A new and flexible rainy season definition: Validation for the Greater Horn of Africa and application to rainfall trends

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Previous studies on observed or projected rainfall trends for the Greater Horn of Africa (GHA) generally focus on calendric 3-month periods, and thus partly neglect the complexity of rainfall seasonality in this topographically heterogeneous region. This study introduces a novel and flexible methodology to identify the rainfall seasonality, the onset, cessation and duration of the rainy seasons and the associated uncertainties from rainfall time series. The definition is applied to the Climate Hazards Group InfraRed Precipitation with Stations (CHIRPS) satellite product and an extensive rain gauge data set. A strong agreement with known seasonal dynamics in the region and the commonly used calendric rainy seasons is demonstrated. Compared to the latter definition, a clear added value is found for the new approach as it captures the local rainfall features (associated with, for example, the sea breeze), thus facilitating evaluations across rainfall seasonality borders. While previously known trends are qualitatively confirmed, trends are amplified in some regions using the flexible definition method. Notably, a drying trend in Tanzania and Democratic Republic of Congo and a wetting trend in central Sudan and parts of eastern Ethiopia and Kenya can be detected. The trends are regionally associated with changes in rainy season cessation. CHIRPS and station trend patterns are consistent over larger regions of the GHA, but differ in regions with known rainfall contributions from warmer cloud tops. Discrepancies are found in coastal and topographically complex areas, and regions with an unstable seasonality of rainfall. As expected, CHIRPS shows spatially more homogeneous trends compared to station data. The more precise definition of the rainy season facilitates the assessment of rainfall characteristics like intensity, rainfall amounts or temporal shifts of rainy seasons. This novel methodology could also provide a more adequate calibration of climate model simulations thus potentially enabling more realistic climate change projections for the GHA.

KEYWORDS
annual cycle, CHIRPS, climate classification, onset, precipitation, rain gauges, rainy seasons, trends

1 INTRODUCTION

The Greater Horn of Africa (GHA) is characterised by a large latitudinal extent, high orography, water bodies and extensive coastal lowlands which lead to a variety of climates and gradients in annual rainfall totals and the seasonal cycle. The latter is tightly associated with the seasonal dynamics of the tropical circulation which includes local factors (e.g., topography and lakes), regional circulation (e.g., the Turkana Jet) and remote forcings such as the...
Walker circulations and the Indian Ocean zonal mode (Nicholson, 2017). In the near-equatorial subregion, the complex interplay of these different factors leads to a mostly bimodal rainfall distribution, with rainy seasons in boreal spring and autumn (e.g., Nicholson, 1996). In the northern and southern parts of the GHA, both seasons merge into one in boreal summer and winter, respectively. Generally, full-month periods are used to define rainy seasons. For example, the rainfall amount and corresponding long-term trends of the spring (autumn) rains are estimated using MAM (OND) totals (e.g., Maidment et al., 2015). An overview of the rainy seasons on national scale, including their local names, can be found in Table 1. However, a calendric approach neglects regional differences in the rainy seasons and/or it is only valid on national scale. Thus, a flexible definition of rainy seasons would be desirable.

Various flexible rainfall onset criteria have been used to define rainy seasons in tropical monsoon regimes. Fitzpatrick et al. (2015) categorise several criteria for the West African monsoon area in regional and local definitions. Regional definitions focus on the seasonal variation of large-scale dynamics and changes in atmospheric parameters on supranational scales. The majority of such approaches use precipitation data sets, either from gauge measurements or satellite estimates, while others use outgoing long-wave radiation (Fontaine and Louvet, 2006), moist static energy (Vellinga et al., 2013) or a combination of mean sea level pressure and 850-hPa zonal wind data (Nguyen et al., 2011). In contrast, local onset definitions use precipitation data of single gauges or grid points without additional spatial information. Most of them are defined for specific local agronomic needs and use absolute thresholds which have to be reached or exceeded for a specific time period (e.g., Stern et al., 1982; Marteau et al., 2009; Yamada et al., 2013; Philippon et al., 2015). However, absolute thresholds need to be adapted for different regions and sources of rainfall data to account for biases. The variety of local climates in the GHA complicates the usage of such onset definitions not only due to the topography but also due to loose links to both the West African and the Indian Monsoon systems (Nicholson, 2017). Moreover, the region is too inhomogeneous to apply local onset definitions while diverse local atmospheric circulation systems also complicate the use of regional onset definitions.

One solution to overcome these shortcomings is to standardise the input data. Wang and LinHo (2002) developed an onset criterion based on local time series of precipitation while retaining suitability for large regions. In their approach, the difference between the pentad (i.e., 5 days) rainfall average and the average of the climatologically driest month in a specific year has to exceed 5 mm to mark the start of the rainy season. Vice versa, the rainy season ends when this difference falls below 5 mm. The threshold value was chosen to yield meaningful results for the monsoon region in East Asia. For West Africa, Sanogo et al. (2015) adapted the threshold to 2.4 mm in order to obtain results comparable to a local criterion. However, this onset criterion is optimised for monsoon regions with a single rainfall peak and less suitable for a bimodal rainfall distribution.

Another approach by Liebmann and Marengo (2001) developed for South America uses accumulated daily rainfall anomalies to determine the onset of the rainy seasons. The onset and retreat are defined as the date of maximum accumulated rainfall deficit and excess in relation to the climatological daily mean rainfall, respectively. Liebmann et al. (2012) applied this criterion on various gridded products for the African continent. Although this method was also originally defined for single-wet-season distributions, Dunning et al. (2016) successfully adapted it for dual-wet-season regions by smoothing and splitting the time series between the climatological rainy seasons. This application is straightforward and does not require fixed thresholds. However, it requires the a priori determination of how many rainfall seasons exist per year. Therefore it can only be used for past

