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Key Points:
- Seasonality of annual maximum flood, precipitation and soil moisture is evaluated in Africa
- Stronger association of the flood timing with soil moisture, rather than with 5-day or 1-day annual maximum precipitation
- Interannual variability in flood magnitude is mostly related to variability in annual maximum soil moisture

Supporting Information:
Supporting Information may be found in the online version of this article.

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Evaluation of the Drivers Responsible for Flooding in Africa

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Abstract Africa is severely affected by floods, with an increasing vulnerability to these events in the most recent decades. Our improved preparation against and response to this hazard would benefit from an enhanced understanding of the physical processes at play. Here, a database of 399 African stream gauges is used to analyze the seasonality of observed annual maximum flood, precipitation and soil moisture between 1981 and 2018. The database includes a total of 11,302 flood events, covering most African regions. The analysis is based on directional statistics to compare the annual maximum river flood with annual maximum rainfall and soil moisture. The results show that the annual maximum flood in most areas is more strongly linked to the annual peak of soil moisture than of annual maximum precipitation. In addition, the interannual variability of flood magnitudes is better explained by the variability of annual maximum soil moisture than by the variability in the annual maximum precipitation. These results have important implications for flood forecasting and the analysis of the long-term evolution of these hydrological hazards in relation with their drivers.

1. Introduction

Floods in Africa have strong impacts on the population and their activities, claiming a large toll in terms of fatalities and economic damage (Di Baldassarre et al., 2010; Tramblay et al., 2020). To develop skillful flood forecasting systems and estimate future changes in flood hazards, there is a need to first understand the main flood characteristics and seasonality, as well as the processes linked to flood occurrence. Several large-scale studies have been conducted across Europe, the United States or Australia, and observed an indirect link between annual maximum rainfall and floods, with this response being modulated by antecedent soil moisture conditions (Do et al., 2020a; Ivancic & Shaw, 2015; Neri et al., 2019; Sharma et al., 2018; Tramblay et al., 2019; Wasko & Nathan, 2019). Indeed, during extreme rainfall events, runoff coefficients can be variable in time and space due to the interplay between precipitation intensity and soil moisture content (e.g., Bennett et al., 2018; Ghajarnia et al., 2020; Woldemeskel & Sharma, 2016).

The influence of antecedent soil moisture conditions for floods in Africa has been the subject of a limited number of studies at the catchment scale (Bangira et al., 2015; El Khalki et al., 2020; Tramblay et al., 2012, 2014; Wolski et al., 2014). For instance, Bischiniotis et al. (2018) analyzed damaging flood events in sub-Saharan Africa reported in the NatCatSERVICE insurance database; they found that these flood events were more strongly related to the seasonal negative anomalies of the standardized precipitation evapotranspiration index (SPEI) than to the 7-day precipitation totals before the flood events. In terms of flood seasonality in Africa, Ficchì and Stephens (2019) evaluated the influence of large-scale climate variability on flood timing using GLOFAS-ERA5 (Harrigan et al., 2020) runoff reanalysis and 65 time series of observed river discharge. They found that both the Indian Ocean Dipole and El Niño–Southern Oscillation have a significant influence on the seasonality of flooding, which depends on the positive/negative phases of these indices. These two studies relied on limited observational data and exemplify how the knowledge of African flood processes is largely hampered by the lack of observations. Indeed, the African continent is currently under-represented in global studies on flood-generation mechanisms (Do et al., 2020b; Stein et al., 2020).

Discharge data in Africa are available only at a limited number of locations, with low-density monitoring networks in most countries. As a consequence, African rivers are strongly under-represented in large-scale databases (Hannah et al., 2011), such as the recent Global Streamflow Indices and Metadata Archive (GSIM) (Do et al., 2018). The same conclusions apply to observed precipitation from rain gauges, a crucial variable to detect changes in precipitation regimes and extremes that could exert a strong influence on flood generating processes. Nevertheless, different variables, including precipitation, derived from global scale products such as reanalysis or remote sensing data, could be valuable proxies to investigate the seasonality of flood hazard. There is indeed a strong interest in model-based or remote sensing estimates of hydrological fluxes, relevant to identify flood processes in data-sparse environments (e.g., El Khalki et al., 2020; Gründemann et al., 2018; Sinclair & Pegram, 2010; Tramblay et al., 2012). However, without long-term and dense ground monitoring networks, no reliable estimate for extreme rainfall is available for Africa (Beck et al., 2017; Masunaga et al., 2019; Satgé et al., 2020; Sylla et al., 2013) and some regions, such as northern or equatorial Africa, show large discrepancies among different products (Gehne et al., 2016). This adds substantial uncertainties, particularly in the analysis of extreme rainfall (Harrison et al., 2019; Nogueira, 2020).

The objective of the present study is to identify the most relevant drivers for flood occurrence in Africa. We apply here a method based on directional statistics to detect the most influential drivers of flood occurrence, previously applied in the United States (Berghuijs et al., 2016; Villarini, 2016), Europe (Berghuijs et al., 2019) and Australia (Wasko & Nathan, 2019; Wasko et al., 2020a). The analysis is targeted to identify the most relevant driver for each basin. This work builds on a recent database, the African Database of Hydrometric Indices (ADHI; Tramblay et al., 2021), that has been developed to better document the hydrology of Africa.

2. Data

Annual maximum discharge was extracted from a data set of 399 stream gauges of the ADHI database (Tramblay et al., 2021) with at least 10 years of discharge data between 1981 and 2018 (mean and median record length of 28 years and 30 years, respectively). The ADHI database also contains metadata about the catchments, including their size, elevation and the presence of dams from the Grand Dam Database (Lehner et al., 2011). For several dams and reservoirs, there is no sufficient metadata to assess the degree of regulation. Sixty-nine basins in the database contains at least one dam, but among them 41 do not have complete metadata to document the building date, the controlled catchment area or storage capacity. Therefore, these basins were kept in the analysis to compare whether including these regulated stations has a noticeable impact on the results.

