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Research papers

How could climate change affect the magnitude, duration and frequency of hydrological droughts and floods in West Africa during the 21st century? A storyline approach

Job Ekolu[a,*], Bastien Dieppois[a], Serigne Bassirou Diop[b,c], Ansoumana Bodian[c], Stefania Grimaldi[d], Peter Salamon[d], Gabriele Villarini[e], Jonathan M. Eden[a], Paul-Arthur Monerie[f], Marco van de Wiel[a,g], Yves Tramblay[b]

[a] Centre for Agroecology, Water and Resilience (CAWR), Coventry University, Coventry, UK
[b] Espace-Dev, Univ. Montpellier, IRD, Montpellier, France
[c] Laboratoire Leïdi "Dynamique des territoires et développement", Université Gaston Berger (UGB), BP 234 Saint Louis, Senegal
[d] European Commission, Joint Research Centre, Ispra, Italy
[e] Department of Civil and Environmental Engineering and High Meadows Environmental Institute, Princeton University, Princeton, NJ, USA
[f] National Centre for Atmospheric Science, Reading, UK
[g] College of Agriculture and Environmental Sciences, UNISA, FL, South Africa

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ABSTRACT

In recent decades, West Africa has been increasingly exposed to hydrological droughts and floods. However, the extent to which these changes are related to climate change and are likely to persist during the 21st century remains poorly understood. To address this gap, this study integrates plausible regional climate change storylines, derived from the 6th phase of the Coupled Model Intercomparison Projects (CMIP6), into physically based hydrological modelling experiments utilising the latest high-resolution setup of Open Source LISFLOOD (OS-LISFLOOD). Despite some limitations over the Sahelian region, OS-LISFLOOD shows good performances in representing the hydrological cycle and specific characteristics of hydrological droughts and floods. While CMIP6 models consistently project warming temperatures over West Africa, greater zonal contrasts and model discrepancies are found in projected rainfall changes. Overall, CMIP6 models tend to project more (less) rainfall, as well as more (less) intense rainfall, over the eastern (western) region of West Africa. However, wetter (drier) conditions are projected over larger regions in CMIP6 models simulating weaker (stronger) warming in the North Atlantic and Mediterranean temperatures. Future changes in hydrological droughts and floods mirror changes in precipitation. In the 21st century, we find robust significant increases (decreases) in the magnitude (duration) of floods. Meanwhile, reduced (increased) intensity of shorter (longer) duration hydrological droughts are found in the eastern (western and coastal) regions of West Africa. Our study stresses the importance of considering future changes in hydrological droughts and floods for effective water resource management and risk reduction across this highly vulnerable region.

1. Introduction

Climate change is manifested by global increases in the frequency and magnitude of hydrological extremes (i.e., floods and droughts), with severe impacts on economies, livelihoods, and the environment (e.g., Jonkman, 2005; Di Baldassarre et al., 2010; Winsemius et al., 2016; Zhang et al., 2019). The impact of such hydrological extremes is particularly pronounced in West Africa, where populations and ecosystems have been regularly exposed to multi-year drought and devastating floods in the 20th and 21st centuries (e.g., Di Baldassarre et al., 2010; Aich et al., 2014; Shiferaw et al., 2014; Serdeczny et al., 2017; Wilcox et al., 2018; IPCC, 2021; Ekolu et al., 2022). There is a need to integrate reliable information about the plausible long-term impacts of climate change on hydrological hazards and risks into adaptative water

* Corresponding author at: Centre for Agroecology, Water and Resilience (CAWR), Coventry University, Ryton Gardens, Ryton on Dunsmore, Coventry CV8 3LG, UK.

E-mail address: ekoluj@uni.coventry.ac.uk (J. Ekolu).

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management and risk mitigation strategies (e.g., Conway et al., 2019; Ward and Conway, 2020).

While some attempts have been made to project future changes in hydrological droughts and floods in West Africa, they are generally limited to a few catchments. These studies suggest that future climate changes could lead to an increasing magnitude of hydrological floods over the Volta, Niger, Bani and Benue River basins (e.g., Kamga, 2001; McCartney et al., 2012; van Vliet et al., 2013; Aich et al., 2014, 2016; Thompson et al., 2017; Rameshwaran et al., 2021; Dembélé et al., 2022). Meanwhile, potential decreases in flood magnitudes have been projected over the Senegal, Gambia and Sassandra River basins during the 21st century (Ardoin-Bardin et al. 2009; Murray et al., 2012). Similarly, during the 21st century, hydrological drought conditions have been projected to increase for the Volta River Basin (e.g., Dembélé et al., 2022; Gebrechorkos et al., 2022), while other authors reported a decrease over the Niger River Basin (Aich et al., 2014; Thompson et al., 2017). However, these catchment-scale studies use different generations of climate and hydrological models to assess the future impact of climate change over different time periods, in different environments, and climates, limiting their intercomparibility (Roudier et al., 2014; Rameshwaran et al., 2021). This also restricts our ability to distinguish the regional impact of climate change and variability from local catchment characteristics, such as groundwater support, land use changes, and human water use (Kingston et al., 2020). Overcoming this limitation remains a key challenge for the hydrological community in the forthcoming decades (Blöschl et al., 2019; Kingston et al., 2020).

Efforts to develop a comprehensive and unified understanding of future changes in hydrological drought and floods in West Africa remain elusive, hindered by high computational demands and a lack of reliable streamflow observations (e.g., Paturel et al., 1998; Servat et al., 1998; Trambauer et al., 2014; Bierkens, 2015; Tramblay et al., 2020; Harrigan et al., 2020; Dixon et al., 2022). To overcome this limitation, existing regional-scale studies concentrated on the potential impact of future climate changes on meteorological droughts and heavy rainfall (e.g., Oguntunde et al., 2017; Shiru et al., 2020; Quenum et al., 2019; Ogunrinde et al., 2022; Ajayi and Ilori, 2020), but meteorological conditions do not always propagate into hydrological flood and drought conditions (van Loon et al., 2012; Van Lanen et al., 2016; Odongo et al., 2023). Taking advantage of a physics-based distributed hydrological model to assess the hydrological responses to climate change, as well as of the limited data provided in open-access by the Global Runoff Data Centre (GRDC) over West Africa (Dixon et al., 2022), Rameshwaran et al. (2021), provided the first projections of annual maximum flow for four major river-catchments. However, the results of Rameshwaran et al. (2021) are based on uncalibrated hydrological modelling experiments due to limited open access data availability over West Africa (Dixon et al., 2022). Equally, like previous catchment-scale studies, the results of Rameshwaran et al. (2021) are based on climate models from the 3rd and 5th phases of the Coupled Model Intercomparison Project (CMIP). We build on recent efforts in compiling a reference regional hydrological dataset (Tramblay et al., 2020; Ekolu et al., 2022) to re-evaluate the plausible effect of climate change on hydrological extremes in West Africa. This is achieved through a comprehensive and unified framework for regional-scale hydrological impact assessment, which combines state-of-the-art climate change scenarios from the 6th phase of CMIP (CMIP6; Eyring et al., 2016) with physics-based spatially distributed hydrological modelling experiments. To further characterise CMIP6 model uncertainties and examine a plausible range of outcomes for climate change impacts on hydrological droughts and floods, we adopt a storyline approach. This approach considers the influence of diverging future changes in North Atlantic and Mediterranean surface temperatures on Sahel rainfall, which has been shown to account for up to 60 % of CMIP6 model uncertainties in projected rainfall changes (Monerie et al., 2023).

Furthermore, previous studies on hydrological extremes narrowly focused on singular characteristics, such as the magnitude of floods (e.g., Aich et al., 2016; Dembélé et al., 2022; Rameshwaran et al., 2021) and droughts (e.g., Dembélé et al., 2022; Gebrechorkos et al., 2022). However, for water management planning and associated risk-mitigation measures, providing information regarding the duration and frequency of hydrological droughts and floods is also crucial (Ward et al., 2020). Critically, existing research often isolates floods and droughts, neglecting their complex interdependencies for water risk management (Di Baldassarre et al., 2010; Rangecroft et al., 2016; Brunner et al., 2021). Our study aims to fill these gaps by providing a holistic analysis of both hydrological droughts and floods in West Africa. While we analyse the impact of climate change on droughts and floods separately, we aim to identify areas where concurrent increases in both extremes may compound hydrological risks. By mapping explicit "hotspots", we provide actionable insights for stakeholders to prioritize regions where adaptive strategies must account for both extremes (Di Baldassarre et al., 2010; Ward et al., 2020).

Through a comprehensive and unified framework, this study thus aims to assess, for the first time, the plausible impact of future climate change on the magnitude/intensity, duration and frequency of hydrological droughts and floods under contrasting shared socio-economical and representative concentration pathways (SSP-RCPs; O'Neill et al., 2016) across this region. This is accomplished by combining information from five bias-corrected CMIP6 climate models with the latest version of the open-source LISFLOOD hydrological model (OS-LISFLOOD; Alfieri et al. 2020). The paper is organized as follows. In Section 2, we present the datasets and methods, including an evaluation of the performance of OS-LISFLOOD over West Africa. Section 3 discusses the projected changes in rainfall and temperature in West Africa, before assessing their potential impacts on hydrological drought and flood characteristics during the 21st century under two contrasted SSP-RCP scenarios. Finally, in Section 4, we summarize our main results and discuss their wider implications.

2. Data and methods

2.1. Bias-corrected climate scenarios

To investigate the impacts of climate change on West African climate, particularly in the context of floods and droughts, this study utilizes daily simulations from five bias-corrected CMIP6 models (Noël et al. 2022; Table 1): MPI-ESM1-2-HR, MRI-ESM2-0, IPSL-CM6A-LR, UKESM1-0-LL, and GFDL-ESM4. These models were selected for their ability to represent the spectrum of uncertainties in projected rainfall changes across West Africa, reflecting diverse warming patterns in the North Atlantic and Mediterranean surface air temperatures (Monerie et al., 2023). The simulations cover a historical period (1850–2015) and extend into the future (2016–2100), focusing on two Shared Socioeconomic Pathways (SSPs; O'Neill et al., 2016): SSP2-4.5, a medium-emission scenario with moderate mitigation efforts, and SSP5-8.5, a high-emission scenario with limited mitigation. From these simulations, we extracted daily values of six key climate variables: precipitation, mean surface temperature, maximum and minimum temperatures,

Table 1
Information for the CMIP6 climate models used in this study.

Climate Model	Institute	Refs.
MPI-ESM1-2-HR	Max Planck Institute for Meteorology (MPI)	Mauritsen et al. (2019)
MRI-ESM2-0	Meteorological Research Institute (MRI)	Yukimoto et al. (2019)
IPSL-CM6A-LR	Institute Pierre-Simon Laplace (IPSL)	Boucher et al. (2020)
UKESM1-0-LL	Met Office Hadley Centre (UKESM)	Mulcahy et al. (2020)
GFDL-ESM4	Geophysical Fluid Dynamics Laboratory (GFDL)	Dunne et al. (2020)

relative humidity, and wind speed.