| Country    | Rainy seasons | Local names          | Remarks                                      | Reference                                           |
|------------|---------------|----------------------|----------------------------------------------|----------------------------------------------------|
| Sudan      | Jun–Sep/Oct   |                      |                                               | Osman and Shamseldin (2002) and Salih et al. (2018) |
| South Sudan| Apr–Nov       |                      |                                               | Osman and Hastenrath (1969) and Osman and Shamseldin (2002) |
| Ethiopia   | MAM           | Belg                 | Relevance of the seasons varies regionally    | Segele and Lamb (2005)                             |
|            | JAS           | Kiremt               |                                               | Bekele-Biratu et al. (2018)                         |
| Somalia    | AM            | Gu                   |                                               | Herrmann and Mohr (2011)                           |
|            | JAS           | Karan                | Northern parts                               |                                                    |
|            | ON            | Deyr                 | southern parts                               |                                                    |
| Kenya      | MAM           | Long Rains           | Northern Uganda: unimodal                     | Phillips and McIntyre (2000)                        |
| Uganda     | OND           | Short Rains          |                                               | Camberlin and Philippon (2002)                      |
| Tanzania   | MAM           | Vuli                 | Northern parts: bimodal, southern and western parts: unimodal | Zorita and Tilya (2002)                             |
|            | OND           | Masika               |                                               | Camberlin and Philippon (2002)                      |
|            | Oct/Nov–Apr   | Msimu                |                                               |                                                    |
In order to extract a robust signal across space and rainfall onset parameters, Boyard-Micheau et al. (2013) proposed an agronomic approach based on principal components of multiple combinations of rainfall thresholds for Kenya. This approach requires an extensive calibration not only for the chosen time period but also for the region.

In the present study, a novel and flexible rainy season approach is introduced and applied to an extensive station data sample and a gridded rainfall product. This criterion does not depend on total rainfall or seasonality of the rains and is applicable in near-real time. This approach was motivated for applications in climate, but not in an agronomic context. Using this new definition, trends and variability of rainfall for the GHA are reassessed.

A summary and discussion follows in section 4.

2 | DATA AND METHODS

A challenging aspect for studies focusing on climate variability over the GHA is the lack of high-quality and high-density observational records. Satellite estimates partly improved the situation, but their algorithms often need ground-based rainfall measurements for calibration. Hirpa et al. (2010), Thiemig et al. (2012) and Cattani et al. (2016) provided evidence that satellite products which consider station data for calibration tend to outperform those products which do not. Data retrieval and interpolation may also lead to lower accuracy of rainfall estimates (Nikulin et al., 2012; Sylla et al., 2013). Finally, reanalysis precipitation estimates are found to be less suitable for studying rainfall variability in Africa (Poccard et al., 2000; Maidment et al., 2013; Salih et al., 2018). Below we list the data products and methodologies used in this study.

2.1 | KASSD precipitation observational database

The Karlsruhe African Surface Station Database (KASSD; Vogel et al., 2018) offers a collection of long-term, in situ observations for the whole African continent on daily and monthly temporal resolution from various sources. For this study, we used daily rainfall observations from 110 stations in the countries Ethiopia, Kenya, Rwanda, South Sudan, Sudan, Tanzania and Uganda for the time period 1983–2013 with a temporal data coverage of at least 75%. Elementary quality checks have been manually performed on the data sets. Several criteria were used to detect outliers: exceeded world record values, values with deviations of more than 200 mm to the daily rainfall distribution and values beyond nine times the 99th percentile were removed. The locations of the stations are displayed in Figure 1. A detailed list of the stations can be found in the supplementary material Table S1 [Colour figure can be viewed at wileyonlinelibrary.com].

FIGURE 1 Area of investigation. Available KASSD stations are marked by purple dots. The red stars and numbers indicate three exemplary stations (see section 2.4). The inset shows the geographic location of the area on the African continent. A complete list of the stations can be found in the supplementary material Table S1 [Colour figure can be viewed at wileyonlinelibrary.com]
and Atmospheric Administration (NOAA) Climate Forecast System, version 2 (CFSv2; Saha et al., 2010). The infrared precipitation estimates are standardised with their long-term means (1981–2012).

In the second step, the product of the infrared estimates and CHPCLim is bias-corrected using daily gauge observations. The incorporation of station data can improve the rainfall estimates in complex topographic regions, as the estimation of orographic rainfall is a substantial challenge for many satellite products (Diem et al., 2014a). Orographic rainfall often consists of so-called “warm rain,” which means that the rain clouds do not build an iced cloud top. These clouds are not sufficiently captured by infrared sensors, which leads to underestimations of rainfall in high-altitude areas (Dinku et al., 2007). Toté et al. (2015) and Kimani et al. (2017) indicate that the station correction procedure in CHIRPS generally improves the overall rainfall estimate. CHIRPS shows a better estimation for annual rainfall totals and higher spatial differentiation of rainfall (Toté et al., 2015). Kimani et al. (2017) demonstrated that CHIRPS performs better than other products in regions with multiple rainfall types. Both studies detected a positive bias of CHIRPS in low rainfall events and rainy days. Still, this approach can also lead to potential accuracy problems depending on the amount of available measurement sites. In fact, the blending procedure does not intend to tune the rainfall amount at the grid point towards the observations or to reproduce the point observations exactly. Instead, the station data is an additional weighting factor, which contributes to the correction of CHPclim at a particular grid point for a specific time period.

2.3 Definition of the rainy season

The onset criterion of the rainy season used herein is based on the criterion proposed by Wang and LinHo (2002) for the monsoon region of Asia. They used pentad precipitation averages of daily rainfall, which were standardised by the daily rainfall average of the driest month. In order to reduce the time series to the seasonal cycle, they truncated a Fourier series and kept only the first 12 Fourier harmonics for every single year. Finally, based on the inter-comparison of different monsoon climates, they defined a universal threshold intensity of 5 mm/day for the monsoon onset. The start of the monsoon season in Asia is defined as the first pentad when the standardised rainfall pentad average exceeds the threshold. Vice versa, the monsoon season ends when the standardised pentad average falls below this threshold. The method can be considered as a local onset definition since only the rainfall at the specific grid point is used. However, due to the standardisation, the method can still be utilised on a supranational scale, thus enabling a comparison of rainy season characteristics.

For this study, we implemented several modifications to the onset criterion of Wang and LinHo (2002). The Fourier truncation was replaced by a low-pass Lanczos filter (Duchon, 1979). Given that the magnitude of the 5-day rainfall rate differs tremendously between the local rainfall climate zones, it was a challenge to define an objective rainfall threshold, which is valid for every location in the region. While the threshold of Sanogo et al. (2015) of 2.4 mm/day for West Africa is valid for the humid rainfall zones in the GHA, a lower (higher) threshold needs to be determined for drier (wetter) regions. Our method defines individual thresholds for each location.

