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YAMEOGO Joseph

josephyameogo10@gmail.com

Ziniaré University Center, Joseph Ki-Zerbo University

SANOGO Fatimata

Ziniaré University Center, Joseph Ki-Zerbo University

OUEDRAOGO Arnaud

Norbert ZONGO University

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Spatial and decadal dynamics of the frequency, intensity and duration of rainfall in Burkina Faso (1981-2023)

YAMEOGO Joseph[1]*, SANOGO Fatimata[2] and OUEDRAOGO Arnaud[3]

[1] Ziniaré University Center, Joseph Ki-Zerbo University,Ouagadougou, Burkina Faso
Email: josephyameogo10@gmail.com ; joseph.yameogo@unz.bf

[2]Ziniaré University Center, Joseph KI-ZERBO University,Ouagadougou, Burkina Faso
Email: diefatibs@gmail.com

[3] Department of Geography, Norbert ZONGO University,Koudougou, Burkina Faso. Email: arnaudobf@gmail.com

* Corresponding author: josephyameogo10@gmail.com ; joseph.yameogo@unz.bf

Abstract Rainfall in the West African Sahel has partially recovered since the droughts of the 1970s and 1980s, but the form of this recovery matters as much as its size, since crops benefit from more wet days whereas heavier rainfall causes flooding. Using daily records from ten synoptic stations in Burkina Faso from 1981 to 2023, we examined three dimensions of rainfall (frequency, intensity and duration), assessing trends in ETCCDI indices and in rainy-season onset and cessation dates with the Mann-Kendall test and innovative trend analysis, decadal dynamics by station and climate zone, and extreme events through return levels. Frequency changed most, with wet days increasing at five stations (by two to three days per decade in the north), whereas intensity changed less, rainfall on very wet days rising by 16 to 27 per cent per decade at four stations without a significant increase for the average wet day or the annual maximum, and duration changed least, only the end of the season shifting slightly. Most of this change occurred between the 1980s and the 1990s, early in the south and east and later in the north and Ouagadougou, and we interpret it as a recovery from drought rather than a new rainfall regime; annual totals rose mainly because wet days became more numerous, while heavy rainfall became more frequent without a notable increase in intensity, except in Ouagadougou. Policy-makers should therefore pay particular attention to the frequency of heavy-rainfall days, whose effects on agriculture, dams and towns could be detrimental.

Keywords: daily rainfall, rainfall frequency, rainfall intensity, rainy season, decadal dynamics, Burkina Faso

Introduction

A warmer atmosphere contains more water vapour, which explains why heavy rainfall has become more frequent and more intense over most of the landmass [1–3]. For societies, however, the way in which rain falls is just as important as the amount received, since whether the water benefits crops, runs off as surface runoff or floods inhabited areas depends on the frequency of rainfall, the amount falling in a single event and the duration of the rainy season.

These issues are particularly acute in the West African Sahel, a region severely affected by the droughts of the 1970s and 1980s, where rainfall has partly recovered since the 1990s without returning to the levels seen in the 1950s and 1960s [4, 5]. This recovery has been described as an intensification of the rainfall regime [6–8], linked to that of mesoscale convective systems [9, 10]. Rivers bear witness to this, as surface runoff has increased even as rainfall has decreased; this 'Sahelian paradox' was initially attributed to land clearing and soil crusting, and subsequently also to more intense rainfall [11, 12]. However, trends vary from one location to another [13] and, over the period 1950–2013, rainfall records indicate a decrease in the number of rainy days, but more pronounced extremes [14].

Located in the Sudano-Sahelian zone, Burkina Faso is directly affected, as agriculture there is predominantly rain-fed and livestock graze during the rainy season. Furthermore, small dams store runoff water for the dry season, whilst towns have expanded into flood-prone areas. Runoff and peak flows have thus increased in the Nakanbé catchment despite the decline in rainfall, as fields have replaced the natural vegetation [15]. In Ouagadougou, reported flooding became more frequent during the 2000s, even though rainfall indices, for the most part, did not vary significantly [16], and it was the record rainfall on 1 September 2009 that caused one of the worst urban floods the country has ever experienced [17]. This situation has attracted the attention of both public authorities and researchers, and several studies have been carried out in Burkina Faso to better understand its climatology. West et al. [18] and Zampaligré et al. [19] have thus highlighted the variability of climatic variables in the country, whilst the perceptions of local populations show only a weak correlation with station records.

According to Sougué et al. [20], indices of extreme events have also decreased at several stations in the south over recent decades, whilst they have increased in the Nakanbé and Sirba basins [21, 22]. Other recent studies have produced mixed results regarding rainfall trends in Burkina Faso. Yanogo and Yaméogo [23] indicate that extreme rainfall was more pronounced in the north (Samba) than in the south (Gaoua) during the period 1990–2020, whilst Yaméogo [24] observes high variability in annual rainfall totals in the Sahel region. Over the period 1993–2023, Yaméogo et al. [25] also noted high variability in annual rainfall, which resulted in a concentration of rainfall along a north–south axis, with intensity indices increasing to varying degrees depending on the climatic zone [26]. Whilst the country's climatology is well documented at the national level, the analysis of extreme rainfall remains very limited, as few studies consider frequency, intensity and duration together to analyse them across the three climatic zones. Consequently, there remains a lack of understanding regarding how the frequency, intensity and duration of rainfall have each changed, the period over which these changes occurred, and their respective contributions to the increase in annual totals.

This article aims to address this gap by drawing on in situ data from ten synoptic stations spread across the country's various climatic zones, and pursues three objectives. The first is to identify trends in the frequency, intensity and duration of precipitation since 1981, as well as their spatial distribution at the national level. The second is to analyse the decadal dynamics of these changes, station by station and by climate zone. The third is to compare these changes with one another, and then to assess the respective contributions of frequency and intensity to the increase in annual totals and daily extremes. The study thus differs from a description of trends on an index-by-index basis in three respects. Frequency, intensity and duration are examined jointly for the same stations, and the trends are corrected to account for multiple testing, with their sensitivity to the starting year being assessed; finally, the increase in annual totals is apportioned between frequency and intensity, whilst daily extremes are characterised by their return levels.

Study area and data

Study area

Burkina Faso (274,200 km²; 9.4–15.1° N) has only one rainy season, from May to October, influenced by the West African monsoon. Three climatic zones are generally distinguished, delineated by the 600 and 900 mm isohyets (Figure 1). This results in distinct production zones across the country. Thus, the Sahelian zone broadly corresponds to the pastoral north, where millet predominates. The Sudano-Sahelian zone corresponds to the densely populated central plateau, dotted with small dams, where crops such as sorghum, millet and maize are grown. In the Sudanese zone, which is more humid, cotton and maize are cultivated.