The catchments considered here represent a wide range of sizes (Figure 1), with catchment areas ranging between 2 km^2 for the Jakkalsrivier in South Africa, to 120,821 km^2 for the Senegal River at Galougo. Only three other basins exceed 20,000 km^2: The Gambie in Senegal, the Sota in Benin and the Bandama in Ivory Coast. The median catchment size is 613 km^2, indicating that the database includes mainly small-to moderate-sized basins. For the majority of the catchments, the mean elevation is below 1,500 m. Consequently, unlike studies that have applied similar methods in other continents (Berghuijs et al., 2016, 2019; Stein et al., 2020) snow is not considered here among the major flood-generating processes. Snow cover is very limited in Africa, and it only impacts a few catchments in our database located in Morocco and South Africa. In four catchments in Morocco, snowmelt contributes up to 48% of the annual streamflow depending on the year (Marchane et al., 2017), but in these catchments snowmelt is not the dominant flood generating mechanism (Zkhiri et al., 2017). In South Africa, the Drakensberg Mountains have a light snow cover during the summer, not significantly affecting streamflow, with the exception of some small headwater catchments (Sene et al., 1998; Taylor et al., 2016; Wunderle et al., 2016) that are not present in the current database. Across the 399 stream gauges available, there are a total of 11,302 flood events (defined as the annual maximum flood (AMF). The hydrological year is defined for each station, with its start after the month with the lowest mean monthly runoff computed across all the available years. The monthly time series of runoff are available from the ADHI database (Tramblay et al., 2021). This method ensures a more consistent definition of the water year (Wasko et al., 2020b).

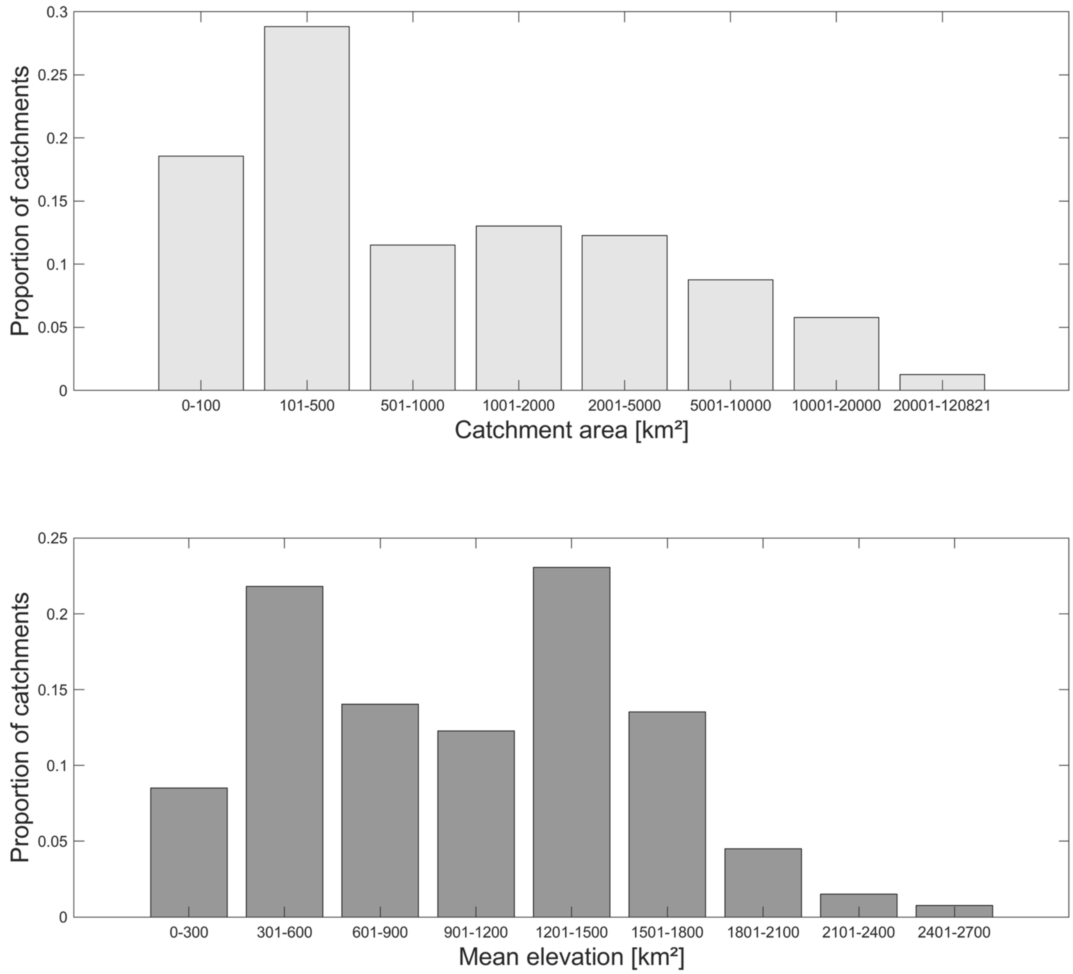

Figure 1. Histograms showing the catchment area (top panel) and elevation (bottom panel) for the 399 catchments in Africa considered here.

We complement the river discharge data with two rainfall products: Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS; Funk et al., 2015) and ERA5 reanalysis (Hersbach et al., 2020). The rationale for using two very different sources of precipitation is to check whether the conclusions obtained can be different depending on the data set, given that there is no benchmark or reference data set for the entire African continent. CHIRPS is a quasi-global rainfall data set merging satellite measurement with rain gauge data, spanning 50°S–50°N. Data are available from 1981 to near-present, with daily temporal resolution and a spatial resolution of 0.05°. ERA5 is a reanalysis data set from 1979 to the present, and provides hourly estimates for a large number of atmospheric, land and oceanic climate variables on a ∼30 km grid. The hourly estimates have been summed to the daily time step. CHIRPS represent a good option to estimate rainfall for different regions of Africa based on results from previous studies (Dinku et al., 2018; Harrison et al., 2019; Satgé et al., 2020). Moreover, the recently developed ERA5 reanalysis has been commonly used for large scale studies including in Africa (Ficchì & Stephens, 2019; Harrigan et al., 2020). For both datasets, we extracted the daily and 5-day annual maximum rainfall (the 5-day annual maximum precipitation is computed from a running sum of daily precipitation, with the date of the selected 5-day accumulation period corresponding to the last day of the accumulation window).