The general method consists of three steps (Figure 2). First, we applied a Lanczos low-pass filter with a cut-off period of six pentads (i.e., 30 days) to pentad averages of rainfall of every hydrological year of the station/grid point time series. The hydrological year needs to start in the dry season to bypass a splitting of continuous rainy seasons. A previous standardisation by the monthly average of the climatologically driest month (as in Wang and LinHo, 2002) is not necessary.

In the second step, we defined a climatological seasonality of the rains for the station/grid point by computing the multi-year averages. These are used to define a threshold from which onset and cessation dates and, thus, the climatological number of rainy seasons are determined. The rainfall onset and retreat can be regarded as a point of inhomogeneity in the climatological time series. To identify this point in the rainfall climatology, we used the homogeneity test of Alexandersson (1986), which results in one or multiple potential inhomogeneity points. Khaliq and Ouarda (2007) presented critical values for the test depending on different sample sizes that are used here as reference. Several cases had to be taken care of. If the test returns one critical inhomogeneity point, the rainfall value of this point is used as threshold. If the test returns multiple critical points, the lowest rainfall value is chosen. If none of the potential inhomogeneity points is critical, the nearest point to the critical value is used. A rainy season is defined as the period of at least five consecutive pentads which exceed the rainfall threshold. As mentioned above, the rainy season “regime” is thus the number of rainy seasons during one hydrological year. The onset and cessation of the rainy season are defined as the first and last pentad which exceed the rainfall threshold, respectively. Contrary to the widespread notion of uni-, bi- or trimodality of rainfall, we have opted to use the terms single-, dual- or triple-wet-season regimes following the terminology of Herrmann and Mohr (2011). As a consequence, a single-wet-season may be bi-modal, for example, it contains two distinct rainfall peaks. In order to estimate the uncertainty of the threshold, we also determined the 5th and the 95th percentile values to set a confidence interval (grey box in Figure 2) at the point of inhomogeneity with a bootstrapping approach. The spread between the 5th and the 95th percentile bounds of the threshold enables an estimation of the variability and/or uncertainty of the rainy season.
characteristics, like regime, onset, cessation and length. If the number of rainy seasons stays constant when using any of the threshold values, the regime can be considered as stable in the long term. Otherwise, the number of rainy seasons can vary depending on which threshold level is used. In such cases, the rainy season regime at the location cannot be determined unequivocally. This situation occurs when two rainy seasons repeatedly merge during wet years or one season fails during dry years. The confidence intervals of the onset and cessation of the rainy season are determined by applying the upper and lower threshold values to the climatology (orange hatching in Figure 2).

In the third step, we used the climatological threshold to determine the rainfall onset and cessation in single years. With this aim, we applied the climatological threshold and its confidence intervals to the Lanczos-filtered pentad time series of the hydrological year of interest. All consecutive rainy pentads, which exceed the threshold, are grouped into blocks. Analogous to step one, the rainy seasons can be set as the first pentad of the first rainfall block, which overlaps with the climatological rainy season. The cessation is set as the last pentad of the last rainfall block, which overlaps with the climatological rainy season. The uncertainty of the rainy season regime and time periods for the particular hydrological year can be determined analogously by applying the 5th and the 95th percentile bounds and the corresponding confidence intervals to the filtered time series.

The methodology is the same for every station and grid point. The number of rainy seasons is determined by the threshold in step two and is not assumed a priori. Isolated rainfall events or light rain from warm clouds, which are typical at the beginning or end of the season, can lead to higher uncertainties of the estimation of the rainy seasons. In such cases, the rain rates may lie between the lower and upper thresholds, leading to an uncertainty in the estimation of the rainfall onset pentad.

2.4 | Representative examples

The performance of the rainy season criterion is visualised on three exemplary stations with distinct rainfall regimes. The first two examples correspond to the typical single-wet-season and dual-wet-season rainfall climatology, respectively.
The third example is a station with an unstable rainfall regime.

**Example 1: Wad Medani, Sudan**

The first example rainfall site is Wad Medani, which is located at the Blue Nile in central-eastern Sudan (Figure 1), a region with a stable single-wet-season regime (Figure 3a). The hydrological year starts here in January, which is the driest month. The seasonal rainfall is expected during boreal summer. According to climatology, the onset of the main season can be generally expected by the end of June. However, the station sometimes experiences a weak rainfall peak already in May that may extend the rainy season. Large uncertainties may cause false onsets in agronomic definitions. The atmospheric mechanisms behind this early rainfall surge are not obvious. Still, such rain events occur at several stations in the area, thus a regional atmospheric cause can be assumed (Figure S3a).

Two representative hydrological years reveal the variability of the rainfall onset in Wad Medani. In 1991, no rainfall was measured in May or June (Figure 3b) and the rainy season onset can be sharply determined in the second pentad of July. The cessation of the rainy season in 1991 is estimated for the end of September although some weak rainfall below the rainfall thresholds occurs afterwards. In contrast, an early onset of the rainy season is detected in the year 2002 at the end of May (Figure 3c). The first wet period ends in mid-June and is followed by three dry pentads, until the main segment of the rainy season starts at the beginning of July. In the year 2002, the rainfall amounts in June are comparable to those of the main rainy season, thus these two rainfall periods cannot be strictly separated. Consequently, two onset dates are estimated: one at the end of May and one at the beginning of July. The interannual variability of these early rains leads to a high uncertainty in the rainfall onset estimation for this station.