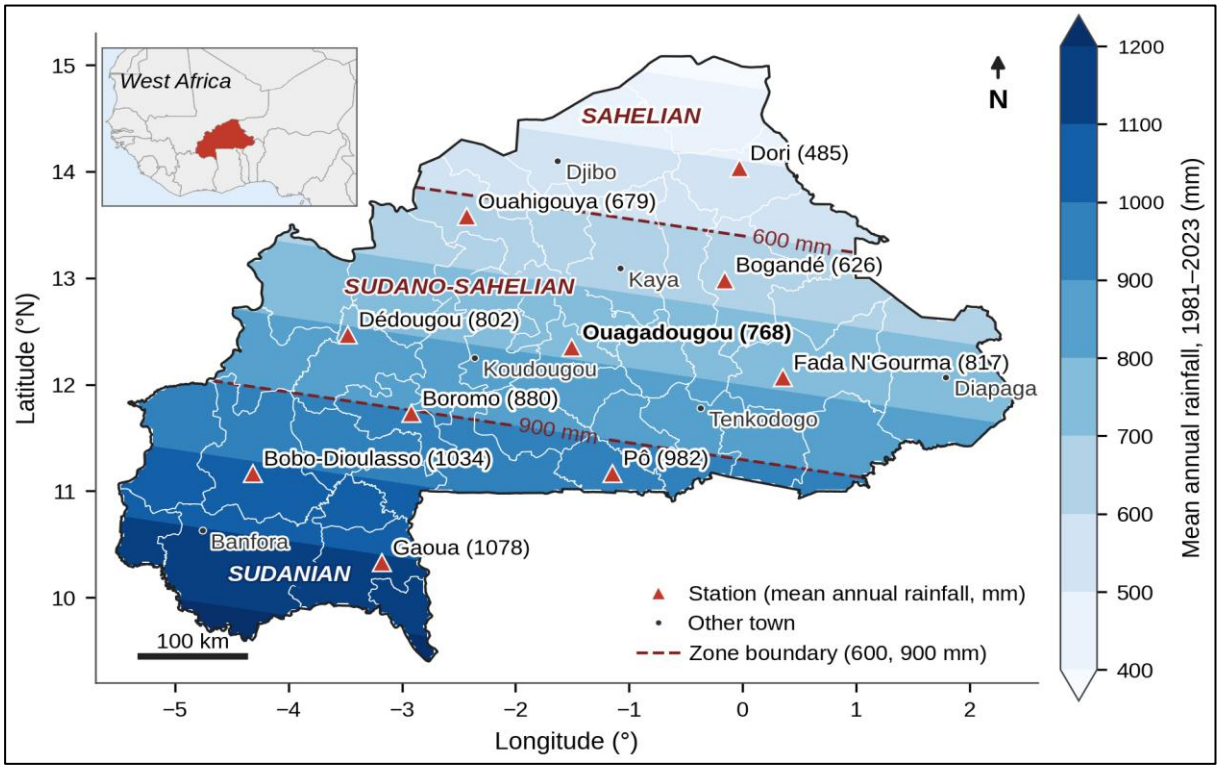


Fig. 1. Burkina Faso: synoptic stations with their mean annual rainfall (1981–2023), climatic zones bounded by the 600 and 900 mm isohyets, and other towns. The isohyets are derived from a linear trend surface fitted to the means of the ten stations ($R^2 = 0.97$) and are indicative beyond the area covered by the stations; the white lines show the provincial boundaries. Inset: location in West Africa.

Figure 1 shows a rainfall gradient running from south-south-west to north-north-east: from Gaoua to Dori, a distance of less than four degrees of latitude – the annual total is halved, corresponding to a decrease of approximately 160 mm per degree. The two isohyets divide the country into three bands of unequal width, with the Sudano-Sahelian band occupying the centre, where the majority of the population is concentrated. Although the stations accurately reflect this latitudinal gradient, the same cannot be said for longitude, as there are no synoptic stations in the north-west or the far east. The drier north is therefore represented only by Dori, Ouahigouya and Bogandé, which are situated close to the 600 mm isohyet, which limits any generalisation to the Sahelian zone.

Data used

The data used consist of daily rainfall records from the ten synoptic stations of the National Meteorological Agency (ANAM) for the period 1981–2023 (Table 1). Data gaps are rare, and only

those years with at least 350 daily readings were included, amounting to between 41 and 43 years per station.

Table 1. Characteristics of the ten synoptic stations (1981–2023)

Station	Lat. (°N)	Long. (°)	Alt. (m)	Annual total (mm)
Dori	14.03	−0.03	276	485
Ouahigouya	13.58	−2.43	335	679
Bogandé	12.98	−0.16	294	626
Dédougou	12.47	−3.48	299	802
Ouagadougou	12.35	−1.51	303	768
Fada N'Gourma	12.07	0.35	308	817
Boromo	11.73	−2.92	264	880
Pô	11.17	−1.15	321	982
Bobo-Dioulasso	11.17	−4.32	432	1034
Gaoua	10.33	−3.18	292	1078

Source: ANAM

Table 1 shows that the stations all lie between 264 and 432 m in elevation, so that their rainfall contrasts are due to latitude rather than to relief, and that their series are almost complete, since at most five days are missing at eight stations. The mean annual total ranges from 485 mm at Dori to 1078 mm at Gaoua, and the mean number of wet days from 36 to 72: the wettest station thus receives twice as much rainfall as the driest, and this over twice as many days. The network is densest in the Sudano-Sahelian zone., which has six stations, than in the Sudanian zone, which has three, and in the Sahelian zone, which Dori alone represents, and this uneven density must be borne in mind in any comparison between the zones.

Methods

Describing frequency, intensity and duration

Daily precipitation is characterised in terms of three dimensions: frequency, intensity and duration. Each of these is measured, for each station and each year, using the standard indices of the Expert Team on Climate Change Detection and Indices (ETCCDI [27]) or seasonal agronomic indicators (Table 2). The annual total number of rainy days (PRCPTOT) serves as a reference. These three dimensions cannot be considered in isolation, as the same annual total may result from numerous days of light rain or from a few days of heavy rain, and may be spread over a long season or concentrated within a short one, with very different consequences for crops, soils and watercourses.

Table 2. Indices used to describe the frequency, intensity and duration of rainfall

Dimension and index (ETCCDI code)	**Definition**	**Unit**
Amount		
Annual total (PRCPTOT)	Total rainfall on days ≥ 1 mm	mm
Frequency		
Wet days (WD)	Number of days ≥ 1 mm	days
Days ≥ 10 mm (R10mm)	Number of days ≥ 10 mm	days
Days ≥ 20 mm (R20mm)	Number of days ≥ 20 mm	days
Intensity		
Mean intensity (SDII)	Annual total divided by the number of wet days	mm day^{-1}
Max. 1-day rainfall (Rx1day)	Highest daily rainfall of the year	mm
Max. 5-day rainfall (Rx5day)	Highest total over five consecutive days	mm
Rainfall on very wet days (R95pTOT)	Rainfall on days exceeding the 95th percentile of the wet days of 1981–2010	mm
Share of very wet days (R95p%)	Rainfall on very wet days divided by the annual total	%
Duration		
Longest dry spell (CDD)	Longest run of days < 1 mm between May and October	days
Season onset	First day from 1 May onward on which three consecutive days total ≥ 20 mm, with no dry spell of more than seven days in the following 30 days [28]	date
Season end	First day from 1 September onward on which the soil water store (capacity of 70 mm, loss of 5 mm per day, empty at the start of the year) falls to zero (water-balance criterion used in West Africa)	date
Season length	Number of days from onset to end	days

The centile thresholds were calculated based on the number of rainy days during the 1981–2010 reference period. The longest drought period was calculated for the period between May and October, as the annual index primarily measures the dry season.

In the formulae below, rd denotes the rainfall on day d in millimetres and y denotes a year; the sums and maxima are calculated over all days d in that year, and 1(·) is equal to 1 when the condition in brackets is satisfied, and 0 otherwise. A year was only taken into account if at least 350 days had been observed during that year; for the calculation of drought periods and seasonal dates, missing days were counted as 0 mm.

Frequency refers to the number of times it rains, that is, the number of days in the year on which rainfall reaches a given level. Three thresholds have been selected: 1 mm, which defines a rainy day; 10 mm, which corresponds to moderate rain that effectively moistens the soil; and 20 mm, which corresponds to heavy rain. Frequency is important because rain-fed crops and pastures depend less on the seasonal total than on the regularity of water supply; indeed, for the same total amount, frequent rainfall keeps the soil moist, whilst infrequent rainfall allows it to dry out between rainfall events. It is, in fact, in this respect that Sahelian rainfall varies most from one year to the next [4].

Thus, for a year y:

$$\mathrm{WD}_y = \sum_{d\in y} \mathbf{1}\,(r_d \geq 1), \quad \mathrm{R10mm}_y = \sum_{d\in y} \mathbf{1}\,(r_d \geq 10), \quad \mathrm{R20mm}_y = \sum_{d\in y} \mathbf{1}\,(r_d \geq 20) \quad (1)$$

Intensity relates to the amount of rain that falls when it rains, and it has been measured across three levels. Thus, the average intensity reflects an ordinary rainy day, whilst the maximum rainfall over a

single day and over five consecutive days represent the most intense episodes. Finally, the category of very rainy days is characterized by the rainfall recorded on days exceeding the 95th percentile and by the proportion of this rainfall in the annual total. Intensity is important because rain that falls faster than crusted soil can absorb it turns into runoff, which fills reservoirs but also erodes fields, silt-ups dams and floods towns [12, 15]. This is why this dimension is the one most closely linked to hydrological and urban risks.