We compared the performance of CHIRPS and ERA5 basin-averaged annual maximum precipitation. In terms of the seasonality of annual maximum daily precipitation, the absolute difference in days between the two products is less than 30 days for 328 out of 399 stations. This result suggests that CHIRPS and ERA5 exhibit a similar seasonality in terms of annual maxima for most basins. When we focus on the magnitude of the annual maximum daily precipitation, the mean Spearman correlation coefficient between the two products is low (i.e., equal to 0.22) and for about 10% of stations the correlation is negative. Yet, the statistical distributions of annual maximum rainfall based on the two products are not significantly different (at the 5% level) for 230 stations based on the Kolmogorov-Smirnov test. This means that the seasonality of rainfall is comparable in the two datasets but the annual maximum precipitation amounts are highly variable. There is no systematic bias in the two products: For 207 basins ERA5 annual maximum rainfall is smaller than in CHIRPS, while for 192 basins it is the opposite. Similar results are obtained with annual maximum 5-day precipitation, yet the correlation coefficient is larger, with a mean Spearman correlation equal to 0.37.

Because soil moisture is also a very important driver for flood generation, we considered soil moisture from the ERA5-Land reanalysis (Muñoz Sabater et al., 2021). ERA5-Land is an improved version of the land surface component of the ERA5 climate reanalysis, with a higher spatial resolution of 9 km, making it more suitable for land applications. The soil moisture is available for four different soils layers, corresponding to 0–7 cm for Layer 1, 7–28 cm for Layer 2, 28–100 cm for Layer 3, and 100–289 cm for Layer 4. Soil moisture from ERA5-Land reanalysis ensures a complete spatio-temporal coverage over the study period, since the African continent is characterized by a very low density of soil moisture measurement networks (Myeni et al., 2019). Other satellite-derived products, such as ESA-CCI (Gruber et al., 2019), were initially considered for the analysis, but many spatial gaps in the data were found in central Africa (Scanlon, 2020).

3. Methodology

Directional statistics (Berghuijs et al., 2016; Burn, 1997; Villarini, 2016; Wasko et al., 2020a) are used to analyze the timing of AMF, annual maximum 1-day and 5-day precipitation, and annual maximum soil moisture with respect to the local hydrological year, since they represent the appropriate statistical framework to identify similarities in the timing of floods. The dates of the quantity of interest are converted into an angular value. From this sample of angular values, the mean date of occurrence (θ) can be computed, together with the concentration index (r) which measures the variability of the flood occurrences around the mean date. From the daily discharge, precipitation and soil moisture data, the annual maximum values are extracted together with their dates of occurrence; then θ and r are computed from the sample of dates.

The first step in the analysis of seasonality is to test against circular uniformity. Circular uniformity refers to the case in which all angular values of flood dates around the circle are equally likely, indicative of the absence of flood seasonality. Circular non-uniformity is considered necessary to analyze the seasonality of floods. The Rayleigh test for uniformity is used to test against uniformity for unimodal distributions. In the case of multimodal distributions, we also tested uniformity with the Hermans-Rasson test (Landler et al., 2019). To avoid the issues of incorrectly rejecting a null hypothesis when several independent statistical tests are performed simultaneously (Wilks, 2006), we implemented the (Bonferroni, 1936) correction procedure to adjust the p-values of the two tests.

To assess the similarity between AMF and annual maximum rainfall and soil moisture occurrences, we compute the difference in days between the mean dates θ of these three indicators. We also use the Kuiper test, a circular analogue to the Kolmogorov-Smirnov test, to assess if the seasonality of floods, annual maximum rainfall, and maximum soil moisture are similar. Finally, as in Berghuijs et al. (2016), the Spearman correlation coefficient is computed between the time series of: (a) AMF and annual maximum 1-day and 5-day precipitation; and (b) AMF and annual maximum soil moisture. This will allow the detection of the best indicator between annual maximum 1-day and 5-day precipitation or soil moisture to explain the interannual fluctuation of flood magnitudes. To assess whether the correlations between the different covariates tested are different, we implemented the approach in Meng et al. (1992). For instance, if the correlation between soil moisture and annual maximum flood is significantly different from the others in some locations according to the Meng test, then that is a strong argument that it is driving the annual maximum flood response in that region.