**FIGURE 3** Climatology and two exemplary hydrological years for the measurement site Wad Medani, Sudan (33.5°E, 14.4°N, no. 1 in Figure 1). (a) Rainfall climatology in pentads. Hydrological years (b) 1991 and (c) 2002. Time resolution on the x-axes is pentads. The rainfall threshold, which determines the rainy season, is marked by the bold horizontal black line. The grey box denotes the confidence interval of the rainfall threshold. Orange boxes show the climatological rainy seasons including the confidence intervals (dashed orange boxes). Dashed grey lines in (a) show the 5% and 95% confidence intervals in the climatology. The onsets and cessations of the rainy season in (b, c) are marked by solid red and green vertical lines, respectively. The uncertainty of the onset (red) and withdrawal (green) are indicated by dashed vertical lines. For more details see text [Colour figure can be viewed at wileyonlinelibrary.com]
Example 2: Mombasa, Kenya

The second example is Mombasa which is located at the coast in southern Kenya (Figure 1). The driest month here is February, and the rainfall regime is dual-wet-season (Figure 4a). The regime can be considered as stable, since the rainfall during the dry season falls below all three thresholds. The rainy seasons correspond to the “Long Rains” with a first rainfall peak during April/May and the “Short Rains” with a second weaker peak during October/November. However, the confidence intervals of both rainy season cessations are large due to the strong sea breeze (Camberlin and Plan- chon, 1997), which can (in case of the “Long Rains”) extend the rainy season into boreal summer for up to a month.

The exemplary hydrological year 1999/2000 (Figure 4b) demonstrates the effect of the sea breeze in combination with a dual-wet-season regime. The confidence intervals of the rainfall threshold separate each rainy season into a period of high rainfall (periods between red and first green dashed vertical lines) and a period with light rainfall events (periods between first and second dashed green lines). The former could correspond to a rainy season phase dominated by the Intertropical Convergence Zone (ITCZ), whereas the latter could be attributed to the sea breeze related convection.

Example 3: Musoma, Tanzania

The last example is Musoma, which is located at the shore of Lake Victoria in northern Tanzania (Figure 1), a humid region with an unstable rainfall regime. The rainfall climatology shows two seasonal rainfall peaks with a modest break (Figure 5a). The driest month is July. The onset of the first rainy season is at the beginning of October and the rainfall maximum is usually reached around the beginning of November. The second rainy season starts at the beginning of February with a light rainfall peak. In April, the season reaches the main peak whereas it ends in the end of May. During the break in January, the rainfall rate in the climatology does not fall below the fifth percentile threshold, and thus depending on the threshold, the station regime can be classified as bimodal single-wet-season or dual-wet-season. The region has been classified by Herrmann and Mohr (2011) and Dunning et al. (2016) as a transition region between single-wet-season or dual-wet-season regimes.

The fluctuations of the regime are demonstrated by two exemplary hydrological years. In the hydrological year 1986/1987 (Figure 5b), two distinct rainy seasons can be identified. The first rainy season starts during the end of October and lasts until the end of December. This season is followed by a break, which lasts until the beginning of February, when the second rainy season begins. The cessation of the second rainy season is at the beginning of June, which is considerably later than the climatology. In contrast, the hydrological year 2004/2005 (Figure 5c) is characterised by multiple peaks and breaks. A late onset of the first rainy season at the end of October and a cessation of the second rainy season at the end of May can be identified. A separation of the two seasons is ambiguous due to a persistent rainfall period which occurs during the climatological break in January. The period can be attributed to both rainy seasons. The usage of the fifth percentile threshold leads to a single rainy season. By applying the climatological threshold, the period in January is added to the second season due to the overlap with its climatological occurrence. The 95th
percentile threshold sets the onset of the second season to the beginning of March.

The above results provide evidence that the methodology permits a flexible and meaningful determination of the onset, cessation and duration of the rainy seasons for the study areas. The confidence intervals can be used for detection of critical periods with “false” onsets (5th percentile) or selection of core periods (95th percentile). Thus, the method is applied to the complete station database and gridded product in the next section.

3 | RESULTS

3.1 | Climatological rainfall regimes

The seasonal regime of rainfall in the GHA depends on modulations of the tropical circulation by the local orography and water bodies. In the first step, the region is classified according to the number of rainy seasons (Figure 6). The region can be subdivided into two large areas with single-wet-season rainfall regimes (yellow), two areas with dual-wet-season rainfall regimes (blue) and two small and spatially incoherent areas with a triple-wet-season regime in the Kenyan Highlands and near the coast of Eritrea and Sudan (orange). The triple-wet-season regime will only be briefly discussed in this study. The two large single-wet-season rainfall areas cover the southern part of the region which includes most parts of Tanzania, Rwanda, and Burundi, and the northern part, which includes Sudan, South Sudan, western Ethiopia, and northern Uganda. The smaller subregion with a dual-wet-season regime includes a strip in Democratic Republic (DR) of the Congo, southern parts of Uganda and the Kenyan shore of Lake Victoria. The large dual-wet-season subregion includes most of Kenya, Somalia, southern and northeastern Ethiopia, Djibouti and southern Eritrea. At the border between different rainfall regimes, the areas are classified as unstable in the long term, that is, the rainfall regime in these areas varies and/or cannot always be clearly categorised as single-wet-season or dual-wet-season. Triple-wet-season rainfall regimes are always unstable and can be seen as a special case of unstable regime. A single-wet-season regime can still show multimodal characteristics and contain multiple peaks and minima. This case occurs in parts of, for example, the DR Congo or Tanzania and is
confirmed by different peak months during the passages of the north–south meandering tropical rain belt (Figure S2).

The regimes of the coastal areas of Somalia, Kenya and northern Tanzania are also classified as unstable. This region can vary between single-wet-season and dual-wet-season regimes due to the strong sea breeze effect (cf., Example 2 in section 2.4). In the desert area of northwestern Sudan, the categorisation is less reliable (Figure S1). In some regions, the comparison of station and grid point modalities reveals different classifications. These regions are classified as unstable in both grid point and station data. However, CHIRPS tends to overestimate the single-wet-season regimes and to underestimate dual-wet-season regimes. This tendency is obvious at the coast of Kenya and northern Tanzania and in the Ethiopian Highlands. In all cases, several station distributions are classified as dual-wet-season although the stations are located within CHIRPS grid points with single-wet-season regimes.

### 3.2 Comparison of rainy season definitions

The following section discusses the seasonal migration of the climatological rainy season onset and cessation estimates as determined in Step 2 of our method compared to calendric rainy season definitions. Depending on the subregion and season, various calendric definitions are used in studies on rainfall variability. For the northern single-wet-season part of the GHA, studies generally suggest that the main rainy season occurs during the boreal summer (June–July–August–September [JJAS], e.g., Camberlin, 1995). A more detailed overview on regional rainy season definitions is given in Table 1. Figure 7a–c shows the respective onset, cessation and seasonal length obtained using the climatological threshold of the northern areas with a single-wet-season regime. The subregion shows a smooth and mostly zonal progression of the season in northwards direction that can be mainly attributed to the circulation associated with the seasonally migrating rain belt. Overall, the results derived from CHIRPS and station data agree well in the estimation of the seasonal rainfall characteristics.