For a year y, these indices are written:

$$\mathrm{PRCPTOT}_y = \sum_{d\in y} r_d \;\mathbf{1}(r_d \geq 1), \quad \mathrm{SDII}_y = \frac{\mathrm{PRCPTOT}_y}{\mathrm{WD}_y} \tag{2}$$

$$\mathrm{Rx1day}_y = \max_{d\in y} r_d, \quad \mathrm{Rx5day}_y = \max_{d\in y} (r_d + r_{d+1} + r_{d+2} + r_{d+3} + r_{d+4}) \tag{3}$$

$$\mathrm{R95pTOT}_y = \sum_{d\in y} r_d \;\mathbf{1}(r_d > P_{95}), \quad \mathrm{R95p\%}_y = 100 \cdot \frac{\mathrm{R95pTOT}_y}{\mathrm{PRCPTOT}_y} \tag{4}$$

where P95 is the 95th percentile of rainfall on the wet days of the 1981–2010 base period, computed as the type 7 quantile in R, that is, for the n ranked values $x_{(1)} \leq \ldots \leq x_{(n)}$:

$$P_{95} = (1-\gamma)\, x_{(j)} + \gamma\, x_{(j+1)}, \quad h = 0.95\,(n-1) + 1, \quad j = \lfloor h \rfloor, \quad \gamma = h - j \tag{5}$$

Finally, duration refers to the temporal dimension of the rainy season, that is to say, its length and the duration of its interruptions. It is measured by the longest period of drought between May and October, as well as by the start, end and duration of the season. The dates are determined on the basis of daily rainfall in accordance with the criteria in force in the Sahel and West Africa, namely Sivakumar's rule [28] for the start and, for the end, the soil water balance criterion applied in the region (70 mm reserve, 5 mm loss per day), as in the PRESAO seasonal forecasts. Duration is important, firstly because the season must be long enough for crops to complete their cycle; secondly, because the start of the season determines the sowing date; and finally, because a drought lasting a week or more after sowing is sufficient to jeopardise the harvest [29]. It is, moreover, the aspect that farmers observe most directly.

Formally, with $\ell_1, \ldots, \ell_m$ the lengths of the runs of consecutive days below 1 mm between 1 May and 31 October, CDD (a, b) the longest of these runs between days a and b, and S_d the soil water store (mm) on day d, the dates being expressed as days of the year:

$$\mathrm{CDD}_y = \max(\ell_1, \ell_2, \ldots, \ell_m) \tag{6}$$

$$\mathrm{Onset}_y = \min d \geq 1 \text{ May such that}$$

$$r_d + r_{d+1} + r_{d+2} \geq 20 \quad \text{and} \quad \mathrm{CDD}(d+3,\, d+32) \leq 7 \tag{7}$$

$$S_d = \min[70,\ \max(0,\ S_{d-1} + r_d - 5)], \quad S_0 = 0$$

$$\mathrm{End}_y = \min d \geq 1 \text{ September such that } S_d = 0 \tag{8}$$

$$\mathrm{Length}_y = \mathrm{End}_y - \mathrm{Onset}_y \tag{9}$$

The daily series were read with *readxl* and then completed with *dplyr* and *tidyr* so as to form a continuous sequence of 15,705 days, from 1981 to 2023, the two dates missing from the 2021 series having been inserted as missing values. The ETCCDI indices of Table 2 were computed, for each station and each year, with the *climdex.pcic* package. The percentile thresholds (type 7 quantiles of the wet days) are established over the 1981–2010 base period, a year is retained only if at least 350 days were observed, and the longest dry spell is restricted to the months of May to October. The onset and end of the season result from applying the criteria of Table 2 to daily rainfall, using the rolling sums of the *zoo* package, and the share of very wet days was obtained with *dplyr*. The records were subjected to quality control covering negative or non-numeric values (none was found) and extreme totals; the daily maxima range from 114 to 261 mm, the highest corresponding to the event of 1 September 2009 in Ouagadougou, documented by Miller et al. [17], and all were retained. In the absence of station metadata, the homogeneity of the series could be examined only through statistical tests (see "Evaluating the changes").

Detecting and mapping the trends

We sought to identify a monotonic trend for each index, at each station and over the period 1981–2023, using three complementary methods: the Mann–Kendall method, Sen's slope and the ITA.

- *Mann–Kendall test.* This reference test for climate time series is based on ranks and requires no assumptions regarding the distribution of the data [30, 31]. The presence of an upward or downward trend is established by comparing all pairs of years and counting the instances where the most recent value exceeds the previous one. The test was carried out using the *trend* package, whose τ statistic is derived from *Kendall* and whose autocorrelation correction [32] is based on *modifiedmk*. Of the corrected and uncorrected p-values, the more conservative value was selected, as the correction may make the test more lenient when successive years are negatively correlated, and the significance level was set at 5 per cent.

For a series $x_1, \ldots, x_n$ of an index at a station, the statistic S counts the pairs of years in which the more recent value is the larger, minus those in which it is the smaller:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}\left(x_j - x_i\right) \tag{10}$$

$$Z = \frac{S - \operatorname{sgn} S}{\sqrt{\operatorname{Var}(S)}},$$

$$\operatorname{Var}(S) = \frac{n(n-1)(2n+5) - \sum_k t_k(t_k-1)(2t_k+5)}{18}, \quad p_{\mathrm{MK}} = 2[1 - \Phi(|Z|)] \tag{11}$$

where t_k is the size of the k-th group of tied values and Φ the cumulative distribution function of the standard normal distribution; Kendall's τ is S divided by the number of pairs, n(n − 1)/2. The autocorrelation correction modifies the variance:

$$\operatorname{Var}^*(S) = \operatorname{Var}(S) \cdot \left[1 + \frac{2}{n(n-1)(n-2)} \sum_{k=1}^{n-1} (n-k)\,(n-k-1)(n-k-2)\,\rho_k\right]$$

$$p = \max(p_{\mathrm{MK}}, p_{\mathrm{HR}}) \tag{12}$$

where ρ_k is the lag-k autocorrelation of the ranks of the detrended series.

Sen's slope. This corresponds to the median of the slopes calculated between all pairs of years [33] and, as it is largely unaffected by extreme years, it indicates the magnitude of the trend in index units per decade. It was calculated using the *trend* function. It is expressed in days per decade for frequency and duration indices and, for intensity indices, as a percentage of the station's average per decade, to enable comparison between stations.

- .

$$\beta = \operatorname{median}\left[\frac{x_j - x_i}{j - i}\right] \ \forall\, i < j, \quad \beta_{\mathrm{decade}} = 10\beta, \quad \beta_{\mathrm{rel}} = \frac{100 \cdot 10\beta}{\bar{x}} \tag{13}$$

where $\bar{x}$ is the mean of the series.

Innovative trend analysis (ITA). In this method, the time series is divided into two halves of equal length, each of which is ranked in ascending order; the values in the second half are then compared, rank by rank, with those in the first [34]. The advantage of this method is that it allows us to see whether the change affects the low, medium or high values of an index, something that a simple slope cannot do. The ITA slope was calculated using the *trendchange* package, and the difference between the two halves – calculated as the average of the lower, middle and upper thirds of the ranked values – is expressed as a percentage of the station's mean (in days for seasonal dates). As the significance test associated with this method [35] is considered to lack some rigour [36], the ITA was used solely to describe the changes, and not to test them.

With $h = \lfloor n/2 \rfloor$ years in each half (the central year being discarded when n is odd), $a_{(1)} \le \ldots \le a_{(h)}$ and $b_{(1)} \le \ldots \le b_{(h)}$ the ranked values of the first and second halves, and $\bar{a}$ and $\bar{b}$ their means, the slope and the rank-by-rank differences are:

$$s = \frac{2(\bar{b}-\bar{a})}{2h}, \quad d_i = b_{(i)} - a_{(i)}, \quad i = 1, \ldots, h \tag{14}$$

and the changes in the lower, middle and upper thirds, with $t = \lfloor h/3 \rfloor$, are, as a percentage of the mean $\bar{x}$ of the series (in days, without the factor $100 / \bar{x}$, for the onset and end dates):

$$\begin{aligned} \Delta_{\text{low}} &= \frac{100}{\bar{x}} \cdot \frac{1}{t} \sum_{i=1}^{t} d_i, \\ \Delta_{\text{middle}} &= \frac{100}{\bar{x}} \cdot \frac{1}{h-2t} \sum_{i=t+1}^{h-t} d_i, \\ \Delta_{\text{high}} &= \frac{100}{\bar{x}} \cdot \frac{1}{t} \sum_{i=h-t+1}^{h} d_i \end{aligned} \tag{15}$$

The trend maps present these results station by station, against the background of the administrative boundaries of Burkina Faso.