To ensure consistency with observational data, CMIP6 models were bias-corrected using the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5-Land reanalysis dataset (1979–2019; Muñoz-Sabater et al., 2021) as the reference (Noël et al., 2022). To address the challenge of unifying spatial scales between the coarse CMIP6 model grids and the finer ERA5-Land grid, the raw CMIP6 simulations were remapped onto the 0.1° × 0.1° ERA5-Land grid. For temperature and wind speed, a bicubic interpolation method was employed to ensure smooth transitions across grid cells, leveraging its ability to preserve spatial gradients. For precipitation, a sequential interpolation process using a conservative remapping method, which preserves the total mass of the variable across grid cells, was used (cf. Famien et al., 2018; Noël et al., 2022). Bias correction of the CMIP6 model outputs were then performed using the Cumulative Distribution Function-transform (CDF-t) method, a quantile mapping-based technique initially proposed by Michelangeli et al. (2009) and later refined by Vrac et al. (2012, 2016). The CDF-t method has been widely used in previous studies globally (e.g. Kallache et al., 2011; Vrac et al., 2012, 2016; Lavaysse et al., 2012; Vrac and Friederichs, 2015) and specifically in Africa (e.g., Oettli et al., 2011; Famien et al., 2018; Ayugi et al. 2022; Babaousmail et al. 2022; Yahaya et al. 2024). Unlike traditional non-parametric quantile–quantile methods, which map future CMIP6 model CDFs directly onto historical observational CDFs (Déqué, 2007), CDF-t accounts for temporal evolution in the CDFs between historical and future CMIP6 model simulations. Note that, for precipitation, a specialized variant of the CDF-t method, known as Singularity Stochastic Removal, was used to address the unique challenges of rainfall occurrence and intensity, particularly the presence of zero values and extreme events (Vrac et al., 2016). To account for the pronounced seasonality in West Africa, the CDF-t correction was performed on a month-by-month basis, ensuring that seasonal patterns in the bias structure were adequately captured. The effectiveness of this approach is evidenced in Famien et al. (2018) and Noël et al. (2022). In addition, to further emphasise the method's efficiency, we illustrate how the bias-corrected spatial distributions of precipitation and temperature characteristics from CMIP6 models align with ERA5-Land in supplementary Figs. S1-S3.

Finally, the bias-corrected data from CMIP6 was re-gridded using bilinear interpolations from a resolution of (0.1° × 0.1°) to the resolution for the OS-LISFLOOD (0.05° × 0.05°) and processed through the hydrological model. This is common practice for distributed hydrological models when using gridded climate datasets, observational, and reanalysis datasets typically used in hydrological modelling experiments (Chen et al., 2011; Chokkavarapu and Mandla, 2019; Banda et al., 2022).

Note that the CMIP6 ensemble used in this study reflects the spectrum of projected rainfall changes over West Africa, which are strongly tied to divergent representations of North Atlantic and Mediterranean surface air temperature trends (Monerie et al., 2023). Identifying which individual model projections are most reliable remains elusive, largely because evaluations show a weak relationship between model biases in simulating the present climate and the magnitude of their future projections (Monerie et al., 2017). Rather than assigning probabilistic likelihoods to individual models, we adopt a storyline approach to explore physically consistent pathways of change (Shepherd, 2019; Sillmann et al., 2021). The storyline approach prioritizes understanding the drivers of variability, such as the North Atlantic and Mediterranean surface air temperatures, over ranking model reliability, as structural biases in climate models prevent definitive probabilistic interpretations (Knutti and Sedláček, 2013; Maraun et al., 2017). Models projecting wetter (drier) futures, such as IPSL (GFDL), are not inherently more "reliable" but instead represent distinct responses to contrasted warming rates in the North Atlantic and Mediterranean (Monerie et al., 2023). For instance, models simulating stronger North Atlantic warming (e.g., IPSL, MPI) enhance moisture advection into West Africa, favouring wetter conditions, while those with weaker warming (e.g., GFDL, MRI) suppress monsoon dynamics, leading to drier projections.

2.2. Hydrological modelling experiments

Hydrological impact scenarios are generated using OS-LISFLOOD, a physics-based spatially distributed hydrological model. More detailed information about this hydrological model is available at https://ec-jrc.github.io/lisflood/. Specifically, we use the setup of the latest high-resolution global implementation of OS-LISFLOOD (version 4.1.3), which allowed the delivery of the version 4 of Copernicus Emergency Management Service Global Flood Awareness System (CEMS GloFAS; https://global-flood.emergency.copernicus.eu/). This latest setup features updates in the hydrological routines, such as pixel-by-pixel computation of water infiltration into the soil, and improvements in the modelling of water abstraction for anthropogenic use, with a 0.05-degree resolution (~5km). This 0.05-degree quasi-global implementation of OS-LISFLOOD was calibrated using 1995 in-situ discharge gauge stations with at least a 4-year-long time series of measurements more recent than 01 January 1980. More information regarding the calibration of OS-LISFLOOD for GloFAS.v4 is available at https://confluence.ecmwf.int/GloFAS+v4+calibration. Compared to the previous version of GloFAS (version 3), the performance of OS-LISFLOOD in GloFAS.v4, has been substantially improved for Africa by the inclusion of new daily hydrological data from two data sources in the calibration process: i) the Système d'Informations Environnementales sur les Ressources en Eaux et leurs Modélisations (SIEREM) hosted by the French Institute for Research and Development (IRD); ii) the Global Runoff Data Centre (GRDC). The climate forcings used for calibration (i.e., total precipitation, 2-metre temperature, and evapotranspiration) were provided by the ERA5 reanalysis (Hersbach et al., 2020). Here, we use a modified version of the FAO-56 Penman-Monteith equation (Allen et al., 1998), which only requires the wind speed, relative humidity, precipitation, maximum and minimum daily temperature for the calculation of potential evapotranspiration rate for reference crop, bare soil surface, and water surfaces.

The calibration of GloFASv4 was conducted using daily observational discharge data, with calibration periods tailored to the length of available records. The calibration used a minimum of four years of daily data, wherever possible extending beyond eight years. Additional details on the methodology and parameters can be found in the GloFASv4 calibration documentation (GloFAS v4 Calibration Methodology and Parameters: https://confluence.ecmwf.int/display/CEMS/GloFAS+v4+calibration+methodology+and+parameters). Here, to assess the stability of the calibration on longer timescales and ensure its applicability for climate change impact studies, we also assess the performance of OS-LISFLOOD over 36 years (1st January 1979 to 31st December 2014) over West Africa, using 69 gap-free daily streamflow time-series from Ekolu et al. (2022). Fig. 1 displays the spatial distribution of the 274 simulated daily streamflow time-series from OS-LISFLOOD, the 180 time-series that were used for the calibration of OS-LISFLOOD, and the 69 time-series that are used to evaluate the performance of OS-LISFLOOD over 36 years using gap-free time-series from Ekolu et al. (2022).

Regarding the performance of the calibration of OS-LISFLOOD, using the modified Kling-Gupta Efficiency (KGE; Kling et al., 2012), we found that 92 % of simulated streamflow outlets have a score greater than −0.4, indicating acceptable model performance over the extended evaluation period (Fig. 2a-b). In addition, 74 % of simulated streamflow outlets show a KGE greater than 0.4, indicating good performance of OS-LISFLOOD during the calibration period (Fig. 2a and b). Examining the performance of OS-LISFLOOD simulations over 36 years using 69 gap-free time-series from Ekolu et al. (2022), we find that 87 % (60 %) of simulated streamflow outlets have a KGE greater than −0.4 (0.4), indicating acceptable (good) performance. Despite a slight decrease in the KGE score, overall, OS-LISFLOOD shows satisfactory performance over 36 years. In both the calibration and the 36-year evaluation, OS-

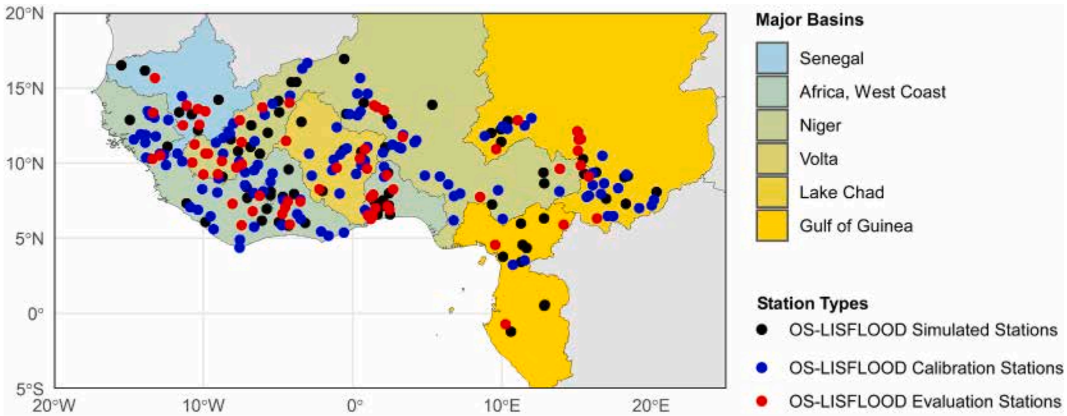

Fig. 1. Spatial distribution of 274 simulated daily streamflow time-series from OS-LISFLOOD (black dots), including 180 time-series used for calibration (blue dots) and 69 time-series selected for evaluation against the gap-free streamflow time-series from Ekolu et al. (2022) (red dots). The map also shows the major hydrological basins of West Africa (colour shades).
Source: FAO-GeoNetwork, accessed March 2024