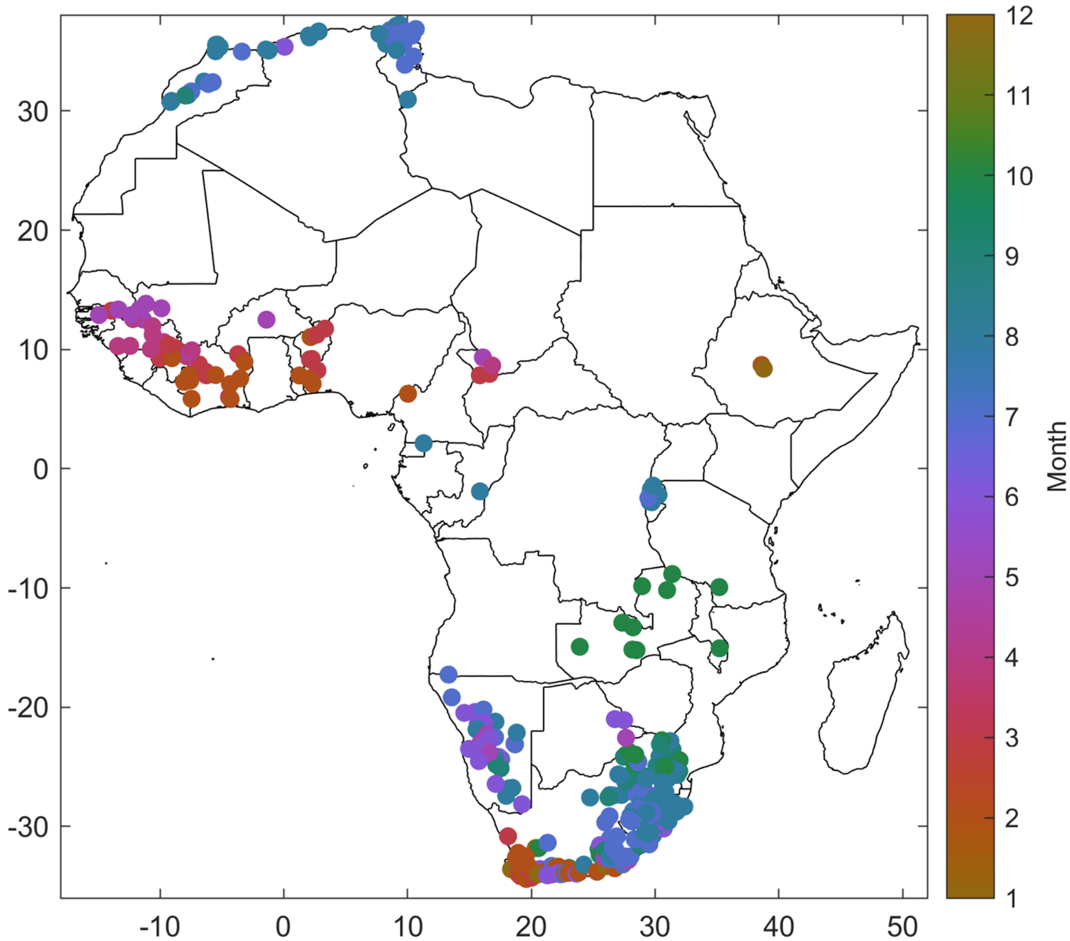

Figure 2. Month with the lowest average discharge. This information is used to identify the beginning of the hydrological year at each site.

4. Results

4.1. Local Hydrological Year

The first analysis is the calculation of the local hydrological year. Figure 2 shows a zonal behavior, with variability from north to south. In North Africa the hydrologic year starts around September, while it begins around March in West Africa. The beginning of the hydrologic year is shifted to August in central Africa. As we move to South Africa, stations under a Mediterranean-type climate are located near the Cape region, with a start of the hydrologic year in January; for stations in the eastern part of South Africa, the local hydrologic year starts in August/September. These findings are consistent with previous knowledge on the hydrological regimes of the different sub-regions in Africa, following the dominant precipitation regimes (Nicholson et al., 2018).

4.2. Test for Circular Uniformity

The first step in the analysis of the seasonality of flooding is to test for circular uniformity (to check if the floods do not occur randomly during the year). Based on the Rayleigh test, that is more appropriate for unimodal distributions, the null hypothesis of circular uniformity is not rejected at the 5% level (accounting for the Bonferroni correction) at 48 stations. In addition to this test, we also used the Hermans-Rasson test, which allows us to test for circular uniformity in the presence of more than one mode. The Hermans-Rasson test rejects the null hypothesis for 35 stations at the 5% significance level. For 27 (6%) basins, the two tests are rejecting the null hypothesis of circular uniformity so we focus on these basins (Figure 3, left

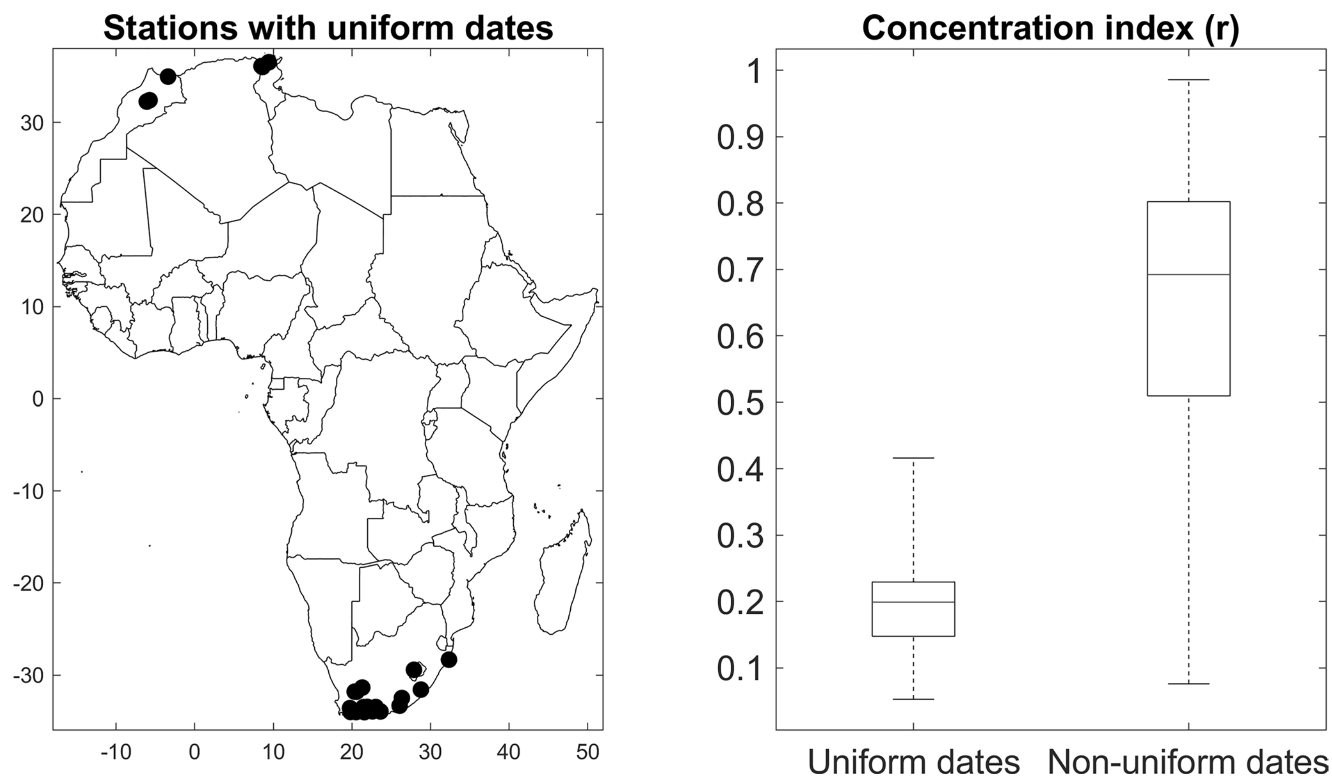

Figure 3. Left panel: Stations (27) with a uniform distribution of floods through the years according to the Rayleigh and Hermans-Rasson tests. Right panel: Boxplot of the concentration index values (r) for stations with uniform dates and stations without uniform dates (right). The limits of the box represent the 25th and 75th percentiles, with the line in the middle that refers to the median; the limits of the whiskers represent the 5th and 95th percentiles.

panel). It means that, according to the results of the two tests, 27 basins are considered to have a uniform occurrence of floods throughout the year.