Analyzing the decadal dynamics

To understand the dynamics of change over time and space, the indices were averaged across four successive periods: 1981-1990, 1991-2000, 2001-2010 and 2011-2023 (the latter covering 13 years). At each station, the value for each period is expressed as a relative deviation from the station's 1981–2023 average, and then plotted on a map, enabling a comparison of the decades at a national level. These same averages were then grouped by climate zone: the Sahelian zone (Dori), the Sudano-Sahelian zone (Ouahigouya, Bogandé, Dédougou, Ouagadougou, Fada N'Gourma and Boromo) and the Sudanese zone (Pô, Bobo-Dioulasso and Gaoua).

With $x_{s,y}$ the value of an index at station s in year y, P a period, $|P|$ its number of years, $\bar{x}_s$ the 1981–2023 mean of station s and n_z the number of stations in zone z, the mean of a period, its departure from the station mean (in %) and the mean of a climatic zone are:

$$\bar{x}_{s,P} = \frac{1}{|P|} \sum_{y \in P} x_{s,y}, \quad \Delta_{s,P} = 100 \, \frac{\bar{x}_{s,P} - \bar{x}_s}{\bar{x}_s}, \quad \bar{x}_{z,P} = \frac{1}{n_z} \sum_{s \in z} \bar{x}_{s,P} \tag{16}$$

The means and standard deviations were calculated using *dplyr* and *tidyr*. It remained to be determined whether the differences between periods exceeded the year-to-year variability; to this end, a single point of change was sought, using Pettitt's test (the `pettitt.test` function from the *trend* package [37]), in the annual mean for the ten stations over the period 1981–2023. The differences between successive periods are accompanied by 95% confidence intervals obtained using the bootstrap method (the *boot* package) and were compared using the Wilcoxon test (*stats*), with the Pettitt test also being applied to each of the stations.

For the mean X_y of the ten stations and two successive periods P and P′, the difference between their means is:

$$X_y = \frac{1}{10} \sum_{s=1}^{10} x_{s,y}, \quad D = \frac{1}{|P'|} \sum_{y \in P'} X_y - \frac{1}{|P|} \sum_{y \in P} X_y \tag{17}$$

its 95% interval being bounded by the 2.5th and 97.5th percentiles of D obtained from 1000 resamples of the years, with replacement, within each period. For a series $X_1, \ldots, X_n$, the Pettitt statistic is:

$$U_t = \sum_{i=1}^{t} \sum_{j=t+1}^{n} \operatorname{sgn}\left(X_j - X_i\right), \quad K = \max_t |U_t|, \quad p \approx 2\exp\left[\frac{-6K^2}{n^3+n^2}\right] \tag{18}$$

the change point being placed after the year t that maximizes $|U_t|$.

Evaluating the changes

The changes identified, along with their trends, were then assessed from three perspectives: the robustness of the trends, the cause of the increase in annual totals, and the behaviour of daily outliers.

• *Robustness of trends.* Given that ten stations are analysed for each index, some of the significant results are due to chance. In order to retain only those trends that are robust to this effect, the false discovery rate procedure [38, 39] was applied at a 5 per cent threshold, separately for each index (ten stations), using the p.adjust function from the *stats* package. We then needed to assess the extent to which the trends were influenced by the drought of the 1980s; we did this by repeating the tests from 1991 onwards, whilst also comparing the direction and distribution of the variations between the Mann–Kendall test and the ITA. In Ouagadougou, the results were checked against the exceptional rainfall of 1 September 2009, with the Mann–Kendall test being repeated whilst excluding that year. Finally, in the absence of metadata, the homogeneity of the time series was examined by subjecting, for each station, the ratio of its values to the mean of the other nine stations to the Pettitt test and the standardised homogeneity test (the snh.test function of *trend*), using the same false discovery rate correction.

With m = 10 stations and $p_{(1)} \leq \ldots \leq p_{(m)}$ the ranked p-values of an index, the adjusted values of the Benjamini–Hochberg procedure are:

$$p_{\mathrm{adj},(k)} = \min_{l \geq k} \left[\frac{m\, p_{(l)}}{l} \right] \tag{19}$$

• *Origin of the rise in annual totals.* Since the annual total is the product of the number of wet days and their mean intensity, the trend in its logarithm is exactly equal to the sum of the trends in the two components, b(ln PRCPTOT) = b(ln WD) + b(ln SDII), where b denotes the least-squares slope (lm function of *stats*). The reason for this increase can be seen in the ratio b(ln WD)/b(ln PRCPTOT), which indicates whether it is due to a greater number of rainy days or to heavier rainfall.. As a check, we recomputed this share without the regression, as $\ln(WD_2/WD_1)/\ln(PRCPTOT_2/PRCPTOT_1)$, where the subscripts 1 and 2 denote the means over the sub-periods before and after a split year, taken in turn as 1995, 2002 and 2009 (for example, 1981–1995 and 1996–2023); splits for which the mean annual total differs by less than 2% between the two sub-periods were discarded, because the ratio then becomes unstable. We interpret the share only at the stations where the annual total shows a significant trend. As regards the weight of very wet days, we compared the two halves of the series (1981–2002 and 2003–2023), relating the change in rainfall on very wet days to that in the annual total, with 90% bootstrap intervals (*boot* package). If rain had merely become more frequent, without any change in its distribution, this share would be about 20%, a value that serves as our benchmark.

• *Daily extremes.* We retained the independent peaks lying above the 95th percentile of wet days (38 to 47 mm), which the declustering function of the *extRemes* package makes it possible to separate, and we fitted to them a generalized Pareto distribution, which is the reference model for threshold exceedances [40]. The return levels are derived from this distribution, that is, the daily rainfall exceeded on average once in T years, according to $x_T = u + (\sigma/\xi)[(\lambda T)^{\xi} - 1]$, where u is the threshold, σ and ξ the scale and shape parameters, and λ the mean number of peaks per year. The fit and the return levels were obtained with *extRemes*. The choice of threshold was checked on mean excess plots (*evd* package) and on plots of the stability of the shape parameter (*extRemes*), as well as by trying the 90th and 97.5th percentiles, the uncertainty being estimated

by bootstrap (*boot*). The changes were tested both on the annual number of peaks (trend by Poisson regression, *stats*) and on the scale parameter (trend by likelihood-ratio test, *extRemes*).

Tools used for data analysis

All calculations were carried out using R 4.4.3 [41], and the packages used are those whose names appear in italics in the preceding sections. The resulting tests, estimates and confidence intervals are derived from these, unless they originate from R's built-in functions. Only the seasonal criteria and decomposition ratios were coded directly, in accordance with the definitions given above. The approach was carried out in four stages, from the daily data to the assessment of changes, with each stage drawing on a subset of these tools (*Figure 2*). Stage 1 involved verifying and organising the daily precipitation data from the ten synoptic stations, and Stage 2 involved converting these into indices of precipitation frequency, intensity and duration. Stage 3 was devoted to detecting and mapping trends in these indices, followed by a description of their dynamics on a decade-by-decade basis, whilst Stage 4 focused on assessing the identified changes in terms of their robustness, the origin of the increase in annual totals and daily extremes.