The onset and cessation dates as well as rainy season length are compared with the calendric definition in Figure 7d–f. Figure 7d shows that the onset of the rainy season can partly be expected in March for northern DR Congo and Uganda, and southern parts of South Sudan and Ethiopia. Farther north, in southern Sudan and western Ethiopia, the onset can be expected in April and May. The calendric onset date of June 1st is met around 12°N in the area of central Sudan and northern Ethiopia (Figure 7d). At the beginning of September, the cessation starts around 15°N in northern Sudan, and reaches northern Uganda and DR Congo at the beginning of November (Figure 7b). In general, the assumption of the rainy season period as JJAS is valid only for Sudan (Figure 7f). For the single-wet-season areas farther south, large parts of the climatological rainy season are underestimated.

Figure 8 compares the rainy season definition and its uncertainties between station data and the nearest CHIRPS grid point. In most cases, the rainy season of the station matches the season of the grid point or deviates by few pentads (see also Figure S3a,d). In central-eastern Sudan, the station rainy season length is slightly prolonged compared to the CHIRPS estimation (Figure 7c, stations no. 9, 12, 13). Other discrepancies between stations and grid points can be located at near-equatorial latitudes where the rainfall regime is unstable (stations no. 58, 60, 67, 68). Several station regimes in the Kenyan and Ethiopian Highlands are characterised as single-wet-season, but the satellite estimations show different regimes. However, both estimations consistently show unstable rainfall regimes for these stations.

For the southern single-wet-season regimes, the climatological rainy season parameters are shown in Figure 9. Northern Tanzania is considered to experience two rainy seasons in MAM and OND (Camberlin and Philippon, 2002; Zorita and Tilya, 2002; Mapande and Reason, 2005). In the rest of the country, the calendric rainy season is assumed to occur from October to April (Zorita and Tilya, 2002; Mapande and Reason, 2005), which is considerably
FIGURE 7  Progression of (a) the rainy season onset (days since January 1st), (b) the rainy season cessation (days since January 1st) and (c) the duration (days) of the rainy season for the northern region with a single-wet-season regime estimated from CHIRPS (contours) and station data (circles). (d–f) Difference of (a–c) with calendric definition of rainy season onset (d, i.e., June 1st), cessation (e, i.e., September 30th) and duration (f, i.e., 122 days) [Colour figure can be viewed at wileyonlinelibrary.com]
longer than in the northern part of the region. The progression of the onset and cessation reflects topographic conditions through an additional meridional component of propagation. The onset starts in DR Congo at the end of August and at the coast at the end of October. It progresses towards central and southern Tanzania until mid-November from both directions (Figure 9a). The cessation of the rainy season in the region starts in the middle of March in the south–west and progresses towards north and east until the middle of May (Figure 9b). The estimation of the rainy season from station data mostly agrees with the estimation from CHIRPS (Figures 9 and 10). Slight differences in the cessation dates are found for some stations due to orographic rainfall (e.g., Kilombero region, Tanzania, 8.25°S, 36.33°E, Figures 9b and 10, stations no. 106, 107) triggered through predominant southeasterly winds in May. In general, the flexible rainy season definition coincides with the calendric rainy season in most parts of the region. Some of the near-equatorial stations also show bimodal characteristics, which are partly captured by CHIRPS (stations no. 75, 85, 87, 88). The difference in season length of the southern part compared to the northern part arises from the topography and the lower polewards extent.

For the area with dual-wet-season regimes, the rainy seasons are commonly known as “Long Rains” (MAM) and “Short Rains” (OND; e.g., Nicholson, 1996; cf., Table 1). The MAM estimation for the Long Rains is valid for the lowland areas of Kenya, most of Somalia and eastern Ethiopia (Figure 11). The onset progresses from the Highlands towards the Horn of Africa (Figure 11a). For the Kenyan Highlands and southern Uganda, the Long Rains start in

**FIGURE 8** Comparison of rainy seasons at stations and satellite grid points for the northern region with a single-wet-season regime. Numbers of the stations are listed on the left side. Coordinates of the grid points are listed on the right side. Station rainy seasons are shown as horizontal black lines, with circles marking the onset and cessation of the rainy seasons. The uncertainty (5th and 95th percentile confidence interval bounds) is shown as thinner black lines below and above the average rainy season. The average grid point rainy season and its confidence interval bounds are shown as yellow, magenta and green bars, respectively. A complete list of the stations can be found in Table S1 [Colour figure can be viewed at wileyonlinelibrary.com]
February. The cessation starts in the Lowlands of Kenya and in northeastern Ethiopia (Figure 11b). A later cessation of the Long Rains occurs at the Kenyan coast and at a strip at the northwestern edge of the Kenyan Highlands. These features lead to a prolonged season compared to the calendric definition (Figure 11c,f).
The onset of the second rainy season progresses from northwest towards the Kenyan Lowlands and Somalia (Figure 12a). The cessation starts near the Horn of Africa and ends in the near-equatorial Highlands (Figure 12b). In northeastern Ethiopia, the season starts in July and ends in September, which corresponds well to the Kiremt (cf., Table 1, Segele and Lamb, 2005). Compared to the commonly used OND definition, Uganda also experiences an earlier onset in July/August. The cessation in Uganda lies mostly in December (Figure 12b), thus the overall season is longer than 3 months (Figure 12f). The OND definition is valid for lower parts of Kenya. For higher elevated areas, the cessation lies in January, and thus is slightly later than in the OND definition (Figure 12b,e).