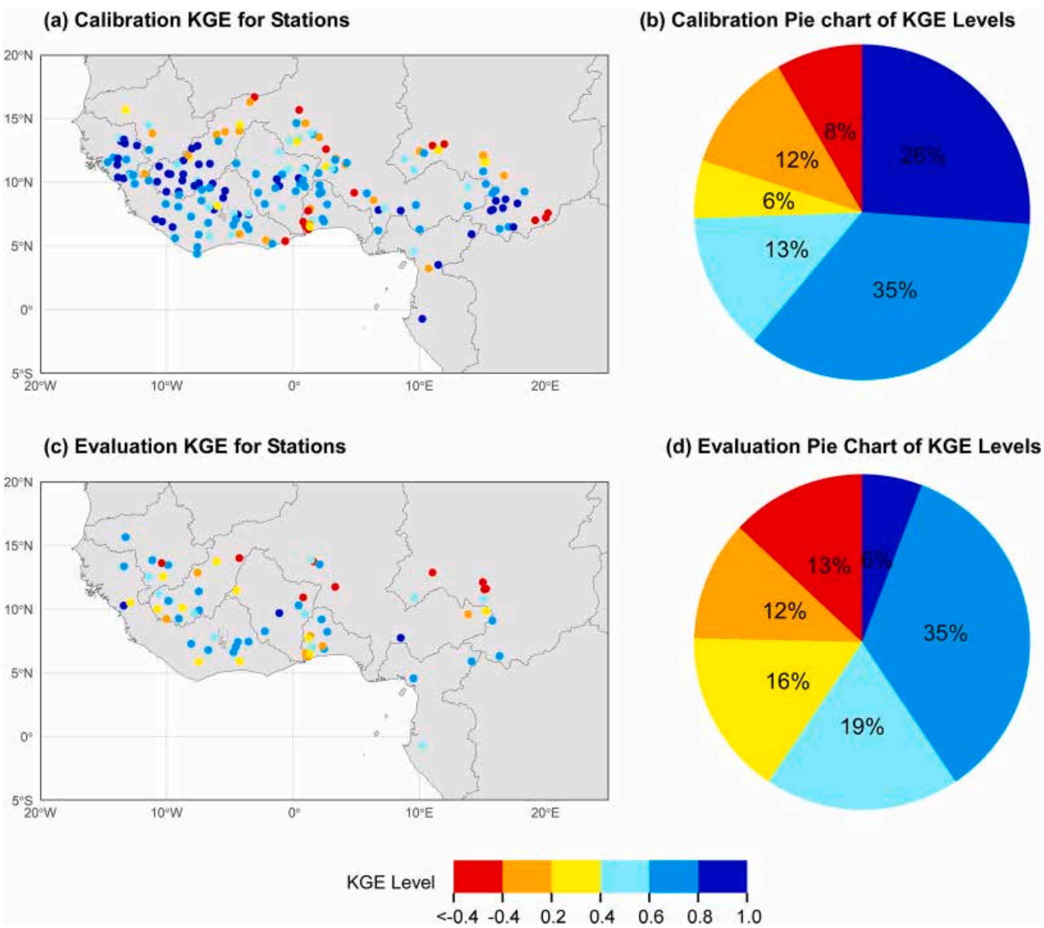

Fig. 2. Performance of OS-LISFLOOD in simulating observed stream discharge in West Africa. a) Spatial distribution of hydrological model performances (KGE) used in calibration b) Pie-chart showing the percentage of stations in each KGE bin used in calibration. c) Spatial distribution of hydrological model performances (KGE) when evaluated against data from Ekolu et al. (2022). d) Pie-chart showing the percentage of stations in each KGE bin when evaluated against data from Ekolu et al. (2022).

LISFLOOD performances are particularly good over the Sudano-Sahelian zone, where KGE varies between 0.4 and 0.8 (Fig. 2a, c). However, despite overall good performances, OS-LISFLOOD shows limited skill over the Sahelian region over the extended evaluation period (KGE < −0.4; Fig. 2a and c). For instance, OS-LISFLOOD performs particularly poorly over the middle reach of the Niger River. This may be due to the impact of the Inner Niger Delta (flooded area ~40,000 km^2 resulting in annual water losses of ~40 %), which significantly modifies downstream rainfall-runoff relationships (Mahé and Paturel, 2009; Roudier et al., 2014). This could also be due to the limited length of data used for calibration of OS-LISFLOOD in the region, as Sahelian rivers are more sensitive to decadal variations (Mahé and Paturel, 2009; Descroix et al., 2018; Sidibe et al., 2018, 2019; Ekolu et al., 2022).

2.3. Detection and model-representation of hydrological flood characteristics

To identify independent hydrological flood events in OS-LISFLOOD simulations and observation, we employ a peak-over-threshold (POT) method, relying on a baseflow separation technique (Mangini et al., 2018; Ekolu et al., 2022; Ekolu et al., 2024). We first determine the recession constant (k) for each monitoring station, following the methodology outlined by Vogel and Kroll (1996), and applied in recent works (e.g., Mangini et al., 2018; Ekolu et al., 2022). This involves computing a 3-day centred moving average of daily streamflow data from 1979 to 2014 for each station. Subsequently, we identify the recession period, starting from a specified peak in the 3-day centred moving average time series and extending until a sudden flow increase occurs. This process is iterated for each peak in the 3-day centred moving average time series, with only recession events lasting longer than 10 days being considered.

We then calculate the recession constant for each recession event by applying regression analysis to find the best fit using ordinary least squares, as described in Eq. (1). We compute the average recession constant (r) across all events from 1979 to 2014. In this context, Q_t represents the total flow at any given time t, and Q_0 is the initial flow at the start of the recession period, with k_i being the recession constant.

$$In(Q_t) = In(Q_0) + In(k_i) \times t + r \tag{1}$$

Using the estimated recession constant k, we calculate the baseflow using the digital filter in Equation (2) by Chapman and Maxwell (1996). We then subtract the baseflow from the total flow to obtain the estimated direct flow. Independent discharge events are separated by intervals during which direct runoff is lower than the baseflow, or lower than the mean annual direct runoff, thereby excluding instances where discharge or baseflow equals zero.

$$Q_{b(i)} = \frac{k}{2-k} \times Q_{b(i-1)} + \frac{1-k}{2-k} \times Q_{(i)} \tag{2}$$

where $Q_{b(i\text{-}1)}$ is the baseflow at time interval i-1, $Q_{b(i)}$ is the baseflow runoff at time interval i, and k is the recession constant. Following the identification of independent discharge peaks across the whole time series, flood series are compiled using the POT selection approach. This is done by ranking flow events from highest to lowest and subsequently selecting the highest 36 events based on a POT criterion of one event per year between 1st January 1979 and 31st December 2014.

To further assess the reliability of OS-LISFLOOD simulations, we compare simulated and observed magnitude, duration, and frequency of floods between 1979 and 2014 (Fig. 3). LISFLOOD-ERA5 and LISFLOOD-CMIP6 simulated flood characteristics were compared to the observed flood characteristics computed from Ekolu et al. (2022) streamflow dataset. To achieve this, we use statistical tests comparing pairs of distributions, we apply the Kolmogorov-Smirnov (KS) test (Smirnov, 1939; Schroer and Trenkler, 1995) to quantify the distance between the empirical distribution functions of simulated and observed flood magnitudes. For the duration of flood events, we use the Kruskal-Wallis (KW) test (Kruskal and Wallis, 1952; Hollander et al., 1973), which is more robust with discrete data, to assess whether simulations show significant differences in the medians. For flood frequency, we examine the difference between the observed probability distribution and each simulated distribution using the Fisher's Exact Test (FE; Fisher, 1934). This test was selected due to its suitability for categorical data, particularly with small sample sizes or when expected frequencies within categories are low (e.g., <5), conditions often met with annual flood counts. The statistical tests comparing pairs of distributions for flood magnitude, duration, and frequency of events between the simulated and observed distributions were considered statistically significant at p-value thresholds of $p \leq 0.1$ and $p \leq 0.05$. Overall, simulations driven by ERA5 (LISFLOOD-ERA5) and CMIP6 (LISFLOOD-CMIP6) show flood magnitudes, durations and frequency of flood events that are statistically comparable to observations (Fig. 3). Comparing the simulations, the LISFLOOD-ERA5 reanalysis-driven simulation demonstrated a closer match to observations regarding flood frequency, with significant similarities detected at stations (38 out of 69) compared (Fig. 3).

Additionally, mapping ratios of simulated-to-observed flood characteristics (magnitude, duration, and event frequency), we evaluate systematic biases in flood characteristics (Supplementary Fig. S4). Overall, with ratios of simulated-to-observed statistics nearing one for most stations, we find that the simulated mean flood magnitude and the 90th percentile of the annual frequency of floods closely match the statistics derived from the gap-free observed daily streamflow datasets (Supplementary Fig. S4). However, although the simulated statistical distribution of the duration of flood events is found comparable to observation (Fig. 3), we found that the simulated mean duration of floods tends to be greater than the observed mean duration of floods (Supplementary Fig. S4).

2.4. Detection and model-representation of drought characteristics

We use a variable threshold approach, which better accounts for the seasonality, to identify and characterise independent hydrological drought events (Van Loon et al., 2015, 2019; Kozek and Tomaszewski, 2019; Sutanto and Van Lanen, 2020; Tomaszewski and Kozek, 2021; Ekolu et al., 2022). For each month, the flow duration curves are computed, and the 80th percentile is calculated, before being smoothed using a centred average of 30 days (Van Loon, 2015; Ekolu et al., 2022). Interdependent droughts are then pooled using the inter-event time method (Fleig et al., 2006; Ekolu et al., 2022). A period of 10 days is used between events, for all catchments, as recommended by Tallaksen et al. (1997) and Fleig et al. (2006). We use a duration limit of 15 days for minor droughts, following previous studies (e.g., van Loon et al., 2012; Kozek and Tomaszewski, 2019; Van Loon et al., 2019; Sutanto and Van Lanen, 2020; Tomaszewski and Kozek, 2021; Ekolu et al., 2022). From this procedure, we estimate the annual frequency, duration, and magnitude of hydrological droughts.

To further assess the reliability of OS-LISFLOOD simulations, we compare the statistical distribution simulated and observed magnitude, duration, and intensity of hydrological droughts between 1979 and 2014 for 69 stations selected for the evaluation in section 2.2 (Fig. 4).

LISFLOOD-ERA5 and LISFLOOD-CMIP6 simulated hydrological drought characteristics were compared to the observed hydrological drought characteristics computed from Ekolu et al. (2022) streamflow dataset. Meanwhile, the hydrological drought characteristics simulated by LISFLOOD-CMIP6 were compared with those from LISFLOOD-ERA5 simulations over the same period. To achieve this, we compare pairs of distributions with the KS and KW tests at $p \leq 0.1$ and 0.05 (Fig. 4). Simulated drought magnitudes present statistical distributions that are significantly comparable to observation for most stations over an extended validation period of 36 years (Fig. 4a, d, g, j, m, p). LISFLOOD-ERA5 and LISFLOOD-CMIP6 also simulate realistic statistics for the annual frequency of hydrological droughts over most stations in West Africa (Fig. 4c, f, i, l, o, r). However, significant limitations are found concerning the simulated duration of hydrological droughts in West Africa (Fig. 4b, e, h, k, n, q). As noted in previous studies (e.g., Faye and Akinsanola, 2022; Gbode et al., 2023), ERA5 and CMIP6 models tend to generate too many consecutive wet days and too heavy rainfall events, which could impact the simulated duration of hydrological droughts.