To evaluate if the detection of uniform flood seasonality is related to river regulation, we analyze the presence of dams in these basins. The presence/absence of dams cannot explain these results because the proportion of basins with uniform flood distribution without a dam (81%) is similar to the overall proportion of non-regulated basins in the sample (82%). This implies that river regulation has no strong influence on the detection of uniform seasonality of floods. However, the interannual variability of flood dates (r) around the mean date (θ) could explain the detection of uniform seasonality (Figure 3, right panel). Most of the stations with a uniform seasonality are located in the semi-arid areas of North Africa and South Africa, characterized by a strong variability of flood occurrence. When looking at the flood dates for these stations (Figure S1), it is possible to identify for most of the stations a single month of maximum flood frequency (the mode of the monthly distribution) mostly during the September-December period. Some stations exhibit a secondary peak during later winter or spring. This shows that the two tests considered are not very robust in the presence of a strong intra-annual variability, since these stations do not exhibit a true uniform distribution of flood events throughout the year. For only six stations (Figure S1), an almost uniform seasonal occurrence of floods throughout the year is observed, with at least two modes occurring in different seasons. These stations are all in very small basins from a few square kilometers to 200 km^2 and without the presence of dams. Consequently, these six stations have been removed from subsequent analyses.

4.3. Analysis of the Seasonality of Floods, Annual Maximum Rainfall, and Soil Moisture Maximum

The flood timing has three distinct patterns (Figure 4, top row): (a) stations with floods occurring during December-February in the northern and southern part of the continent, and with a strong variability in the date of occurrence, corresponding to semi-arid climates; (b) stations in West Africa with floods during the

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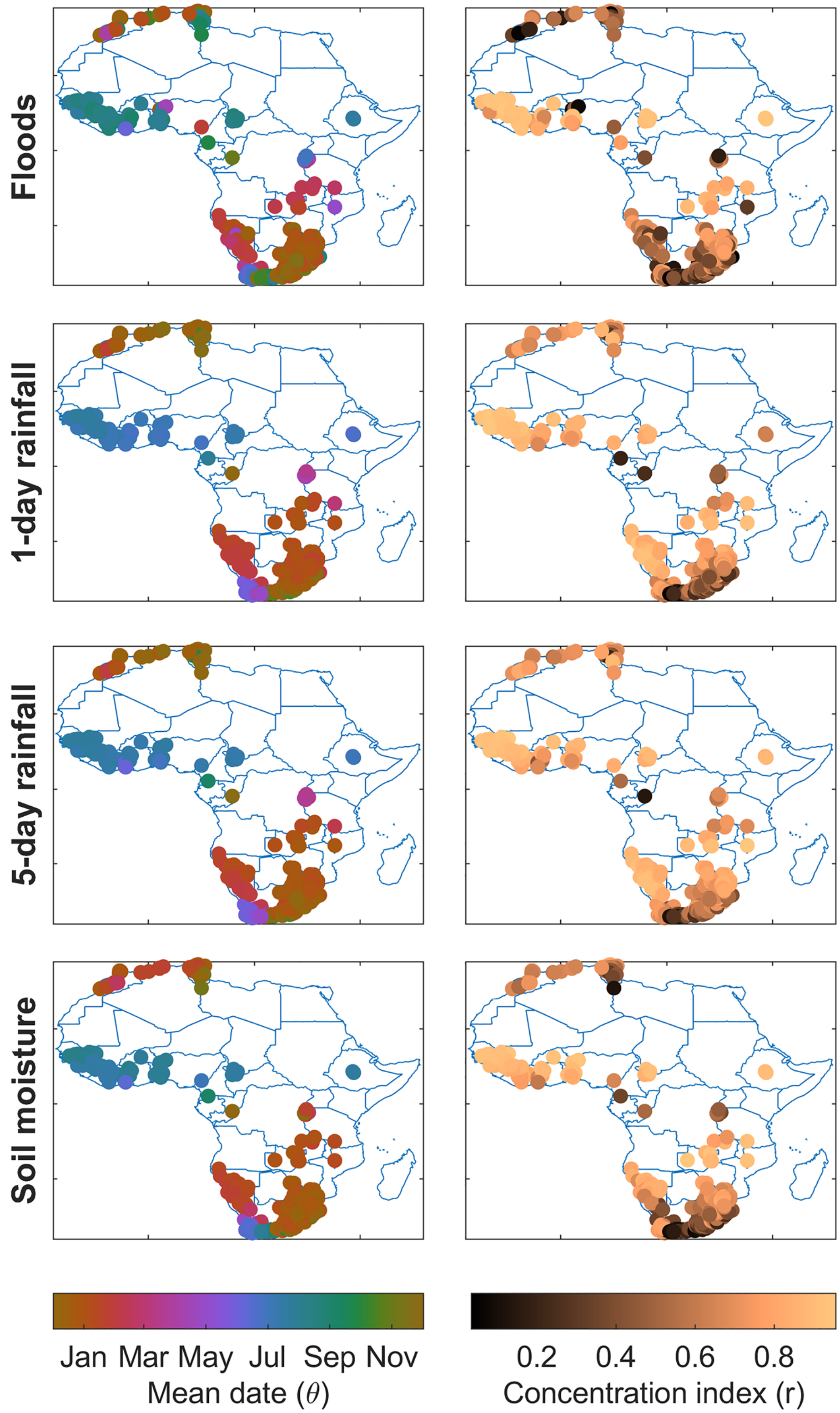

Figure 4. Mean dates of occurrence of annual maximum flood (top row), 1-day (second row) and 5-day (third row) annual maximum precipitation (based on CHIRPS), and annual maximum soil moisture (based on ERA5-land's second soil layer) (bottom row). The concentration around these dates is shown in terms of the concentration index (r) in the right column.

Table 1
Results of the Kuiper Tests to Identify Stations With a Similar Seasonality Between AMF, Annual Maximum Precipitation or Soil Moisture

Annual maximum:	Number of stations with the same seasonality as AMF	Mean difference in days with AMF
Soil moisture	345	19.6
5-day precipitation	320	20.2
1-day precipitation	309	22.5

summer and low seasonal variability; and (c) stations in central-south Africa (from Kenya to Namibia), with floods occurring in boreal spring and early summer with various degrees of variability depending on the sub-region considered.