The direct comparison between the station and grid point estimations for the subregion shows consistent results for both, the station and the gridded product (Figure 13). A more detailed view on the uncertainties reveals that the CHIRPS estimation coincides with the station rainy season, when the season is well pronounced and the 95th percentile threshold is reached. Weakly pronounced rainy seasons or parts are often underestimated (as in case of the sea breeze, stations no. 86, 90, 94, 95). In case of modest or short breaks between two rainy seasons, CHIRPS tends to overestimate rainfall during the break, thus only one merged rainy season is estimated (e.g., Nairobi area, stations no. 77–80). This tendency can also be confirmed by the triple-wet-season stations (Figure S4). Consequently, the border between the two main regimes is set to a different location in the CHIRPS estimation than in the station estimation. In Uganda and the Kenyan Highlands, the Short Rains can be equal to the Long Rains or even longer. Nonetheless, the Short Rains are usually associated with lower rainfall rates as compared to the Long Rains.

### 3.3 Rainfall trends for flexible rainy season definition

The flexible rainy season definition can be applied to determine long-term trends of seasonal rainfall metrics (e.g., onset,
cessation, rainfall amount). The adapted rainy season definition can lead to different trends in rainfall amount compared to those obtained by using the calendric rainfall onset and cessation (i.e., MAM, OND). In case of the rainfall amount, two adjustment steps can be performed. The seasonal rainfall amount can be determined for the climatological rainy season.
(resulting from step 2, section 2.3, Figure 2) or for each individual rainy season in every hydrological year (resulting from step 3, section 2.3, Figure 2). However, the latter option can lead to complicated assignments in regions with unstable regimes and without a unequivocal distinction between the rainy seasons. Therefore, the trends of the rainfall amount are
calculated using the nonparametric Mann–Kendall test and the Sen’s slope estimator (Hirsch et al., 1982) for the adjusted climatological rainy season from step 2 and for the calendric definition. In general, the spatial pattern of trends from station data agrees with the results from the gridded satellite product (Figures 14 and 15). Areas with single-wet-season regimes show a significant positive trend in central Sudan, western Ethiopia and northeastern Uganda (Figure 14a). The trend for Tanzania and single-wet-seasonal areas of DR Congo is predominately negative and significant in DR Congo and southeastern Tanzania (Figure 14d). However, the trend sign over Ethiopia, eastern Uganda and western Tanzania is not coherent and some nearby stations reveal opposed trend signs (Figure 14a,d).

For the Long Rains, the weak trend is coherently negative for the Kenyan Lowlands and Ethiopia (Figure 15a) with only few significant station or grid point trends. The highest and significant trend magnitudes are estimated for the coastal region. The Kenyan Highlands and most stations in Uganda show a wetting trend. For Uganda, the satellite estimation does not underline this wetting trend. The Short Rains reveal a significant wetting trend for large parts of Ethiopia and Somalia (Figure 15d). Stations in these countries and in northern and coastal Kenya agree in the sign of the trend, but the trends are generally not significant. The coastal stations in northern Tanzania and parts of south-central Kenya point towards drier conditions. The drying is coherent with the trends in most parts of Tanzania (compare with Figure 14d). The trend from the flexible rainy season definition also agrees with the estimation from the calendric definition in terms of sign (Figures 14 and 15b,e), but reveals an amplified trend magnitude (Figure 14c,f). The largest differences occur in regions which have a longer rainy season compared to the calendric definition. In case of
the region with dual-wet-season regimes (Figure 15c), there is a general consensus between the calendric and the flexible trend estimation for the Long Rains. The Short Rains reveal different trend estimates in northeastern Ethiopia, the Kenyan Highlands and parts of Uganda due to a different timing of the second rainy season (Figure 15e,f).

In general, the overall trend pattern of the flexible rainy season definition matches the trend pattern of the calendric method. Some regions disagree in trend patterns, like the northeastern part of Ethiopia for the Short Rains and the Kenyan coast whose calendric definition needs to be adapted. The second rainy season in northeastern Ethiopia usually occurs from July to September rather than in OND, thus the definition of Kenyan Short Rains does not fit here. In any case, the trend signal is more pronounced when applying the flexible rainy season criterion.

3.4 Trends of rainy season onset and cessation dates

One important advantage of a flexible rainy season definition is to determine the onset and cessation of a particular rainy season irrespective of a strict climatological definition in order to quantify its interannual variability and trends. These results extend the analysis on trends in the GHA with additional metrics that describe the rainy season in more detail. For convention, a negative sign indicates a trend towards an earlier onset/cessation and vice versa.

Figure 16 displays scores that indicate the significance of the trends of onset and cessation dates for the four main rainy seasons. The trend magnitudes can be obtained from Figure S5. For example, the highest score is obtained when the trend is significant at 5% level for all three thresholds. Other combinations leading to lower scores are explained in Table 2. The scores can be regarded as a measure of sensitivity of the trends to the threshold level. The trend for the rainy season onset of the northern single-wet-season region (Figure 16a) is predominantly not significant. In the northernmost parts of the region, the area is dry and the number of years with a detectable onset is reduced (cf., Figure S6a, b). In general, the results for stations are coherent with those for grid points. However, several stations in Sudan (stations no. 8, 16, 22, 24) and Ethiopia (stations no. 20, 34, 38, 42, 43) show insignificant delaying trends in the onset that are not depicted in CHIRPS. The trend for the cessation of the rainy season (Figure 16b) reveals a negative sign in northern DR Congo, although no station observations are available to support this sign. A strong and robust positive trend region is located near the border between Sudan, South Sudan and Ethiopia, which is also found at several stations in the area (e.g., stations no. 22, 24). The trend pattern of the onset and cessation for the northern subregion expands the results from Figure 14a–c, where a negative trend in the DR Congo and a positive trend in the rainfall amount in central Sudan has been shown. Still, the region with the positive trend in cessation is located south of the region with the increase in rainfall amount during the climatological rainy season. As for the onset, several stations in Ethiopia also show a negative trend in cessation, which is not confirmed by the grid point product. In the areas with a trend towards a delayed cessation, the climatological rainy season ends at the end of October or beginning of November. For the area with trends towards an earlier cessation in DR Congo, a climatological cessation at the beginning of December is estimated (Figure 7b).