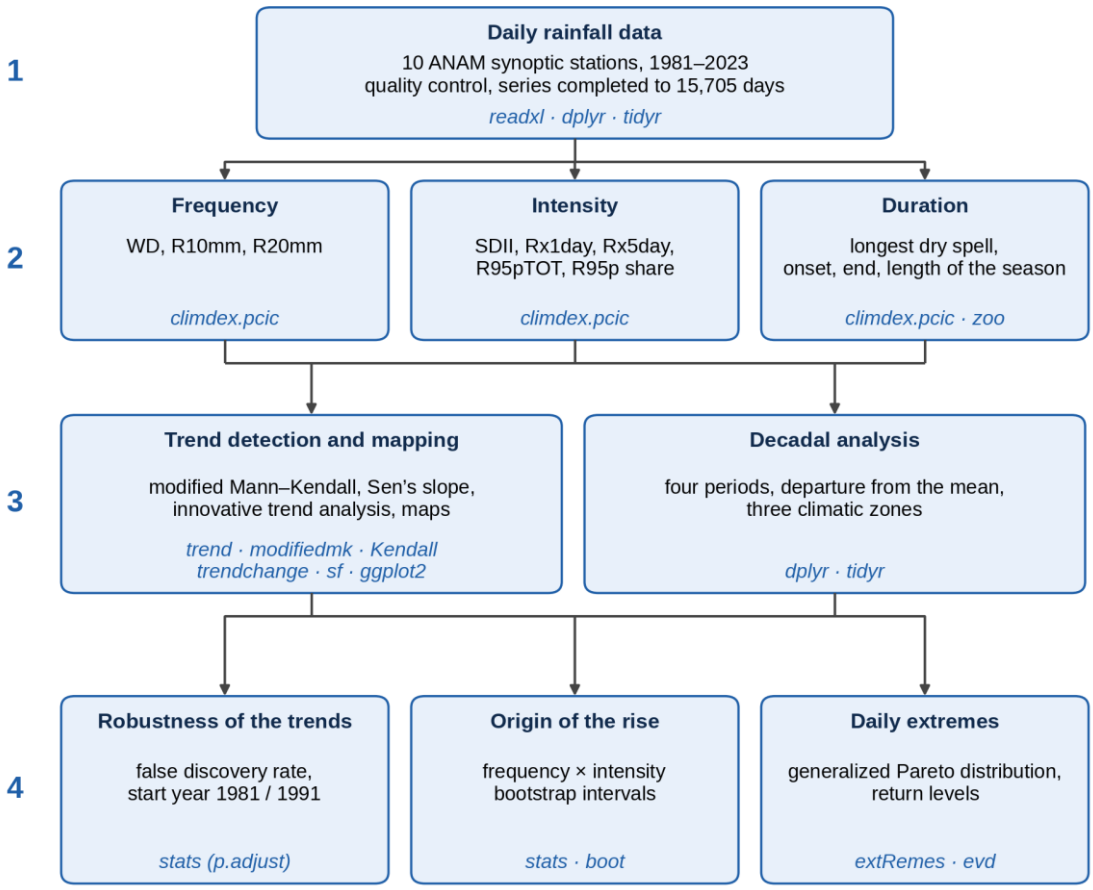


Fig. 2. Methodological sequence of the study, from the daily rainfall data to the evaluation of the changes, with the R packages used at each stage.

Results

Spatial trends in the frequency, intensity and duration of rainfall

Frequency and intensity: more wet days in the north, more rain on very wet days

Frequency is the simplest way of measuring how regularly crops and soils receive water. Figure 3 shows three counts of days, each illustrating the trend observed at each station. The first relates to all rainy days recording at least 1 mm of rainfall, which reflects the frequency of rainfall in general. The other two, which relate respectively to days recording at least 10 mm and at least 20 mm of rainfall, correspond to moderate and heavy rainfall, which replenish groundwater reserves and contribute to surface runoff. As the trends are all expressed as the number of days per decade, the three maps can be compared directly. The symbols help to distinguish significant trends, and those that remain significant after correction for multiple testing from those that are not.

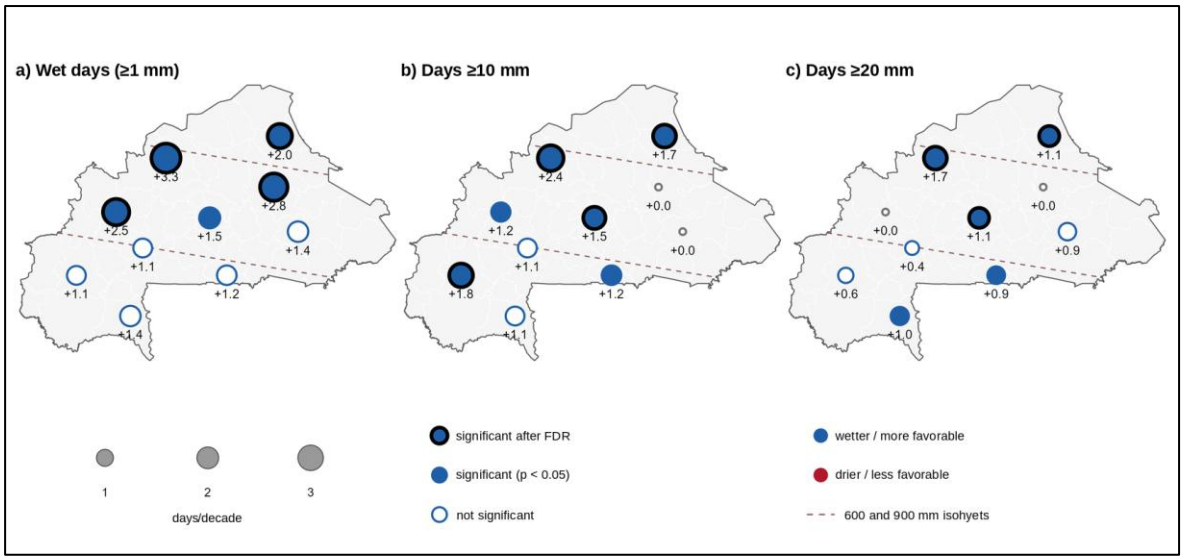


Fig. 3. Trends in rainfall frequency, 1981–2023 (Sen's slope, in days per decade): (a) wet days of at least 1 mm (WD), (b) days of at least 10 mm (R10mm) and (c) days of at least 20 mm (R20mm). Symbol size is proportional to the trend; filled symbols are significant ($p < 0.05$), with a black outline when they remain so after false discovery rate (FDR) correction. Dashed lines: 600 and 900 mm isohyets.

Rainfall has become more frequent almost everywhere, albeit unevenly. It is in the north that the number of rainy days has increased the most, rising from two to three days per decade in Ouahigouya, Bogandé, Dédougou and Dori, with an increase that remains significant even after correction for multiple testing. By contrast, at the other stations, the increase is only from one to one and a half days, with only Ouagadougou reaching the significance threshold. As for days on which at least 10 mm of rain is recorded, the increase is more widespread and also affects Ouagadougou, Bobo-Dioulasso and Pô. This means that, in the wetter south, this change affects moderate rainfall more than the total number of rainy days. The east, around Fada N'Gourma, is the only region where the frequency has remained virtually unchanged.

Intensity, defined as the amount of rain that falls when it rains, can be measured in several ways. Figure 4 shows the trends for four indices: average intensity on rainy days, the wettest day of the year, the five wettest consecutive days and, finally, total rainfall on very wet days, i.e. those exceeding the 95th percentile. As these indices are not expressed in the same units, the trends are presented as a percentage of each station's average per decade, with the symbol conventions being those used in Figure 3.