Additionally, the ratio of simulated-to-observed mean annual drought characteristics (intensity, duration, and event frequency) were evaluated to assess systemic biases in drought characteristics (Supplementary Fig. S5). Across most stations, the ratios of simulated-to-observed statistics are close to one for the drought duration and annual frequency of drought events (Supplementary Fig. S5). While the simulated statistical distribution of the intensity of drought events is

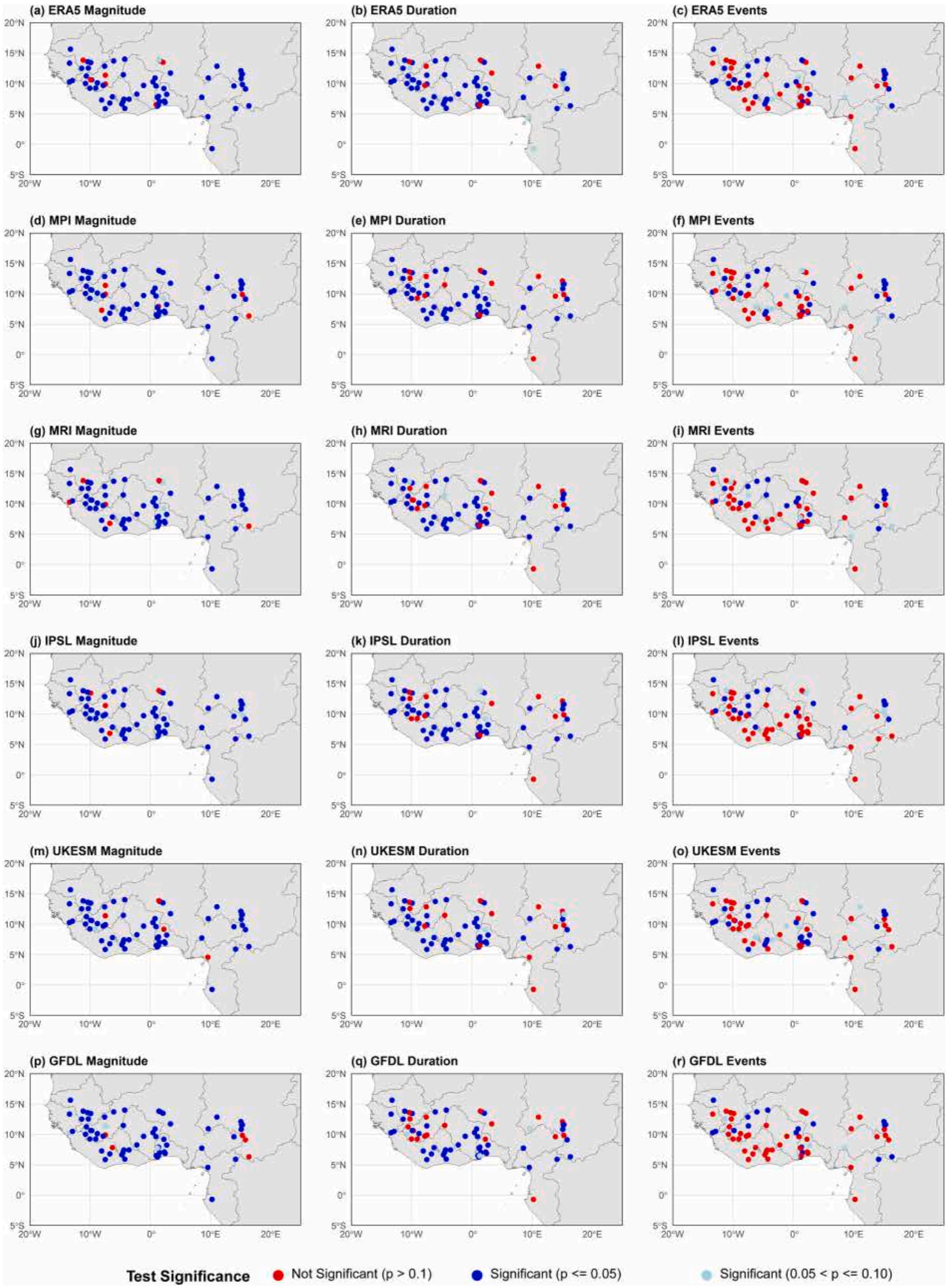

Fig. 3. Comparison of the statistical distribution of observed and simulated hydrological flood characteristics between 1979 and 2014. (a-c) Statistical significance of the differences between the statistical distribution of the magnitude (left), duration (middle), and annual frequency (right) of flood events simulated by LISFLOOD-ERA5 and the gap-free observed streamflow time-series from Ekolu et al. (2022). (d-r) same as (a-c) but for LISFLOOD-CMIP6 simulations (MPI, MRI, IPSL, UKESM, and GFDL). Statistical significance was tested at $p \leq 0.05$ and 0.1 for the KS and KW tests. The KS test was only used for flood magnitudes, the KW test was used for the duration, and FE test was used for annual frequency of floods.

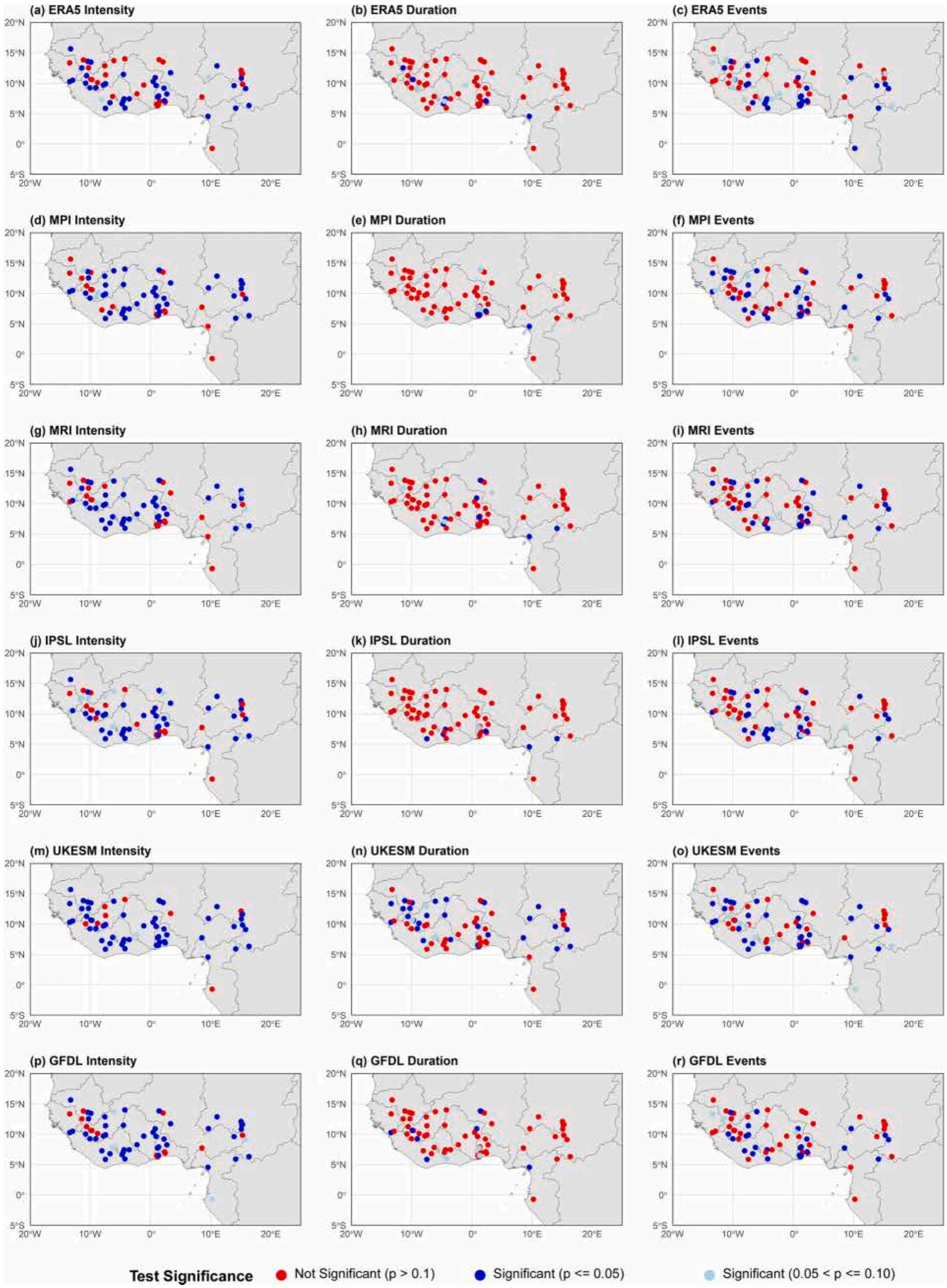

Fig. 4. Comparison of the statistical distribution of observed and simulated hydrological drought characteristics between 1979 and 2014. (a-c) Statistical significance of the differences between the statistical distribution of the magnitude (left), duration (middle), and annual frequency (right) of drought events simulated by LISFLOOD-ERA5 and observation. (d-r) same as (a-c) but for LISFLOOD-CMIP6 simulations (MPI, MRI, IPSL, UKESM, and GFDL). Statistical significance was tested at $p \leq 0.05$ and 0.1 for the KS and KW tests. The KS test was only used for drought magnitudes, and the KW test was used for the duration and annual frequency of droughts.

found comparable to observation (Fig. 4), yet we found that the simulated mean intensity of droughts tends to be weaker than the observed mean intensity of droughts (Supplementary Fig. S5).

3. Results

3.1. Projected changes in rainfall characteristics and temperature

Using five bias-corrected CMIP6 models, we examine mid-term (2030–2059) and long-term (2071–2100) projected climate changes in West Africa under SSP2.45 and SSP5.85, compared to the historical baseline (1985–2014). Fig. 5 displays the CMIP6 model agreements in simulating positive or negative changes in cumulated annual rainfall, 5-day maximum rainfall, and mean daily temperature. Meanwhile, Fig. 6 shows the magnitude and significance of the future climate changes for each climate model in the long-term future under SSP5.85.