To analyze the seasonality of annual maximum soil moisture, the data for the four soil layers of ERA5-Land are first considered. The objective of this comparison is to identify if the data from a particular soil layer are best related to the occurrence of floods. For this comparison, we used the Kuiper test to verify for which soil layer the seasonal distribution of floods is best associated with the seasonal distribution of annual maximum soil moisture. When examining the results of the Kuiper test, the lowest rejection rate of the null hypothesis (i.e., the two seasonal distributions are the same) is with the ERA5-land second soil layer for most basins (Figure S2). This is consistent with the fact that the top two layers react quickly to a rainfall event, whereas the deeper soil layers 3 and 4 show a more delayed response of soil moisture to a rainfall event. Overall, similar results are obtained with soil moisture from the soil layers 1 and 2; the soil moisture data from the second soil layer were used for all further analyses.

The three spatial patterns for floods, annual maximum rainfall and soil moisture, are remarkably consistent, with very similar timing for the three indicators. The correlation between the mean day of occurrence of AMF is stronger with soil moisture (rho = 0.55) than with 5-day (rho = 0.47) or 1-day rainfall (rho = 0.44) on average over the African continent. A similar range of correlations are obtained if considering three distinct regions: North Africa (above 25°N), Central/West Africa (between 25°N and 8°S), and South Africa (below 8°S), yet with the smallest correlations obtained for North Africa.

Some areas in South Africa (notably the middle part along the south coast) come out as having floods in different seasons. This is partly because the local convective systems can occur almost at any time in the year and are not confined to the more typical rainy seasons. This is particularly true for the Eastern Cape region where the biggest floods can occur in July and August, which are otherwise dry months (Blamey & Reason, 2013). In smaller catchments, floods can be generated by extreme rainfall events in a single day during thunderstorms; however, these rain events may not necessarily produce big floods in larger catchments mainly because of the limited spatial extent of the convective systems (Kijazi & Reason, 2009; Manhique et al, 2015; Smithers et al, 2001). There are also some of the largest floods in the eastern part of the country that are related to tropical cyclones that also make landfall in Mozambique (Rapolaki & Reason, 2018). These events tend to be confined to KwaZulu-Natal Province, but can also stretch further northwards.

With the soil moisture data from the second soil layer, the Kuiper test only rejects the null hypothesis at the 5% level for 54 (13%) stations, indicating that for 345 (87%) stations we cannot reject the null hypothesis that the seasonal distributions of AMF and annual maximum soil moisture are the same (Table 1). The mean absolute difference in days between AMF and annual peak of soil moisture is 19.6 days. The results for annual maximum precipitation are similar, with the Kuiper test rejecting the null hypothesis for 84 (21%) stations when we consider 1-day annual maximum precipitation and floods, and for 73 (18%) stations for 5-day rainfall and floods. The mean absolute difference in days between the annual flood and annual peak of rainfall is 22.5 days for 1-day rainfall, 20.2 for 5-day rainfall. The stations with a uniform flood seasonality, detected previously by the Rayleigh and Hermans-Rasson tests, only represent 6 (7%) stations and 5 (9%) stations, respectively, of the stations where the Kuiper test rejects the null hypothesis between floods and rainfall or soil moisture. This further confirms that these stations with circular uniformity erroneously detected by the two tests do not impact the results.

From the results of the Kuiper test, among the 84 and 54 catchments where neither precipitation nor soil moisture seasonality explain flood occurrences, 34 of them are the same. These 34 stations with neither soil moisture nor rainfall as valid flood drivers are mostly located in Western Africa and Southern Maghreb. The causes can be manifold, in particular related to data quality or the interplays between different flood drivers. These basins are mostly unregulated, with only one catchment that contains a dam. Meanwhile, the basins located in West Africa tend to be larger than the catchments with either soil moisture or annual maximum rainfall as the main flood drivers. In western Africa, drastic changes in land use,

Table 2
Result of the Correlation Analysis Between AMF and Annual Maximum Precipitation or Soil Moisture

Annual maximum	Number of significant correlations with AMF (5% level)	Mean correlation coefficient	Number of significantly different correlation coefficients, compared to soil moisture
Soil moisture	242	0.57	-
5-day precipitation	205	0.53	63
1-day precipitation	136	0.47	108

notably cropland expansion, but also changes in natural vegetation over the last decades have modified the rainfall-runoff relationships (e.g., Aich et al., 2015, 2016; Descroix et al., 2012, 2018; Gal et al., 2017; Mahe et al., 2013; Séguis et al., 2004). In Maghreb countries, stations are located close to the margins of the Sahara Desert, where flood generating processes are hardly captured at the daily time step (El Khalki et al., 2020). In addition, these basins are prone to be disturbed by human activities, such as water withdrawals for irrigation, even if the presence of large dams or reservoirs is not reported (Bouimouass et al, 2020).

4.4. Correlations Between Floods, Annual Maximum Rainfall and Soil Moisture

We computed the Spearman correlation coefficient between the AMF time series and the covariates (annual daily maximum precipitation from CHIRPS, and soil moisture from ERA5-land), similar to previous studies (Berghuijs et al., 2016; Do et al., 2020a). As shown in Table 2, we find that the overall strongest correlation with floods is with soil moisture (rho = 0.57), then with annual maximum 5-day rainfall (rho = 0.53) and lastly with annual maximum 1-day rainfall (rho = 0.47). If considering the best significant correlations at the 5% level for each station (Figure 5), for 169 stations (43%), the correlation coefficient is strongest between annual maximum soil moisture and floods. For 88 stations (22%), the 5-day rainfall provides the highest correlations, and only for 32 stations (8%) this is the case for the 1-day rainfall maxima (Figure 5). However, it should be noted