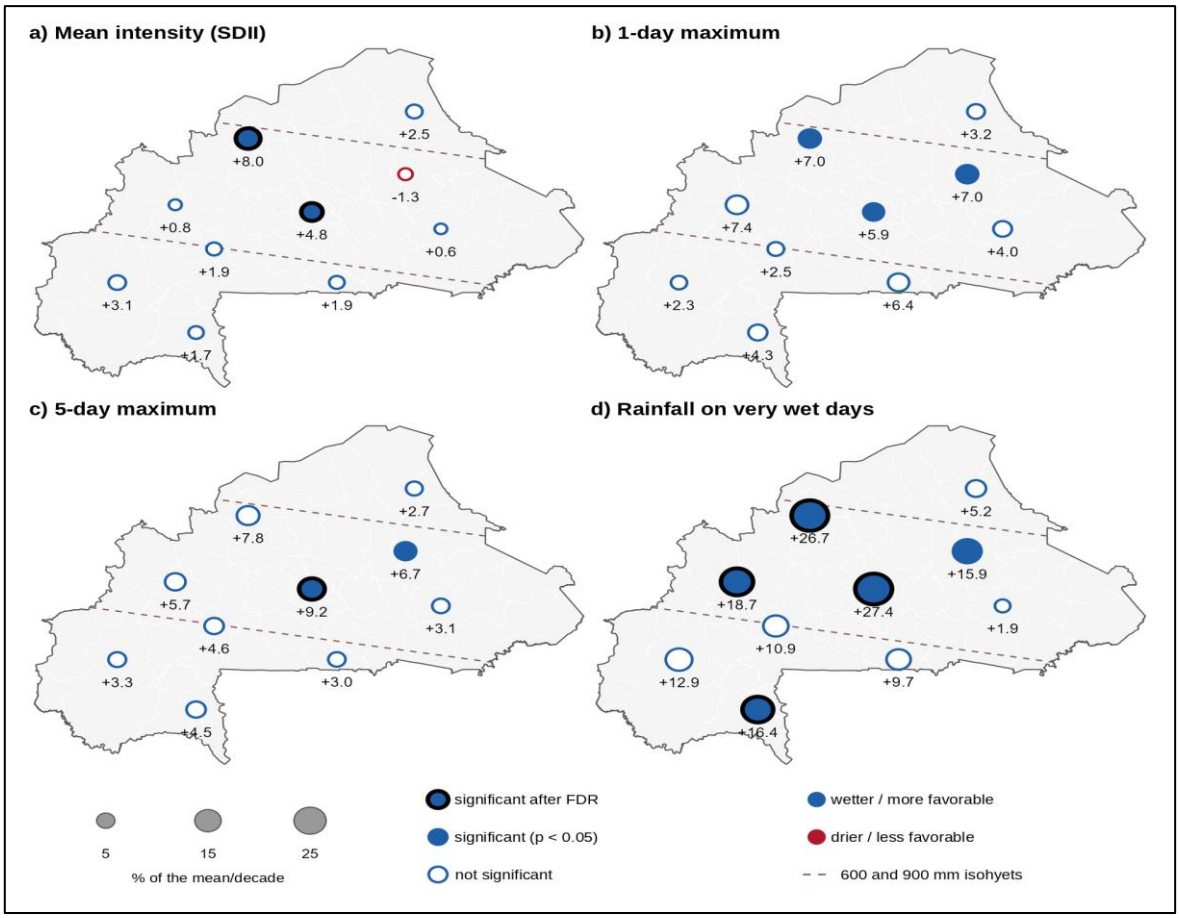


Fig. 4. Trends in rainfall intensity, 1981–2023 (Sen's slope, as % of the station mean per decade): (a) mean intensity of wet days (SDII), (b) maximum 1-day rainfall (Rx1day), (c) maximum 5-day rainfall (Rx5day) and (d) rain that fell on very wet days, above the 95th percentile (R95pTOT). Symbols as in Figure 3.

These maps show that ordinary rainy days have hardly become any wetter, with the average intensity having increased significantly only at Ouahigouya and Ouagadougou. The wettest day of the year saw an increase at three stations, but none of these increases withstood correction. As for maximum five-day totals, these increased significantly at Bogandé and Ouagadougou, but only at the latter station was the increase statistically significant. In contrast, rainfall on very wet days has risen sharply, by between 16 and 27 per cent per decade at Ouahigouya, Dédougou, Ouagadougou and Gaoua, with a clearly marked trend in each case. It is therefore the total rainfall on very rainy days that has increased in intensity, mainly along an axis running from Ouahigouya to Ouagadougou.

Duration: a rainy season that ends slightly later

Duration highlights the temporal aspect of the season, that is, how long it lasts and how long it is interrupted. Figure 5 presents four indicators: the longest period of drought between May and October, followed by the start, end and duration of the rainy season. Determined on the basis of daily rainfall according to agronomic criteria, the start and end dates describe the season as experienced by crops. Trends are expressed in days per decade and, for ease of interpretation, any change favourable to agriculture is shown in blue, whether it be a shorter dry spell, an earlier start, a later end or a longer season.

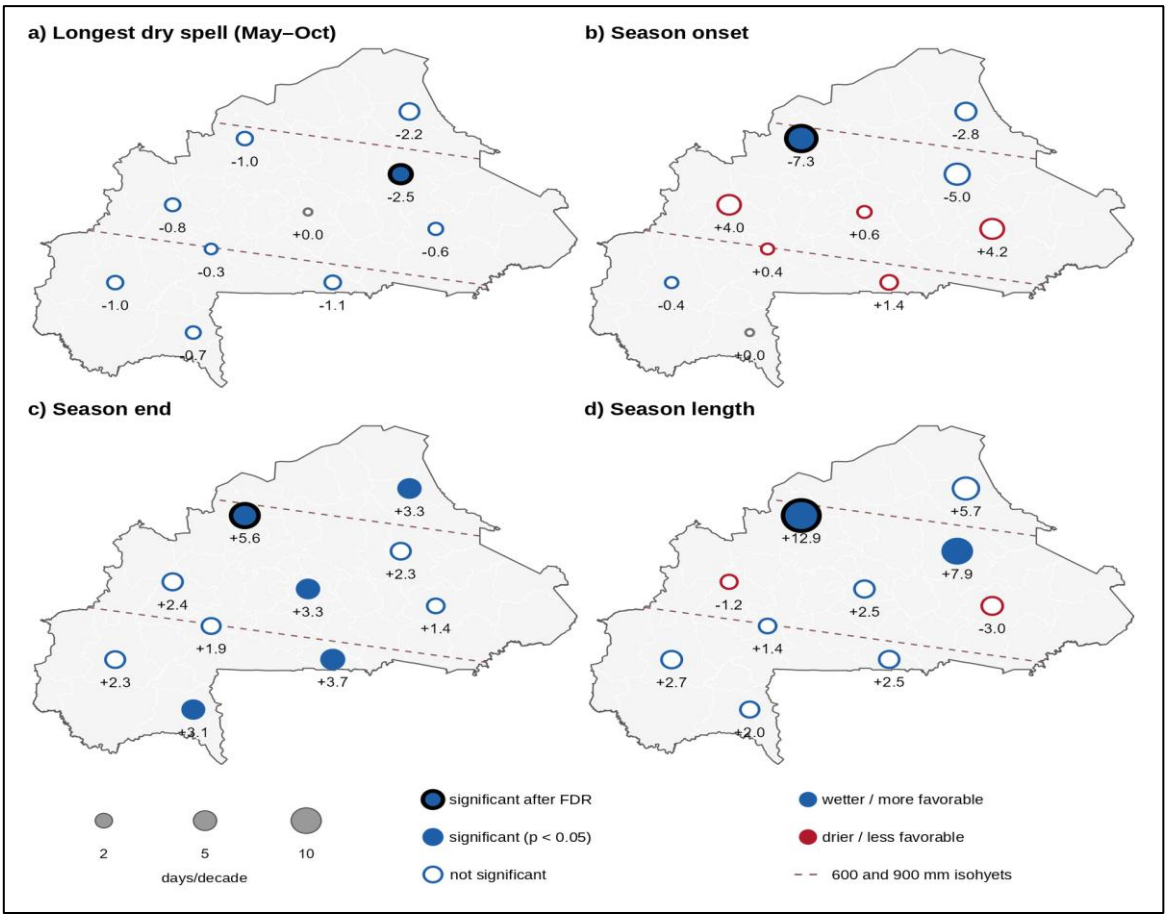


Fig. 5. Trends in the length of the rainy season and in dry spells, 1981–2023 (Sen's slope, in days per decade): (a) longest dry spell between May and October (CDD), (b) onset, (c) end and (d) length of the rainy season. Blue indicates a favorable change (shorter dry spell, earlier onset, later end, longer season). Symbols as in Figure 3.

