AND CONCLUSIONS

Drought is a connection of several components including the atmosphere, hydrosphere and biosphere. Drought events may lead to a series of environmental problems impacting a wide range of sectors such as water resources, agriculture, food security, environmental ecosystem and migration, malnutrition and water-related diseases. Therefore, identifying regions more prone to droughts is paramount for the implementation of disaster risk reduction practices.

In this paper, we conducted a comprehensive analysis of historical droughts and their variations over Africa from 1928 to 2017. To ensure the robustness and reliability of our findings, we utilized long-term CRU, UDEL and GPCC monthly precipitation datasets as the basis for computing the SPI-12 index. A REOF method was applied to identify regions with similar drought features. In addition, changes in precipitation and drought characteristics including maximum drought duration, frequency and severity were explored for three subperiods, that is, 1928–1957 (far past), 1958–1987 (intermediate past) and 1988–2017 (recent past). Finally, drought hot spots and the seasons providing the largest contribution to the hot spots identification have been investigated. The main findings of our study can be summarized as follows:

1. Based on the REOF method, we identified five main regions in Africa with distinct spatial and temporal drought features: Sahel, East Africa, East Southern Africa, West Southern Africa and Gulf of Guinea. The corresponding time series show that the 1970s, 1980s and to a lesser extent 1990s were the periods with the most common occurrences of droughts in Africa.
2. Changes in precipitation and drought characteristics show a persistent drying tendency and robust increases of drought duration, frequency and severity in areas extending over most Sahel countries, the Gulf of Guinea and some areas of Southern Africa, including Madagascar, during both the intermediate and the recent past (compared to the far past period). However, changes are of lower (higher) magnitude in the Sahel (Southern Africa and Madagascar) during the recent past, highlighting a precipitation recovery over the Sahel after the drought episodes of the 1970s and 1980s and a trending drought in recent years in southern part of Africa.
3. Finally, we found that robust features of drought hot spots are identified in the intermediate and recent past periods and correspond to localized areas mainly in the Sahel (central Mali and Niger, northern Nigeria, southern Chad and over Sudan) during the intermediate past and over Central Africa (i.e., central and northeastern DRC), Southern Africa (i.e., Zambia, Botswana and Mozambique) and in Madagascar during the recent past. These hot spots are mostly due to considerable drought severity occurring during their respective wet seasons, that is, JJA and SON for the Sahel, and DJF and MAM for Central and Southern Africa as well as Madagascar.

Meanwhile, it is essential to acknowledge certain limitations and areas that require further investigation. Specifically, there is a notable disagreement between CRU and GPCC datasets when compared to UDEL dataset for non-semi-arid regions during the recent period, especially in Central Africa (10°S–10°N). According to recent studies (e.g., Lawal et al., 2021a, 2021b), there is a growing recommendation to incorporate independent data sources, such as the Normalized Difference Vegetation Index (NDVI). This approach highlights the insights that vegetation indices, like NDVI, can provide into the way ecosystems respond to drought conditions, especially in CAF region.

In addition, the scarcity of weather stations in East, West and Central Africa during the pre-1950s period limits the robustness of our findings during that period. However, this consideration has limited effect on our results as most of the conclusions are pertaining to the intermediate and recent period. Furthermore, despite the observed recurrence of droughts in East Africa since the 2010s (e.g., Gebrechorkos et al., 2020), our study did not find significant signals for drought in this region during the recent period. This discrepancy can be attributed to several factors, including the interannual control on drought variability (i.e., 1–5 years) observed in the corresponding RPCs. Additionally, the limitations of the chosen recent past period (1988–2017), with data ending in 2017 and recent droughts predominantly occurring between February and June, may have influenced the results. Future research should consider using more up-to-date data and capture the specific temporal patterns of drought in East Africa.

Nevertheless and in light of the findings, it is evident that most of Africa is prone to severe and widespread droughts with diverse characteristics and magnitudes, posing significant stress on both human societies and ecosystems throughout the continent. This is particularly true for areas identified as drought hot spots. Therefore, it is crucial to continue investigating drought phenomena in Africa, exploring relevant underlying mechanisms, and not only relying on the observation record but also considering future climate projections under global warming conditions. Importantly, our study has strong implications for drought risk management and preparedness. The identification of historically drought-prone regions in Africa highlights their central role as critical case studies. These regions are key places to identify best practices for future drought management, offering lessons that can inform strategies to reduce the risks. These initiatives are paramount for mitigating the adverse impacts of drought on vulnerable regions and sectors, including water resources, agriculture, food security, environmental ecosystems and human health. Our results not only establish a robust foundation for further research but also emphasize the urgency of addressing drought challenges in Africa to advance sustainable development and enhance resilience in the face of climate change.

AUTHOR CONTRIBUTIONS

Moustapha Tall: Visualization; conceptualization; writing – original draft; methodology; writing – review and editing; data curation; software; formal analysis; investigation. **Mouhamadou Bamba Sylla:** Conceptualization; writing – review and editing; supervision; methodology. **Alima Dajuma:** Methodology; writing – review and editing. **Mansour Almazroui:** Methodology; writing – review and editing. **Djan'na Koubodana Houteta:** Methodology; writing – review and editing. **Nana Ama Browne Klutse:** Methodology; writing – review and editing. **Alessandro Dosio:** Methodology; writing – review and editing. **Christopher Lennard:** Methodology;

writing – review and editing. **Fatima Driouech:** Methodology; writing – review and editing. **Arona Diedhiou:** Methodology; writing – review and editing. **Filippo Giorgi:** Methodology; writing – review and editing.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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