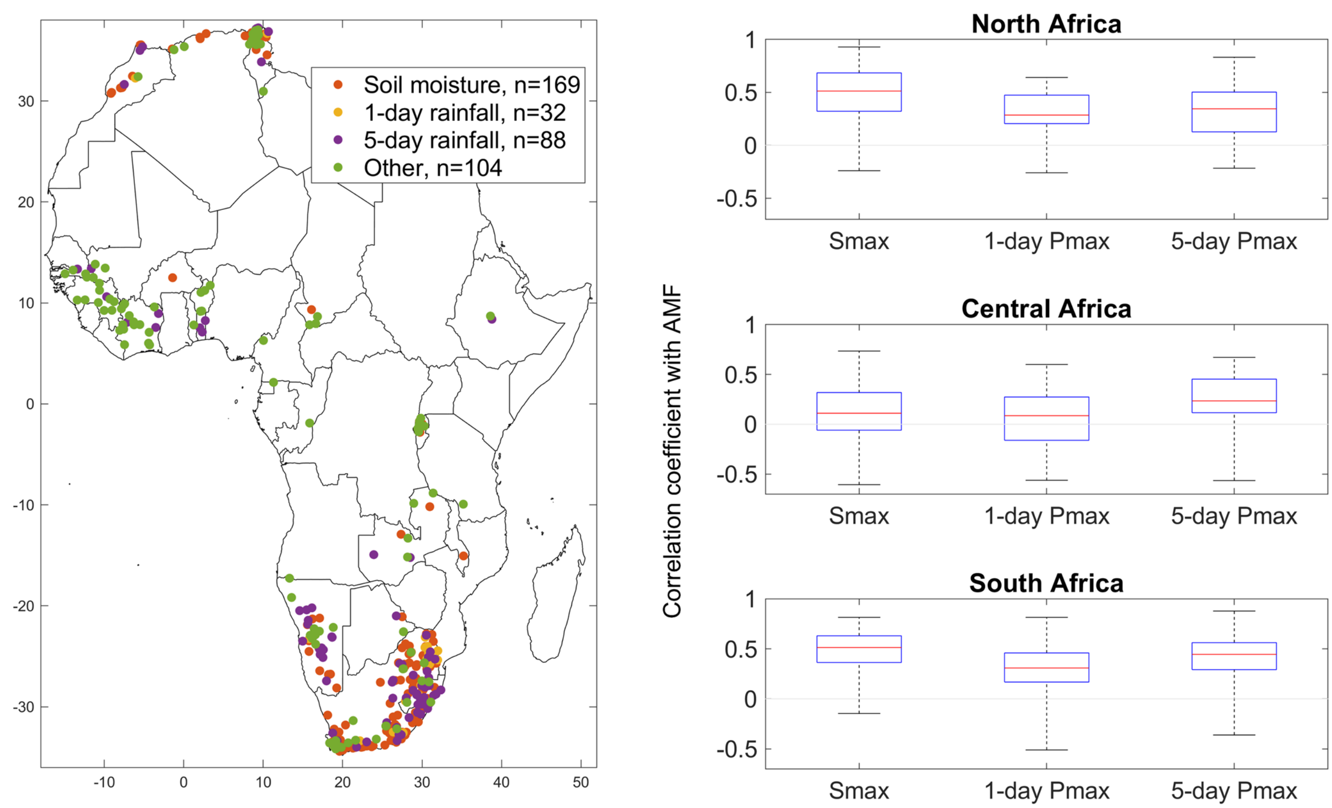

Figure 5. Main drivers associated with annual maximum flood (AMF): annual maximum soil moisture, 1-day and 5-day precipitation from CHIRPS. Stations belonging to North Africa are located north of 25°N, to Central Africa between 8°S and 25°N, and to South Africa south of 8°S. The left panel shows a map of Africa with the regional variability of the best driver identified for each station according to the correlation analysis. Stations labeled as "other" are those where no significant correlations are found. The box plots in the right panels show the strength of the Spearman correlation coefficient between annual maximum discharge and each of the three drivers. The limits of the box represent the 25th and 75 percentiles, the line in the middle refers to the median, and the limits of the whiskers represent the 5th and 95th percentiles.

that for about one third of stations (27%) no significant correlations are found with the drivers considered in the present study.

The median catchment size where 1-day annual maximum rainfall is the dominant process is slightly smaller, with a median size equal to 492 km^2, compared to 613 and 682 km^2 for 5-day rainfall or soil moisture, respectively. Conversely, the median basin altitude is greater, on average, in catchments where 1-day or 5-day rainfall is the dominant driver, compared to catchments where floods are mostly driven by soil moisture. This indicates that rainfall extremes are more strongly linked to flood occurrences in smaller catchments in mountainous areas. Even if the database does not contain basins strongly impacted by urbanization, it is likely that urban basins may react similarly to intense rainfall.

These rather low correlations between annual maximum rainfall and AMF indicate that the temporal changes in annual maximum precipitation alone are not a sufficient indicator for flood changes, as previously observed on other continents (Do et al., 2020a; Wasko & Nathan, 2019). We obtain stronger correlations with respect to soil moisture, which indicates that changes therein may strongly influence flood seasonality (Wasko et al., 2020a). These correlations between AMF and annual maximum soil moisture are significantly different from the correlations of AMF with annual maximum rainfall mostly in the Northern and Southern part of Africa, as shown by the results of the Meng et al. (1992) test (see Figure S3).

The results obtained are consistent with the current state of knowledge on flood processes in these regions. In North Africa, floods are caused by intense rainfall events that rarely last several consecutive days (Tramblay et al, 2013). As in many Mediterranean countries, the flood magnitudes are strongly influenced by antecedent soil moisture conditions (El Khalki et al., 2020), and this influence is gradually decreasing toward the southern regions with the increasing aridity. In South Africa, the largest floods are caused by conditions resulting from advection from the Indian and Atlantic Oceans over a period of approximately 3–5 days, and can result in rainfall totals above 150 mm during these events. Therefore, floods are resulting from a combination of short-term increases in soil moisture as well as high rainfall amounts over consecutive days (Kijazi & Reason, 2009; Manhique et al., 2015; Smithers et al., 2001; Wolski et al., 2014). As shown on Figure 5, there is a high variability of the flood generation processes in this area, as previously noted by Stein et al (2020). A possible explanation could be that, depending on the catchment type, antecedent soil moisture before the start of the rainfall event leading to flood is probably not that important; however, the soil moisture will rapidly increase during the first part of the event and, therefore, contributes to flood producing conditions later during the event, when the rainfall can also be quite high. In Central and West Africa, for some stations the 5-day annual maximum precipitation is related to the AMF (Nka et al, 2015), but for the majority of cases no significant correlations could be found. This further highlights the complexity of the runoff response in this region, influenced by land use changes as noted in the previous section.