While all CMIP6 models agree in simulating warmer temperatures across all of West Africa in the mid-term and long-term futures under SSPP2.45 and SSP5.85 (Fig. 5c, f, i, l), we note that GFDL (+3 to +4C), MRI (+3.5 to +4.5C), and especially MPI (+0.5-+1.5C) models show weaker warming than IPSL and UKESM (+4.0-+5.5C and + 5.5–6.5C; Fig. 6c, f, i, l, o). According to previous studies (Monerie et al., 2012, 2020, 2023; Audu et al., 2024), greater zonal contrasts are found in projected changes in cumulated annual rainfall. Bias-corrected CMIP6 models tend to agree on a decrease (increase) in cumulated annual rainfall over the western (eastern) part of West Africa in the mid-term

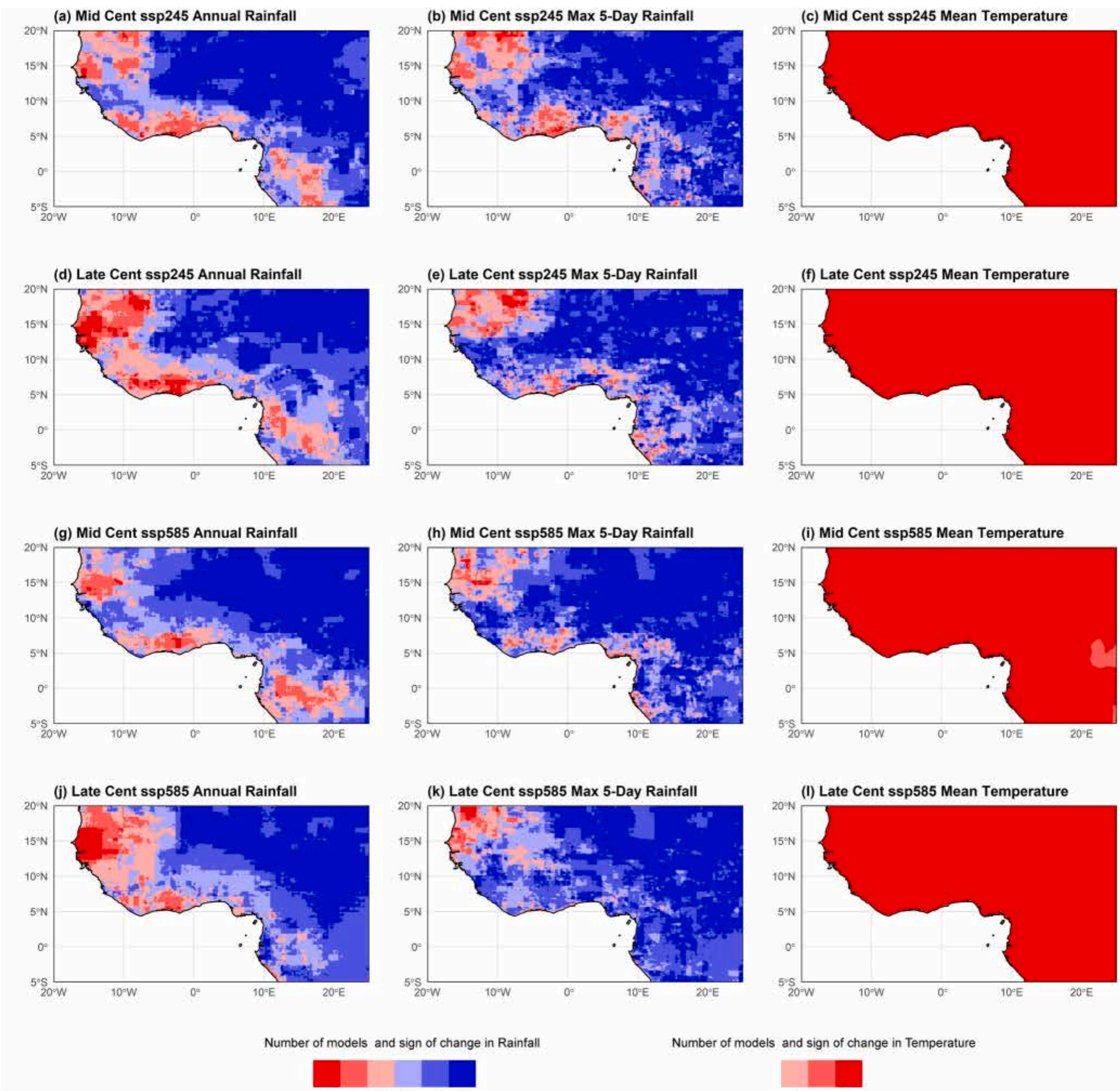

Fig. 5. Bias-corrected CMIP6 model agreement on the direction of change in rainfall characteristics and mean temperature in the mid-term (2030–2059) and long-term future (2071–2100), relative to the reference historical period (1985–2014), in West Africa under SSP2.45 and SSP5.85 scenarios. (a-c) Number of bias-corrected CMIP6 models simulating positive or negative changes in cumulated annual rainfall (left), 5-day maximum rainfall (middle), and mean temperature (right) in the mid-term future under SSP2.45 scenarios. (d-f) same as (a-c) but in the long-term future. (g-i) same as (a-f) but under SSP5.85 scenarios.

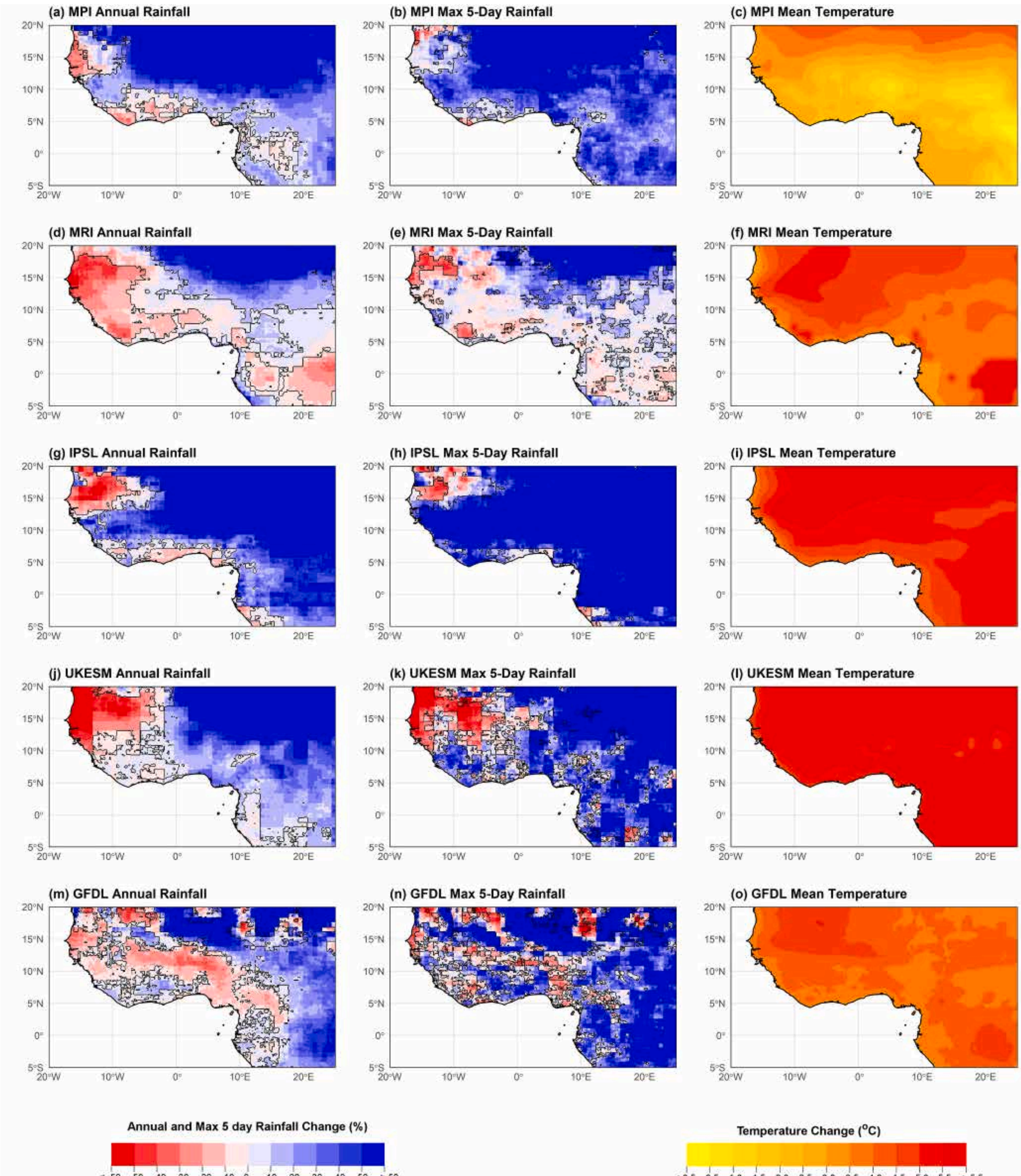

Fig. 6. Projected changes in rainfall characteristics and mean temperature in the long-term future (2071–2100), relative to the reference historical period (1985–2014), in West Africa under SSP5.85 scenarios in five bias-corrected CMIP6 models. (a-c) MPI simulations of projected changes in cumulated annual rainfall (left), 5-day maximum rainfall (middle), and mean temperature (right) in the long-term future under SSP5.85 scenarios. (d-o) same as (a-c) but for MRI, IPSL, UKESM, and GFDL simulations. Grey contours indicate the statistical significance of projected changes according to the Wilcoxon test at $p \leq 0.05$.

and long-term futures under SSPP2.45 and SSP5.85 (Fig. 6a, d, g, j). Very similar patterns are found in projected changes of 5-day maximum rainfall (Figs. 5 and 6), with an increase over the eastern Sahel that is consistent with observed trends in the frequency of extreme storms-mesoscale convective systems and extreme rainfall intensity over this region (Taylor et al., 2017; Chagnaud et al., 2022). However, we note that the tendency of the CMIP6 models to simulate drier conditions over the western part of West Africa is substantially weaker in terms of 5-day maximum rainfall (Figs. 5 and 6).

Furthermore, significant differences between CMIP6 projected rainfall changes persist after bias-corrections. In CMIP6 models projecting weaker warming rates in the North Atlantic and Mediterranean air surface temperatures, e.g., GFDL and MRI (Monerie et al., 2023), drier conditions are projected over significantly larger regions (−30 to 40 % spanning over 40 % of West Africa). Meanwhile, CMIP6 models projecting greater warming in the North Atlantic or Mediterranean air surface temperature, e.g., MPI and IPSL (Monerie et al., 2023), tend to simulate wetter conditions over a major part of West Africa (+40 to 120 % spanning over 84 % of West Africa; Fig. 6a, d, g, m).

3.2. *Projected changes in flood characteristics*

We examine projected changes in the magnitude, duration, and frequency of floods in the mid-term (2030–2059) and long-term (2071–2100) futures, using five LISFLOOD-CMIP6 models under SSP2.45 and SSP5.85 scenarios. Fig. 7 presents the model consensus in simulating positive or negative changes in flood characteristics during the 21st century.