Overall, the rainy season has retained its typical characteristics. The longest dry spell has shortened slightly at most stations, but this shortening is significant only at Bogandé. As for the start of the season, it shows no spatial pattern, with Ouahigouya being the only station to experience a marked change. The same cannot be said of the end of the season, which is later at all ten stations, by between one and six days per decade; this delay is significant at five of them and robust only at Ouahigouya. The lengthening of the season is significant at only two stations: it is robust at Ouahigouya (13 days per decade), where an earlier start is accompanied by a later end, whilst at Bogandé (8 days), it does not withstand correction.

Decadal dynamics at the national scale: by station and by climatic zone

By station: the decades mapped for each dimension

A trend line does not indicate when a change occurred, nor whether that change occurred at the same time across different stations. This is why Figure 6 presents an index for each dimension over four successive periods, namely the 1980s, 1990s, 2000s and 2011–2023: the number of rainy days for frequency; rainfall on very rainy days for intensity; and, for duration, the longest period of drought and the length of the season. For each station, the value for the period is expressed as a deviation from the station's 1981–2023 average, which allows for a comparison between dry and wet stations. Blue indicates a wetter or more favourable period than average, with a shorter drought period, whilst red indicates a drier period. The size of the symbol reflects the magnitude of the deviation. By reading each

row from left to right, you can see when the change occurred, and by reading each column, you can see the regions where it was concentrated.

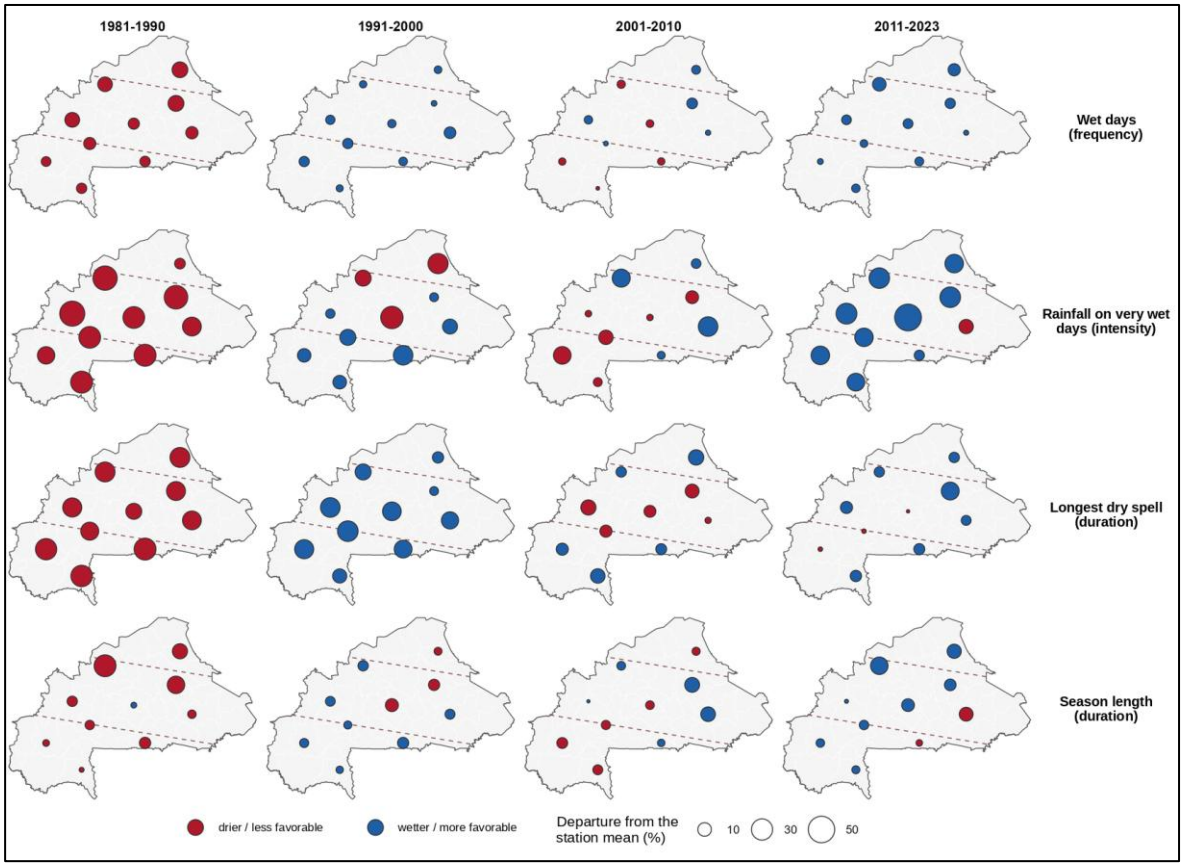


Fig. 6. Decadal departures from the station mean (1981–2023, in %) of one index per dimension: wet days (frequency), rainfall on very wet days (intensity), longest dry spell between May and October and length of the rainy season (duration), for 1981–1990, 1991–2000, 2001–2010 and 2011–2023 (13 years). Blue: period wetter or more favorable than the station mean (shorter dry spell in the third row); red: drier. Symbol size is proportional to the departure; dashed lines: 600 and 900 mm isohyets.

According to Figure 6, rainfall trends vary from one station to another, ranging from a generally unfavourable 1981–1990 decade to a 2011–2023 period characterised by predominantly favourable anomalies. During the first period, the frequency of rainy days and the cumulative rainfall totals for very rainy days were below average at all stations, with longer periods of drought and a generally shorter rainy season. The decade 1991–2000 saw a recovery in the frequency of rainfall at all stations and a shortening of drought periods, although neither the rainfall on very wet days nor the duration of the rainy season followed this trend everywhere. Between 2001 and 2010, unfavourable anomalies in rainfall frequency and the cumulative number of very rainy days particularly affected the south-west and a few stations in the centre, whilst periods of drought lengthened mainly in the central belt. The situation was different between 2011 and 2023, a period during which an excess of rainy days was observed at all stations and the cumulative number of very rainy days increased almost everywhere, with generally larger deviations for this second indicator. In most cases, periods of drought shortened and the rainy season lengthened; nevertheless, certain unfavourable anomalies persist, particularly regarding the duration of the rainy season in the east and south. As the responses differ on either side of the 600 and 900 mm isohyets, we conclude that local trends vary and that the frequency, intensity and duration of rainfall are changing partly independently of one another.

By climatic zone: changes that differ according to the period

Figure 7 offers a synthesis of these maps, since it uses the same four periods for the annual total and for seven indices covering the three dimensions. For each period, the index is averaged at each station and then by climatic zone, bearing in mind that the Sahelian zone is represented by Dori alone, and the thick

black curve shows the mean of the ten stations. Given in the unit specific to each index, the values complement the relative departures of Figure 6. Read from left to right, each panel shows whether the change was gradual or took place in steps, which can then be verified by a change-point test on the mean of the ten stations and by 95% intervals for the differences between successive periods.

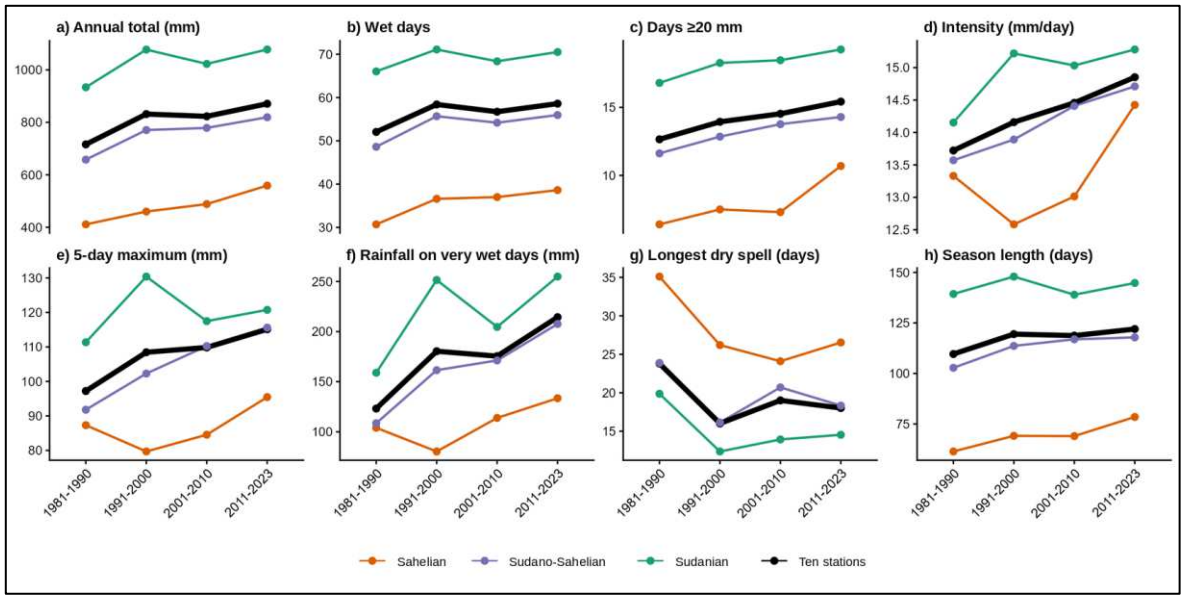


Fig. 7. Decadal means of the annual total and of indices of frequency (b, c), intensity (d–f) and duration (g, h), by climatic zone and for all ten stations. Periods: 1981–1990, 1991–2000, 2001–2010 and 2011–2023 (13 years).