The southern area with single-wet-season regimes reveals a trend towards a later rainy season onset and earlier cessation in parts of central and southern Tanzania. The signal for the later rainy season onset (Figure 16c) mostly prevails in the southern part of the country and is predominately not significant. Two stations in this region agree on the negative trend (one of which is significant at the 5% level, stations no. 106, 107). The signal towards the earlier rainy season cessation (Figure 16d) focuses on two strips through the central and coastal parts of Tanzania. This trend is emphasized by several stations in the region in both, sign and partly significance level. In the context of Figure 14d–f, the region can be divided into an area with a tendency towards a weaker rainy season with less rainfall in the south of Tanzania, and an area with a shorter rainy season without much rainfall decrease in central Tanzania. The climatological cessation in the areas with the latter trends is estimated for mid-April (Figure 9b).

The pattern for the Long Rains can be described as weak and patchy, with only few local trends in onset and cessation. The onset based on CHIRPS outlines weak tendencies towards an earlier onset in the mountainous region of western Kenya and Uganda (Figure 16e). Conversely, the onset in northern Kenya, Somalia and Ethiopia tends to occur slightly later. The northeast of Ethiopia is exceptional here, featuring both a trend towards a later onset and a trend towards an earlier cessation (Figure 16f). Generally, the trends for the cessation of the Long Rains show a more coherent and stronger pattern than for the onset. Here, the Kenyan coast, the northeast of Ethiopia and, with a weaker magnitude, the northeast of Kenya reveal trends towards an earlier cessation. The trends for grid points are more coherent in sign than those for stations, which often show no

**FIGURE 14** Rainfall trends (mm/10 years) based on (a) the flexible rainy season definition and (b) the calendric rainy season definition for the northern single-wet-season regime estimated from CHIRPS (colours) and station data (coloured circles). Grid points and stations with significant trends at 5% level are indicated by black squares and dots, respectively. (c) Difference (a, b) in trends (colours) and significance (squares, dots) between the rainy season definitions. (d–f) Same as (a–c) but for the southern single-wet-season regime. Note that the label bar in (c, f) differs from those in (a, b, d, e) [Colour figure can be viewed at wileyonlinelibrary.com]
significant or opposing trends. The Kenyan Highlands and parts of Uganda show weak and incoherent trends towards a prolonged rainy season. The region with negative trends at the Kenyan coast and the southern country parts lie adjacent to the regions with the earlier cessation in Tanzania. The patterns also mirror the trends in rainfall sum (Figure 15a–c), as

**FIGURE 15** Same as Figure 14, but for the Long and Short Rains in the dual-wet-season regimes [Colour figure can be viewed at wileyonlinelibrary.com]
only few stations reveal significant trends in onset and cessation.

The pattern of the Short Rains onset is dominated by a robust trend towards an earlier onset in northern Kenya, southern Ethiopia and Somalia (Figure 16g). Three stations in the region emphasize this trend (two being significant, stations no. 48, 51). The trend of the cessation does not show a uniform pattern for the region (Figure 16h). The results from CHIRPS show a trend towards an earlier cessation, while the trends from stations only partly confirm this tendency. The Horn of Africa and eastern Ethiopia show a strong and robustly significant trend towards a later cessation of the rainy season. Gode (station no. 44), as the only available station in eastern Ethiopia, fits in this pattern and shows a significant trend of more than 2.5 pentads per decade (Figure S5h). Although the percentage of detectable OND seasons is decreased at the Horn of Africa (Figure S6), the patterns coincide with the trends in rainfall sum, which were discussed in Figure 15d–f. The climatological onset and cessation of both regions with significant trends is estimated for the end of October or beginning of November, respectively (Figure 12a,b).

**TABLE 2** Scoring rules for Figure 16

| Sum of uniform trend signs | Sum of significant trends at 5% level | Score |
|---------------------------|--------------------------------------|-------|
| 0                         | 0                                    | 0     |
| 2                         | 0                                    | ++/-  |
| 2                         | 1                                    | 1× significant |
| 2                         | 2                                    | 2× significant |
| 3                         | 3                                    | 3× significant |
4 | CONCLUSIONS AND DISCUSSION

A novel method to determine the onset and cessation of rainy seasons across a wide range of GHA’s climates has been developed, tested, and discussed for representative examples. It neither requires a priori assumptions on the number of the rainy seasons nor on suitable thresholds, and enables to estimate the stability of rainfall modes and uncertainties in onset and cessation dates in the GHA. The method was applied to estimate the seasonality and trends based on CHIRPS and station data for the period 1983–2013. The following main conclusions can be drawn:

1. The application of the method to three exemplary stations demonstrates the meaningfulness of the methodology for different rainfall regimes in spite of some peculiarities due to local effects. Unlike many previous methods, our approach can also estimate the uncertainty in the onset date, cessation date and duration of the rainy seasons.

2. The classification of seasonal regime (number of rainy seasons) for the GHA is in good agreement with previous results. The areas with low stability of rainfall seasons correspond to regions characterised by known disagreements in terms of rainfall regimes between different data sets and studies. Patterns of onset and cessation dates estimated by the new method are consistent with known regional characteristics of rainfall in the GHA, including, for example, the effects of coastlines and mountains.

3. The comparison of the adjusted climatology of rainy season onset and cessation to the traditional calendric definition (e.g., MAM and OND) reveals that the latter is only valid for a limited latitudinal and altitude range. Deviations can reach up to several months. Thus, the results provide evidence that the calendric definitions cannot always be assumed to be valid on supranational scale without appropriate adjustments.

4. The trends based on the adjusted and calendric rainy seasons do not differ in pattern, but the former possess a higher magnitude. Significant trends could be identified for the following regions: Central Sudan tends towards a wetter rainy season of constant length. In contrast, the southern part of Sudan reveals a trend towards a prolonged rainy season without significant changes in the rainfall sum. Tanzania can be divided into a southern area with a tendency towards a drier rainy season and less rainfall and a central area with a shorter rainy season. For the Long Rains, a trend towards a shorter rainy season with less rainfall can be observed in the eastern parts of the GHA. The Kenyan coast shows a consistent drying trend. For the Short Rains, a wetting trend is estimated for northern Kenya, eastern Ethiopia and Somalia.

5. Irrespective of the seasonality, the shortening of the rainy season is predominately found in areas with a climatological cessation in April. Areas with a climatological cessation during the end of October and beginning of November coincide with areas showing trends towards later cessation dates.