Under both SSP2.45 and SSP5.85, most LISFLOOD-CMIP6 simulations project an increase in the magnitude of floods, ranging from +15 to +225 %, across most of West Africa in the mid-term and long-term future (Fig. 7a, d, g, j). LISFLOOD-CMIP6 simulations also tend to agree in projecting a decrease in flood duration across most of West Africa (−9 to 50 %), but, apart from the eastern Sahel, model agreements are weaker suggesting higher uncertainties (Fig. 7b, e, h, k). Regarding the annual number of floods, most LISFLOOD-CMIP6

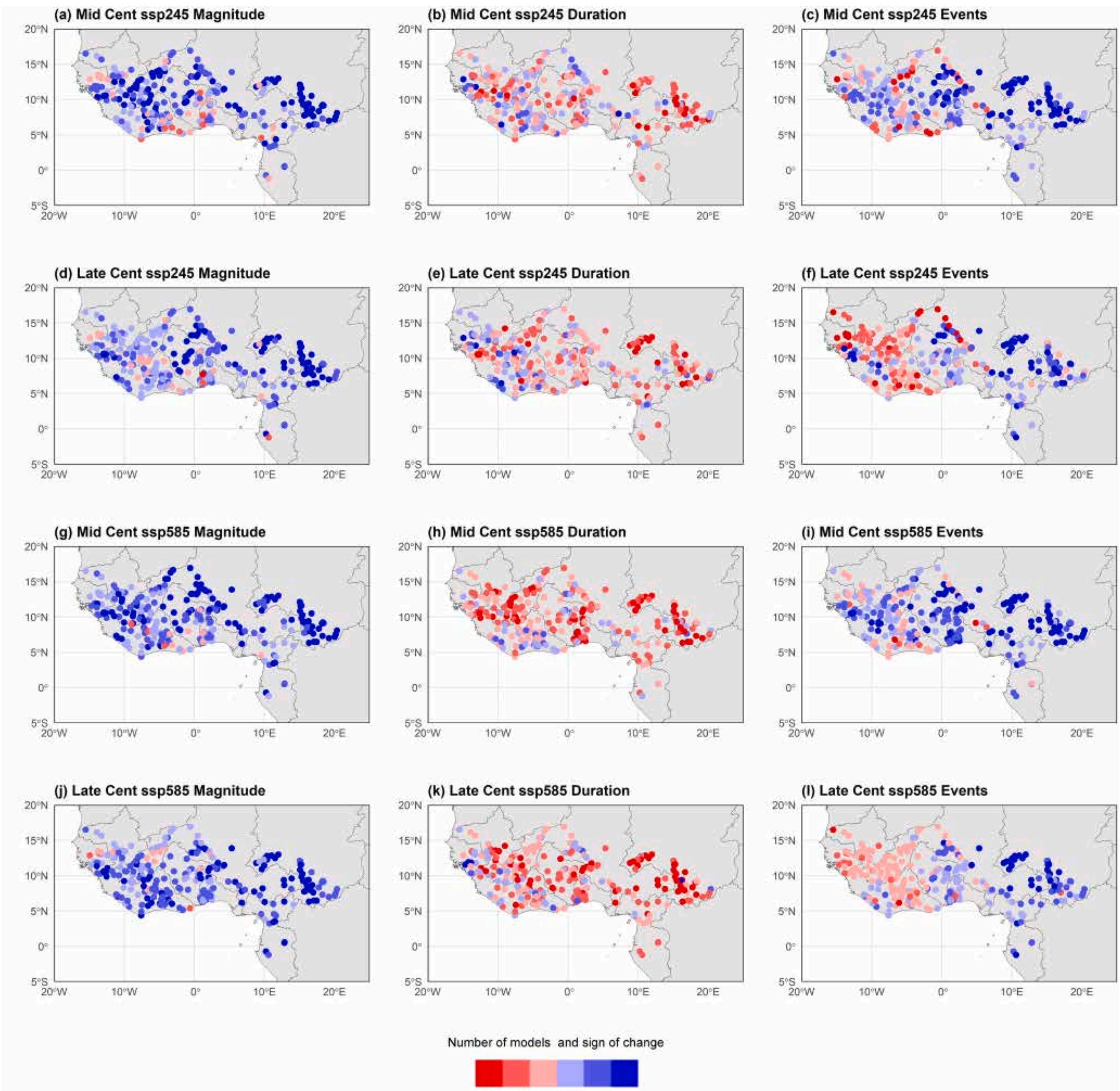

Fig. 7. LISFLOOD-CMIP6 model agreement on the direction of change in flood characteristics in the mid-term (2030–2059) and long-term future (2071–2100), relative to the reference historical period (1985–2014), in West Africa under SSP2.45 and SSP5.85 scenarios. (a-c) Number of LISFLOOD-CMIP6 models simulating positive or negative changes in flood magnitude (left), duration (middle), and frequency (right) in the mid-term future under SSP2.45 scenarios. (d-f) same as (a-c) but in the long-term future. (g-i) same as (a-f) but under SSP5.85 scenarios.

simulations project an increase spanning most of West Africa (+20 to 200 %), especially over the eastern Sahel (+50 to 200 %) in the mid-term future under both SSP2.45 and SSP5.85 scenarios (Fig. 7c, i). Meanwhile, in the long-term future, most LISFLOOD-CMIP6 models suggest greater regional contrasts, with a decrease (increase) in the annual number of floods over the western (eastern) part of West Africa (Fig. 7f, l). We note, however, that the model agreement is generally lower over the western and coastal regions of West Africa in the mid-term and long-term future and under both SSP-RCP scenarios.

Therefore, we analyse the differences between LISFLOOD-CMIP6 models in simulated future changes in flood characteristics (Fig. 8). More widespread and pronounced increases in the magnitude, and

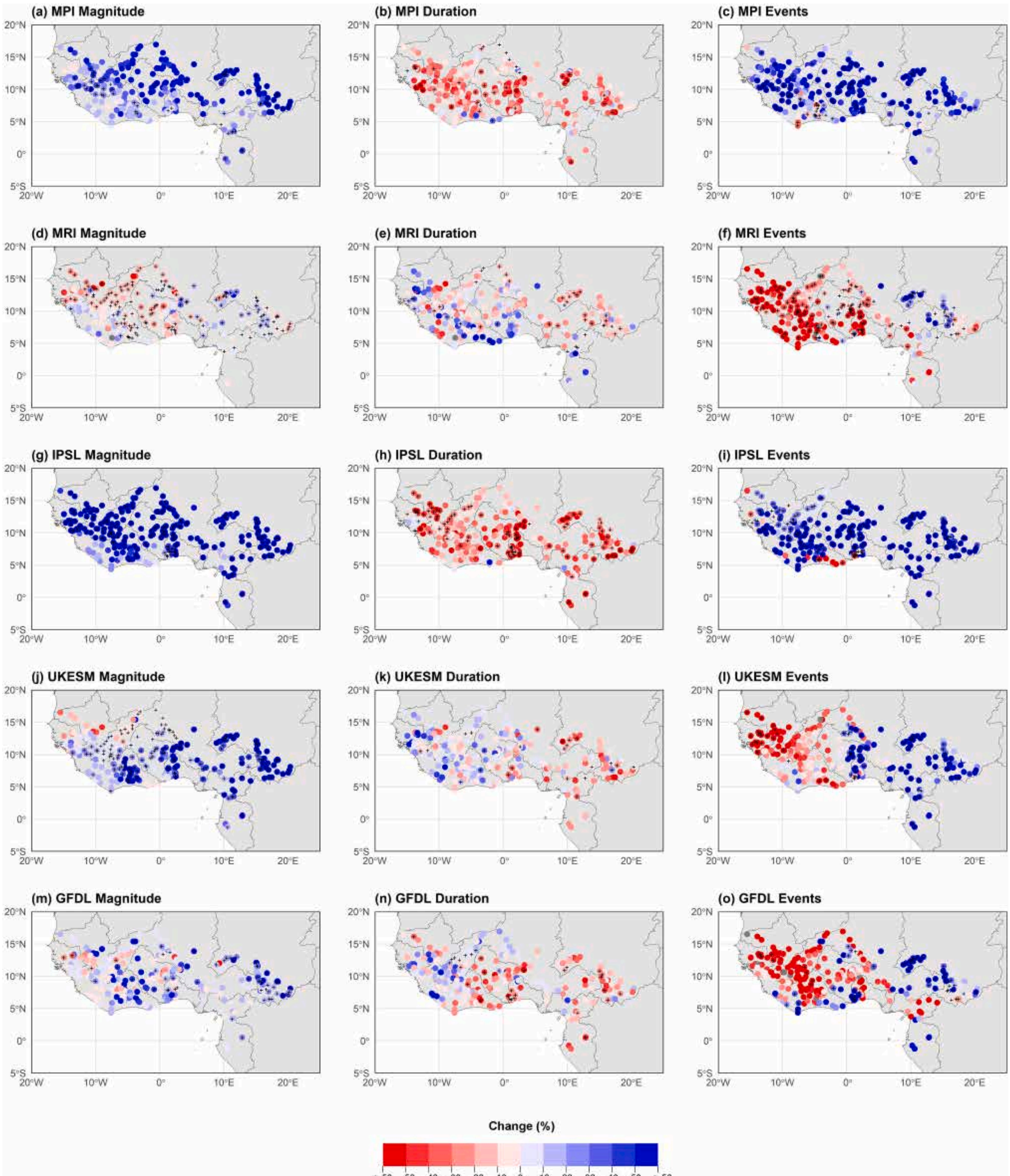

Fig. 8. Projected changes in West Africa hydrological flood characteristics in the long-term future (2071–2100), relative to the reference historical period (1985–2014), under SSP5.85 scenarios in LISFLOOD-CMIP6 models. (a-c) LISFLOOD-MPI simulations of projected changes in flood magnitude (left), duration (middle), and frequency (right) in the long-term future under SSP5.85 scenarios. (d-o) same as (a-c) but for MRI, IPSL, UKESM, and GFDL simulations. Black crosses indicate the statistical significance of projected changes according to the Wilcoxon test at $p \leq 0.05$.

frequency of floods are found using CMIP6 models that projected larger increases in cumulated annual rainfall and 5-day rainfall maximum, i.e., MPI and IPSL (+40 to 120 % spanning over 84 % of West Africa; Figs. 6, 8a, g). In contrast, much weaker increases and more widespread decreases in flood magnitude are found using CMIP6 models that projected significantly drier conditions over West Africa, i.e., GFDL and, especially, MRI (Fig. 8d, m). These simulations, especially LISFLOOD-MRI, also show spatially coherent and significant decreases in the frequency of flood events over the western and coastal regions of West Africa, while more localised increases in flood frequency persist over the eastern Sahel (Fig. 8f, l). Interestingly, CMIP6 models with drier projected conditions also tend to project increases (decreases) in flood durations over the western (eastern) regions of West Africa (Fig. 8e, k). This suggests that, in all LISFLOOD-CMIP6 simulations, regions displaying a projected increase (decrease) in the magnitude and frequency of floods consistently project a decrease (increase) in flood durations. This is consistent with recent studies highlighting potential shifts in wet and dry spell characteristics over West Africa under climate change. For instance, recent studies project a reduction in wet day probabilities, alongside increased probabilities of consecutive dry days, across West and Central Africa (Klutse et al., 2018; Wainwright et al, 2021; Basse et al., 2024). These shifts correlate with the heightened intensity of extreme rainfall (Berthou et al., 2019), suggesting that fewer wet days coincide with more intense precipitation. Collectively, these studies underscore a transition toward more erratic rainfall regimes in West Africa, characterized by shorter, less frequent wet periods and prolonged