5. Discussion

The African continent suffers from a lack of observed data in terms of precipitation, river discharge and more generally with regard to hydroclimatic data. Given that the present analysis is based on data from remote sensing merged with rain gauges (CHIRPS) or reanalysis (ERA5), one can wonder whether the fact that annual maximum precipitation is not identified as a major triggering factor for floods is linked to the lack of representativeness of these data. However, given that very similar conclusions are obtained with these two very different data sources for rainfall (see Figures S4–S6, showing the results obtained with ERA5 precipitation), it is likely that the known biases of these two products have little influence on our results. Although the analysis of seasonality is fully consistent between CHIRPS and ERA5, the results of the correlation analysis between floods, annual maximum rainfall and soil moisture time series reveals some differences between the two rainfall products (Figure S5). ERA5 can overestimate precipitation occurrence and underestimate extremes (Beck et al, 2020), while CHIRPS is sensitive to changes in the rain gauge station network over time, leading to time-varying systematic errors (Harrison et al., 2019). Additional issues are related to the use of gridded precipitation products with averaging effects resulting in the underestimation of extremes (Ensor & Robeson, 2008). Furthermore, the daily time step of the products may not be adequate to document flood generating processes in small arid and semi-arid basins, which are characterized by a strong spatiotemporal variability of rainfall. In these environments, flash flooding lasts few hours with relatively low runoff coefficients and the daily time step may not be adequate to capture flood dynamics (El Khalki et al., 2020).

Furthermore, our results showed that there was no distinct difference between regulated or unregulated basins. The small influence of the river regulation status was previously observed in the study on flood trends in Africa (Tramblay et al., 2020) or in research about hydrologic regime changes in the United States (Ficklin et al, 2018). This demonstrates that the sole indicator of the presence/absence of dams is not necessarily relevant to document a modification of the hydrological regime and disentangle the relationships between floods and their drivers. More details about the location within the watershed, the area controlled, their size, storage capacity and management rules are probably needed to characterize the level of regulation of a river. Moreover, it should be noted that beside the dams and reservoirs listed in the Grand Dam Database (Lehner et al., 2011), many small regulation structures may also exist. Even if agricultural productions are mostly rainfed and the irrigation coverage is very limited in most parts of Africa (Biswas, 1986; Burney et al, 2013), in several regions there are artisanal and informal irrigation practices (Drechsel et al, 2006; Woltering et al, 2011) that can have an impact on river runoff (Bouimouass et al, 2020). In these largely unmonitored systems, it remains a challenge to estimate the water uptake for irrigation. However, recent advances in remote sensing makes it possible to envisage an indirect estimate with the monitoring of soil moisture (Dari et al, 2020).

One of the main limitations of this study is related to the use of univariate methods, which is similar to previous studies at the continental or global scale on different datasets (Berghuijs et al., 2016, 2019; Wasko et al., 2020a). According to our results, the correlations obtained between annual floods and their potential triggering factors are relatively low, and for about a third of the basins no valid drivers could be identified. Beside the potential data issues, these low correlations may be due to the fact that we aimed at identifying only the best covariate for floods at each location. However, floods can be caused by a mix of different generating processes, and the drivers of larger floods can be quite different from those of smaller floods (e.g., Bertola et al, 2020; Smith et al, 2018; Tarasova et al, 2020). For instance, Bertola et al (2020) have shown that antecedent soil moisture is the main contributor to changes in moderate floods (i.e., the median of annual maxima), whereas for more extreme events it has an influence similar to extreme rainfall. This issue could be best addressed with a peaks-over-threshold sampling to extract flood samples of different intensities and a shift toward an event-based approach. Then, methods such as decisions trees (Stein et al., 2020) could be valuables tools to determine the best combination of drivers leading to floods in a given region. An additional uncertainty would be related to the fact that the largest events are rare, therefore limiting the sample size to produce robust statistical inference. There is also a need to isolate the processes not only linked to climate, but also to the temporal evolution of land use and catchment properties, which can play a significant role on flood generating processes as observed in Western Africa (Descroix et al, 2012).

6. Conclusions

This study provides a continental assessment of the main flood drivers in Africa. A large database of river discharge data combined with CHIRPS and ERA5 precipitation estimates and ERA5-Land soil moisture was used to compare the seasonality of floods with those of annual maximum rainfall and soil moisture. There is a strong seasonal cycle of floods in the different African regions: Floods occur mostly during late fall and winter in North and South Africa, and in the summer in Western and central Africa. This seasonal behavior is related to annual maximum rainfall and soil moisture patterns, but the seasonality of floods is more strongly related to soil moisture than to annual maximum rainfall. Indeed, the correlation between the mean day of occurrence of annual maximum flood is more strongly tied to annual maximum soil moisture than to 5-day or 1-day rainfall maxima. We can conclude from these results that the flood occurrence is more strongly related to the annual maximum soil moisture than annual maximum precipitation. Furthermore, the temporal variability in annual maximum precipitation alone is not a sufficient indicator of flood changes for most basins. However, we found that changes in the maximum soil moisture may modulate flood intensity in the majority of the cases, despite relatively low correlations with the annual maximum flood. Overall, annual maximum daily rainfall is only a weak predictor of annual floods, therefore inferring variability in flood risk from annual maximum rainfall alone would not be very relevant. It is worth mentioning that the links to flood seasonality and their drivers identified here are very similar to the results obtained in very different climatic zones, such as North America, Europe or Australia, indicating that antecedent soil moisture plays a key role globally across multiple regions. To conclude, it therefore appears important to consider the state of saturation of the soil in the approaches used for flood design (Cea & Fraga, 2018), but also to infer changes on flood risk based on their triggering drivers (Wasko et al, 2021).

Data Availability Statement

The annual maximum discharge data were obtained from the ADHI data set: https://doi.org/10.23708/LXGXQ9. The indices computed in the present work are made available upon request to the contact author. CHIRPS rainfall data was downloaded from: https://www.chc.ucsb.edu/data/chirps. ERA5 rainfall and ERA5-land soil moisture were retrieved from the Copernicus Climate Change Service Climate Data Store: https://climate.copernicus.eu/climate-data-store.

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