6. CHIRPS and the station data sets exhibit discrepancies in terms of rainfall seasonality, onset and cessation dates primarily in coastal areas and areas with complex topography. A large area with differences in season regime between stations and the gridded product covers the border between regions with single-wet-season and dual-wet-season climates as well as climates with rains from warmer clouds. These differences can also be identified in the trend estimation.

While the seasonal pattern agrees well with previous studies (Nicholson, 1996; Herrmann and Mohr, 2011; Yang et al., 2015; Dunning et al., 2016), differences to the first three studies may be attributed to the use of different data bases and classification criteria. For example, Nicholson (1996) only distinguished according the number of rainfall peaks. Herrmann and Mohr (2011) used a more detailed classification, which distinguished between the number of rainy seasons and the number of the associated peaks, resulting in a classification of up to eight classes. Comparing our results with those of Yang et al. (2015) and Dunning et al. (2016), several regions differ in terms of rainfall regime, namely, northeastern Ethiopia, the coastal and mountainous parts of Kenya and parts of Uganda. Dunning et al. (2016) characterised all of these regions as single-wet-season or dual-wet-season in different satellite data sets. The different assessment can be partially attributed to diverse algorithms of the satellite products and the underlying representation of the local conditions (e.g., topography). Additionally, Dunning et al. (2016) pointed out that the harmonic analysis may suggest a dual-wet-season regime at grid points where one of the wet seasons is weak and features low rainfall totals. Thus, and despite the classification as a dual-wet-season regime, only one rainy season can be clearly identified there. An additional reason can be the stability of the seasonality classes. At a particular location, this factor can lead to alternating seasonality classes in different years. Herrmann and Mohr (2011) pointed out that there is a gradient in temporal stability of the seasonality classification, which decreases from arid (stable) to humid (unstable) classes. The areas with differences in seasonality, when compared to Yang et al. (2015) and Dunning et al. (2016), coincide well with regions herein identified as of “unstable” classification.

Observational studies on climate variability often use strict calendric time periods (e.g., MAM, OND), which may be valid at national scales and might lead to inaccuracies for enlarged areas. In some of the analyzed countries, calendric
definitions also vary on subnational scale. On the contrary, modelling studies require basic information on rainy seasons for large (sub-)domains. The adjusted definition of rainy seasons captures all commonly used calendric definitions and agrees with patterns from supranational studies as derived by Liebmann et al. (2012) and Dunning et al. (2016). Consequently, the method can be applied in both observational and modelling studies. In contrast to anomaly-based methods like that applied by Dunning et al. (2016), the method introduced in the present study can also be used on subannual timescale and it can also be applied to forecast products. For the application in near-real time, the method either requires at least 20-day forecasts or tapering with at least four climatological pentad values. Unlike in Boyard-Micheau et al. (2013), the calibration can be implemented locally at the particular station/grid point. For example, the method is less reliable for regions without a clear seasonal cycle, like very arid (e.g., northern Sudan, parts of Puntland in Somalia) and very humid regions (e.g., DR Congo). In general, the method does not distinguish between rainfall events from local rainfall triggers (e.g., sea breeze) and large scale atmospheric processes (i.e., ITCZ), thus knowledge of local atmospheric conditions is always required.

Compared to agronomic definitions (e.g., Philipp et al., 2015), the method leads to different results due to the different objectives. Crop growth requires a minimum rainfall amount over a specific time period, thus their results can lead to longer rainy seasons in humid regions and shorter seasons in arid regions compared to the results of this study. In terms of observed trends, the analysis for the estimated rainy season onset and cessation enables a more detailed view on the development of the rainy seasons in the GHA. Overall, the trends of rainy season cessation are more robust, while onset trends show weaker magnitudes and varying significance. While the results suggest trends towards a more intense rainy season in central Sudan, trends in South Sudan and southern parts of Sudan suggest a prolonged rainy season due to a later cessation. Ethiopia reveals predominantly wetting trends in the western parts, despite of single stations with opposed trends. The rainy season tends to weaken and shorten in DR Congo, west-central Uganda and large parts of Tanzania. The results fit in well with the observed increase of greenness over eastern Sahel (e.g., Herrmann et al., 2005) which is linked to the West African monsoon. Seleshi and Zanke (2004) detected both, a widespread (but insignificant) rainfall increase and dramatic decreases at single stations in Ethiopia. A recent drying trend is observed in west-central Uganda and DR Congo (Zhou et al., 2014; Diem et al., 2014b; Hua et al., 2016).

For the dual-wet-season regimes of the GHA, the results point towards longer Short Rains, either due to a regionally earlier onset or a later cessation in the lowlands. A weaker reversed signal towards shorter Long Rains can be assumed for the same region. To date, several studies have identified an abrupt decline in the Long Rains since the end of the 1990s (e.g., Lyon and DeWitt, 2012; Maidment et al., 2015; Schmocker et al., 2016). Williams and Funk (2011) attributed the descending trend to a major shift in the Walker Circulation, which results in an increased subsidence over the GHA that leads to persistently drier atmospheric conditions. Several studies ascribe the increase of the Short Rains to an enhanced SST gradient of the Indian Ocean (e.g., Kabanda and Jury, 1999; Zorita and Tilya, 2002; Cook and Vizy, 2013; Liebmann et al., 2014). The region around Lake Victoria does not follow these trends irrespective of the regime. Several stations point towards wetter conditions, while CHIRPS does not underline these results. As the seasonal regime is unstable here, the region might require a more detailed analysis, which goes beyond the scope of this study. Further investigations could include a more detailed view on the seasonal stability and the associated trends.

The comparison of CHIRPS and station data reveals recurring biases of the satellite product in particular subregions. In mountainous and coastal subregions, CHIRPS shows shortened rainy seasons due to well-known underestimations of “warm rainfall” (Dinku et al., 2007; Kimani et al., 2017). In regions with a modest or short break between the rainy seasons, CHIRPS tends to overestimate rainfall during the break, leading to an overestimation of single-wet-season regimes. The agreement between stations and CHIRPS is best when high intensity rainfall periods can be detected. The new criterion can be adjusted and applied locally and requires solely a time series of about 30 years of precipitation for calibration. Thus, the method can also potentially be used in the context of identification and correction of biases in climate model simulations. The additional information on the onset and cessation of rainy seasons might allow identifications of possible season shifts in present and future climate scenarios.

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