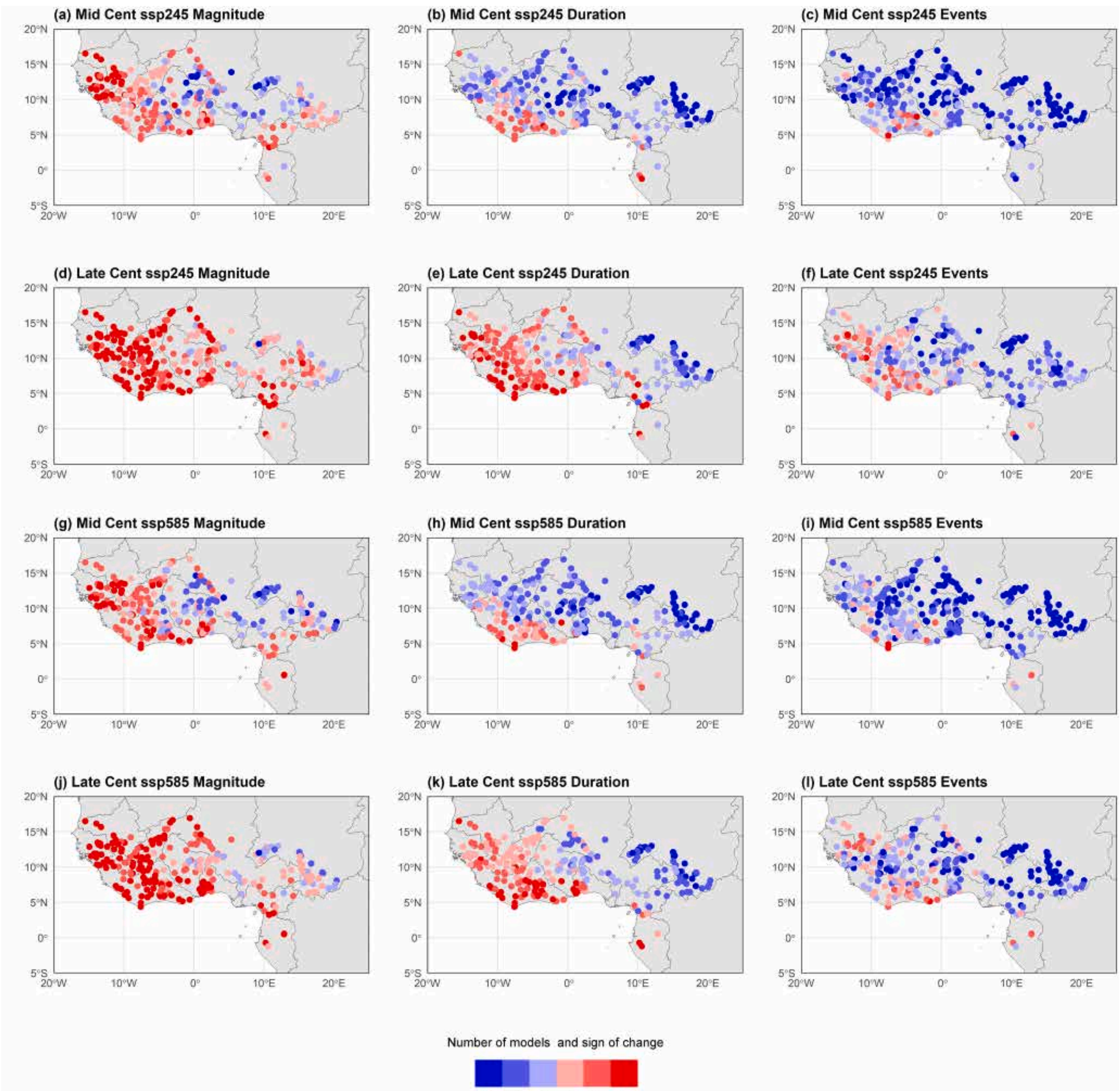

Fig. 9. LISFLOOD-CMIP6 model agreement on the direction of change in hydrological drought characteristics in the mid-term (2030–2059) and long-term future (2071–2100), relative to the reference historical period (1985–2014), in West Africa under SSP2.45 and SSP5.85 scenarios. (a-c) Number of LISFLOOD-CMIP6 models simulating positive or negative changes in drought intensity (left), duration (middle), and frequency (right) in the mid-term future under SSP2.45 scenarios. (d-f) same as (a-c) but in the long-term future. (g-i) same as (a-f) but under SSP5.85 scenarios.

dry spells, particularly in the Sahel, which could explain the reduction in flood duration whilst seeing an increase in flood magnitude under the climate models projecting wetter conditions and reverse for those projecting direr conditions under climate change.

3.3. Future changes in hydrological drought characteristics

Fig. 9 presents the model consensus in simulating positive or negative changes in hydrological drought characteristics during the 21st century.

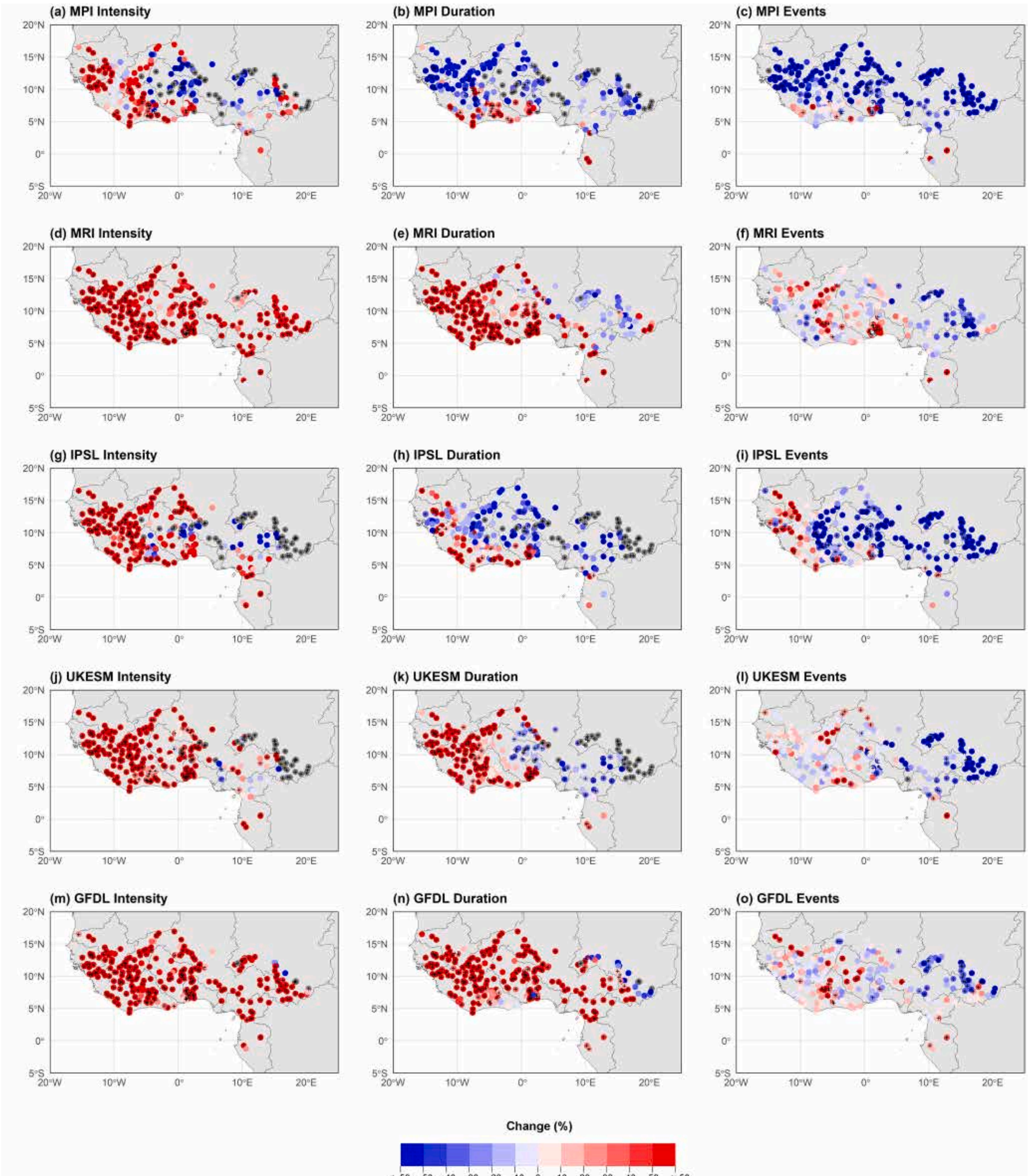

Fig. 10. Projected changes in West Africa hydrological drought characteristics in the long-term future (2071–2100), relative to the reference historical period (1985–2014), under SSP5.85 scenarios in LISFLOOD-CMIP6 models. (a-c) LISFLOOD-MPI simulations of projected changes in drought intensity (left), duration (middle), and frequency (right) in the long-term future under SSP5.85 scenarios. (d-o) same as (a-c) but for MRI, IPSL, UKESM, and GFDL simulations. Black crosses indicate the statistical significance of projected changes according to the Wilcoxon test at $p \leq 0.05$. Grey dots indicate the locations for which no droughts are detected.

Under both SSP2.45 and SSP5.85, LISFLOOD-CMIP6 simulations tend to project an increase in the intensity of hydrological droughts, ranging from +20 to +300 %, over the western and coastal regions of West Africa in the mid-term and long-term futures (Fig. 9a, d, g, j). Most LISFLOOD-CMIP6 simulations project a decrease in drought intensity over the eastern Sahel (−10 to 70 %; Fig. 9a, d, g, j). This model agreement in projecting reduced drought intensity over the eastern Sahel appears more robust in the mid-term future at first glance, but this is mainly because no droughts are detected in the long-term future under SSP5.85 in models with wetter projected climatological forcings (e.g., MPI, IPSL; Fig. 10a, g, j). We also note that most LISFLOOD-CMIP6 simulations project more and longer-duration drought over the southern coastal regions of West Africa in the mid-term future (+6 to 73 %), expanding to the entire western region of West Africa in the long-term future (Fig. 9b-c, e-f, h-i, k-l). Meanwhile, LISFLOOD-CMIP6 simulations consistently project shorter-duration droughts over the eastern regions of West Africa (Fig. 9b-c, e-f, h-i, k-l).

Comparing individual LISFLOOD-CMIP6 models over the long-term future and under SSP5.85, we note that only simulations with wetter projected climatological forcings (e.g., MPI and IPSL; Fig. 6) suggest a significant decrease in drought intensity, duration, and frequency over the eastern Sahel (Fig. 10a-c, g-i). In models with drier projected climatological forcings (e.g., MRI and GFDL; Fig. 6), we note significant increases in the intensity, and duration of hydrological droughts across all West Africa (Fig. 10d-f, m-o), but no significant increase in the frequency of hydrological droughts. UKESM, which shows greater zonal contrasts with drier (wetter) conditions over the western (eastern) regions of West Africa (Fig. 6), changes in drought characteristics follow the same patterns (Fig. 10j-l).

4. Discussions and conclusions

This study aims to evaluate the plausible impact of future climate change on hydrological extremes in West Africa. Previous research in this area has primarily focused on individual catchments, narrowly focused on the magnitude/intensity of floods and droughts, and employed different climate and hydrological models (e.g., Descroix et al., 2018; Nka et al., 2015; Aich et al., 2016; Do et al., 2017; Wilcox et al., 2018; Degefu et al., 2019; Dembélé et al., 2022; Gebrechorkos et al., 2022). However, this approach has limited the comparability between studies and hindered our ability to discern broader regional climate-related patterns from local-scale factors, such as groundwater support, land-use changes, and anthropogenic water usage (Blöschl et al., 2019; Kingston et al., 2020). Furthermore, for water management planning and associated risk-mitigation measures, providing information regarding the duration and frequency of hydrological droughts and floods is also crucial (e.g., Brunner et al., 2021; Kreibich et al., 2022).

To address these gaps, we integrate information from five bias-corrected CMIP6 under two contrasted SSP-RCP scenarios (SSP2.45 and SSP5.85) in physics-based spatially distributed hydrological modelling experiments to provide a comprehensive and unified assessment of regional climate change impacts on the magnitude, duration, and frequency of hydrological droughts and floods. Hydrological modelling experiments are performed using the setup of the latest high-resolution global implementation of OS-LISFLOOD, which allowed the delivery of GloFAS.v4 and offered greater performances over Africa. Testing the performances of this model, we found that OS-LISFLOOD shows relatively good performances in representing the hydrological cycle, even using an extended evaluation period (36 years). Some limitations are, however, noted for Sahelian Rivers, which are more sensitive to decadal variations (Mahé and Paturel, 2009; Descroix et al., 2018; Sidibe et al., 2018, 2019; Ekolu et al., 2022; Ekolu et al., 2024). OS-LISFLOOD simulations also show realistic representations of flood magnitude, duration, and frequency of floods, as well as of the intensity and frequency of droughts, across most of West Africa, ensuring the robustness of our assessment of future climate change impact on hydrological extremes. Further development should nevertheless include re-calibrating OS-LISFLOOD using longer observational hydrological datasets, as provided by Ekolu et al. (2022).

Regarding future regional climate changes, bias-corrected CMIP6 models consistently projected warming trends over the 21st century. However, greater regional contrasts and model discrepancies are found in projected rainfall changes. The majority of CMIP6 models project more (less) rainfall, as well as more (less) intense rainfall, over the eastern (western) region of West Africa. Such zonal contrasts in projected rainfall changes over West Africa are consistent with previous studies using CMIP models (Monerie et al., 2012, 2020, 2023; Audu et al., 2024) and appear even more pronounced in higher-resolution convection-permitting models (Berthou et al., 2019). Nevertheless, projected regional rainfall changes are strongly influenced by large-scale changes in air surface temperature over the North Atlantic and Mediterranean areas. According to Monerie et al. (2023), drier conditions are projected over significantly larger regions in CMIP6 models simulating weaker warming in the North Atlantic and Mediterranean air surface temperatures during the 21st century (e.g., GFDL and MRI). Meanwhile, wetter conditions (including heavier rainfall) are projected over most of West Africa in CMIP6 models simulating stronger warming in the North Atlantic or Mediterranean air surface temperatures during the 21st century (e.g., MPI and IPSL).

Future changes in hydrological droughts and floods mirror changes in precipitation patterns, and are, therefore, equally impacted by contrasted warming rates in the North Atlantic and Mediterranean air surface temperatures. This is consistent with Ekolu et al. (2024), who emphasised that sea-surface temperature anomalies in the North Atlantic and the Mediterranean Sea are the primary large-scale drivers of historical and future changes in flood hazards over West Africa. In both mid-term and long-term climate change impact projections, LISFLOOD-CMIP6 simulations indicate significant alterations in floods and drought dynamics across West Africa under SSP2.45 and SSP5.85. In most simulations, flood magnitudes are projected to increase, while flood durations are projected to decrease, across most West African regions. This divergence is consistent with climate projections indicating a tendency towards increased rainfall intensity alongside decreased wet spell duration (Klutse et al., 2018; Berthou et al., 2019; Wainwright et al, 2021; Basse et al., 2024). Such changes would favour higher peak discharges, thus increasing flood magnitudes, but simultaneously reduce the persistence of conditions conducive to prolonged flooding, leading to shorter durations. However, consensus on changes in flood frequency is less clear, with varied model agreements. While the mid-term outlook generally indicates widespread increases in the number of floods, long-term scenarios reveal nuanced regional shifts, with fewer floods in the west and more floods in the east. In addition, we note that CMIP6 models with wetter projected climatological forcings tend to project more pronounced increases in flood magnitudes, whereas CMIP6 models with drier projected climatological conditions suggest milder increases or even decreases. Conversely, in most CMIP6 models, drought severity is projected to increase over the western and coastal territories but decrease over the eastern Sahel. Nevertheless, this decline in drought magnitude over the eastern Sahel predominantly occurs when combining CMIP6 models anticipating wetter climates with OS-LISFLOOD. CMIP6 models projecting drier climate conditions suggest increases in drought magnitude and duration throughout West Africa, with regional nuances mirroring projected climatic shifts.

It is however, important to note that bias correction uncertainties arising from the CDF-t approach, despite showing improved fidelity of CMIP6 outputs for hydrological modelling, do not preserve inter-variable dependencies (e.g., rainfall-temperature correlations), potentially altering the physical coherence of compound extremes (Vrac et al., 2022; He et al., 2024). Furthermore, bias correction can inflate extreme rainfall magnitudes when applied to high-resolution data (Maraun, 2013; Trentini et al., 2023), which may affect flood simulations. Additionally, while OS-LISFLOOD performed well overall, its sensitivity to

Sahelian hydrology, where groundwater interactions and anthropogenic water use are poorly constrained, highlights structural limitations in representing arid-region processes (Dembélé et al., 2022; Alexander et al., 2023). Hydrological models' calibration focused on aggregate metrics (e.g., KGE) may inadequately capture extremes, as flood and drought dynamics depend on non-linear processes underrepresented in single-objective frameworks (Mizukami et al., 2019; Yang et al., 2022). Future studies should prioritize multivariate bias correction, multi-model hydrological ensembles, and calibration strategies explicitly targeting extremes.

Further understanding of land–atmosphere mechanisms driving such changes in flood and drought dynamics in the 21st century is particularly crucial and should be the focus of future studies. For instance, as the frequency of extreme storms-mesoscale convective systems and extreme rainfall intensity increased in West Africa during the last decades (Taylor et al., 2017; Chagnaud et al., 2022), Tramblay et al. (2022) showed that more observed floods were driven by short extreme rainfall events in the last decades, while, historically, excess rainfall (from more prolonged events) on saturated soils is the primary flood generation mechanism. Notably, upcoming studies should examine the interplay between rainfall characteristics (intensity, frequency, and durations), soil moisture, vegetation covers, groundwater supports, and its potential impacts on floods and droughts under future climate conditions (Brunner et al., 2021).

Through advancing the understanding of the plausible impacts of future climate change on hydrological droughts and floods in West Africa, our study thus provides valuable information for effective disaster risk reduction and management. For instance, our result suggests that the western and coastal regions of West Africa could be increasingly impacted by more severe and prolonged droughts while being exposed to more severe, but shorter-duration floods. This is particularly critical for water and risk disaster management, as measures taken to mitigate floods (droughts) often exacerbate droughts (floods) (Di Baldassarre et al., 2010; Ward et al., 2020). Dykes and levees intended to mitigate flood risks can worsen drought conditions when they fail or are wettened during dry periods to reduce failure probability, thus limiting water availability for other uses (Vicuña et al., 2006; van Lanen et al., 2016). Similarly, flood protection requires low water storage in dams and reservoirs to avoid overtopping during heavy rains, but this lowers drought preparedness (Ward et al., 2020). Equally, our results suggest that the eastern Sahel could be increasingly exposed to multiple short-duration floods over the 21st century, but existing flood mitigation strategies fail to reduce the impact of multiple flood events (Kreibich et al., 2022). Future studies should nevertheless evaluate the performance and sustainability of existing flood and drought risk mitigation strategies under a changing climate in West Africa.

5. Code availability

The code used in this study to produce the data analysed was developed in R programming and can be provided upon reasonable request to JE.

CRediT authorship contribution statement

Job Ekolu: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Data curation, Conceptualization. **Bastien Dieppois:** Writing – review & editing, Writing – original draft, Validation, Methodology, Data curation, Conceptualization. **Serigne Bassirou Diop:** Writing – review & editing, Writing – original draft, Validation, Methodology, Data curation, Conceptualization. **Ansoumana Bodian:** Writing – review & editing, Methodology, Data curation, Conceptualization. **Stefania Grimaldi:** Writing – review & editing, Methodology, Data curation, Conceptualization. **Peter Salamon:** Writing – review & editing, Methodology, Data curation, Conceptualization. **Gabriele Villarini:** Writing – review & editing, Methodology, Data curation, Conceptualization. **Jonathan M. Eden:** Writing – review & editing, Methodology, Data curation, Conceptualization. **Paul-Arthur Monerie:** Writing – review & editing, Methodology, Data curation, Conceptualization. **Marco van de Wiel:** Writing – review & editing, Methodology, Data curation, Conceptualization. **Yves Tramblay:** Writing – review & editing, Methodology, Data curation, Conceptualization.

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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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhydrol.2025.133482.

Data availability

Daily streamflow data are available through the SIEREM (http://www.hydrosciences.fr/sierem/) and the GRDC databases (https://portal.grdc.bafg.de/). CMIP6 data are publicly available at https://esgf-index1.ceda.ac.uk. ERSST.v5 is available at https://climexp.knmi.nl.

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