According to Figure 7, the climatic gradient persists from one period to the next. The Sudanese region continues to have higher cumulative rainfall, rainfall frequency and a longer rainy season than the Sudano-Sahelian and Sahelian regions. For the ten stations, the average annual rainfall rose from around 710 mm in 1981-1990 to 870 mm in 2011–2023. In the Sahelian region, the increase ranged from around 410 to 560 mm. Across all stations, the number of rainy days has also increased, with the average rising from around 52 to 59 days. However, a slight decline was observed in 2001-2010. All three regions have seen an increase in the number of days with at least 20 mm of rainfall, with the rise being particularly marked in the Sahel during the most recent period. The average rainfall intensity has also increased, from around 13.7 to 14.9 mm/day across the ten stations. In the Sahel, the trend is less consistent, as it first declined and then rose sharply in 2011-2023. In the Sudano-Sahelian region, the five-day rainfall maximum has been gradually increasing. In the Sudanese region, however, it peaked in 1991–2000, at around 130 mm. Between the initial and final periods, the cumulative total of very rainy days also increased, from approximately 125 to 215 mm across all stations. As for the longest dry spell, it shortened significantly across all three regions between the first two periods. It then fluctuated, without returning to the levels seen in 1981–1990. Spatial contrasts, however, remained pronounced in 2011–2023. This dry spell lasted for around 26 days in the Sahel, compared with 18 days in the Sudano-Sahelian region and 15 days in the Sudanese region. Finally, the duration of the rainy season increases between the extreme periods. It rises from around 61 to 79 days in the Sahel and from 103 to 118 days in the Sudano-Sahelian region. In the Sudanese region, it fluctuates between 140 and 150 days.

Evaluation of the changes: robustness of the trends and weight of frequency and intensity

Are the identified trends robust in light of the decadal dynamics?

The trend analysis established where rainfall has changed (Figures 3 to 5), and the decadal analysis when it did so (Figures 6 and 7). The step that separates the 1980s from the 1990s, however, has a bearing on the interpretation of the trends. When the increase is concentrated between the 1980s and the 1990s, there is a risk that significant trends will appear over 1981–2023 that would not exist without the dry 1980s, and it may also be that this increase mainly concerns the driest years. Table 3 therefore indicates, for each index, the number of stations showing a significant change over 1981–2023 and the

number of those that retain it after correction for multiple testing, the same count then being repeated for series starting in 1991, that is, after the driest decade. The last three columns give the result of ITA, namely the change between the two halves of the series for the low, medium and high values of each index, as the median of the ten stations. Comparing the columns brings out the trends that depend on the recovery from drought, as well as the part of the distribution that they concern.

Table 3. Number of stations showing a significant change ($p < 0.05$) by dimension, and sensitivity to the start year

Dimension and index	**Significant change 1981–2023 (after FDR)**	**Start in 1991**	**ITA: low values**	**ITA: medium values**	**ITA: high values**
Amount					
Annual total (PRCPTOT)	6 (4)	3	+13	+13	+8
Frequency					
Wet days (WD)	5 (4)	0	+10	+5	+3
Days ≥ 10 mm (R10mm)	6 (4)	2	+7	+10	+8
Days ≥ 20 mm (R20mm)	5 (3)	3	+14	+11	+8
Intensity					
Mean intensity (SDII)	2 (2)	2	+7	+4	+4
Max. 1-day rainfall (Rx1day)	3 (0)	0	+10	+10	+16
Max. 5-day rainfall (Rx5day)	2 (1)	1	+7	+13	+17
Rainfall on very wet days (R95pTOT)	5 (4)	1	+26	+32	+41
Share of very wet days (R95p%)	4 (1)	1	+27	+20	+25
Duration					
Longest dry spell, May–Oct (CDD)	1 (1)	1	0	−11	−15
Season onset	1 (1)	0	−1	+1	−1
Season end	5 (1)	0	+11	+5	+4
Season length	2 (1)	0	+6	+4	+4

The changes counted are increases for amount, frequency and intensity, and shorter dry spells, earlier onsets, later ends and longer seasons for duration; no station shows a significant change in the opposite direction, except a later onset at one station with a start in 1991. FDR: Benjamini–Hochberg procedure at the 0.05 level. ITA: median, over the ten stations, of the change between the two halves of the series, as % of the station mean (in days for the onset and end of the season), for the lower, middle and upper thirds of the ranked values; a negative value for the longest dry spell and the season onset is a favorable change.

Over the period 1981–2023, the increase remains significant after FDR correction at four stations for the annual total, the number of rainy days, the number of days with at least 10 mm of rainfall and rainfall on very rainy days, and at three stations for the number of days with at least 20 mm of rainfall. However, for time series beginning in 1991, the increases recorded relate to three, zero, two, one and three stations respectively for these same indices, which means that sensitivity to the period under consideration varies depending on the index. These results are supplemented by the ITA, which compares the two halves of each time series; we present the median value across the ten stations as a percentage of the station-specific averages, with only the start and end dates of the season expressed in days. For the annual total, the deviation is +13 per cent in both the lower third and the middle third of the ranked values, and +8 per cent in the upper third. It is in the lower third that the number of rainy days has increased the most (+10 per cent, compared with +5 per cent and +3 per cent in the middle and upper thirds), which mainly reflects an increase in the number of years with few rainy days. Precipitation on very rainy days follows

the opposite trend, with the increase becoming more pronounced towards the upper end of the distribution, at +26 per cent, +32 per cent and +41 per cent respectively. The same applies to the one-day and five-day maximums, with the sharpest rise occurring in the top third (+16 per cent and +17 per cent respectively); however, the trend remains significant after FDR correction at only zero and one station. The maximum duration of drought periods remains unchanged in the lower third, but decreases by 11 per cent and 15 per cent in the middle and upper thirds, with the change being significant at only one station. The median change in the start of the season remains close to zero (between −1 and +1 day), whilst the end of the season is delayed by 11, 5 and 4 days across the three tertiles, and the season lengthens by 6 per cent, 4 per cent and 4 per cent respectively. Apart from the later start to the season recorded at one station where the analysis begins in 1991, the significant variations follow the trends shown in the table.

Rise in annual totals and extremes: the weight of frequency and intensity

Trend analysis has shown that the frequency of rainfall is increasing overall, whilst intensity is rising mainly due to an increase in the number of very rainy days; however, it remains to be determined which of these two variables accounts for the rise in annual totals. As the annual total is the product of the number of rainy days multiplied by their average intensity, its trend can be broken down precisely into a component attributable to frequency and a component attributable to intensity. These two components are shown, for the ten stations, in Figure 8a, where the whiskers indicate the variation in the result when the trend is replaced by a comparison of two sub-periods separated by a one-year break; only the six stations, marked with an asterisk, whose annual total has increased significantly are taken into account. Figure 8b addresses a related question, namely the proportion of rainfall recorded between the two halves of the series (1981–2002 and 2003–2023) that fell on very rainy days. This proportion is shown relative to the grey band, which corresponds to the proportion that would be expected if rainfall had simply become more frequent, whilst its distribution remained unchanged.

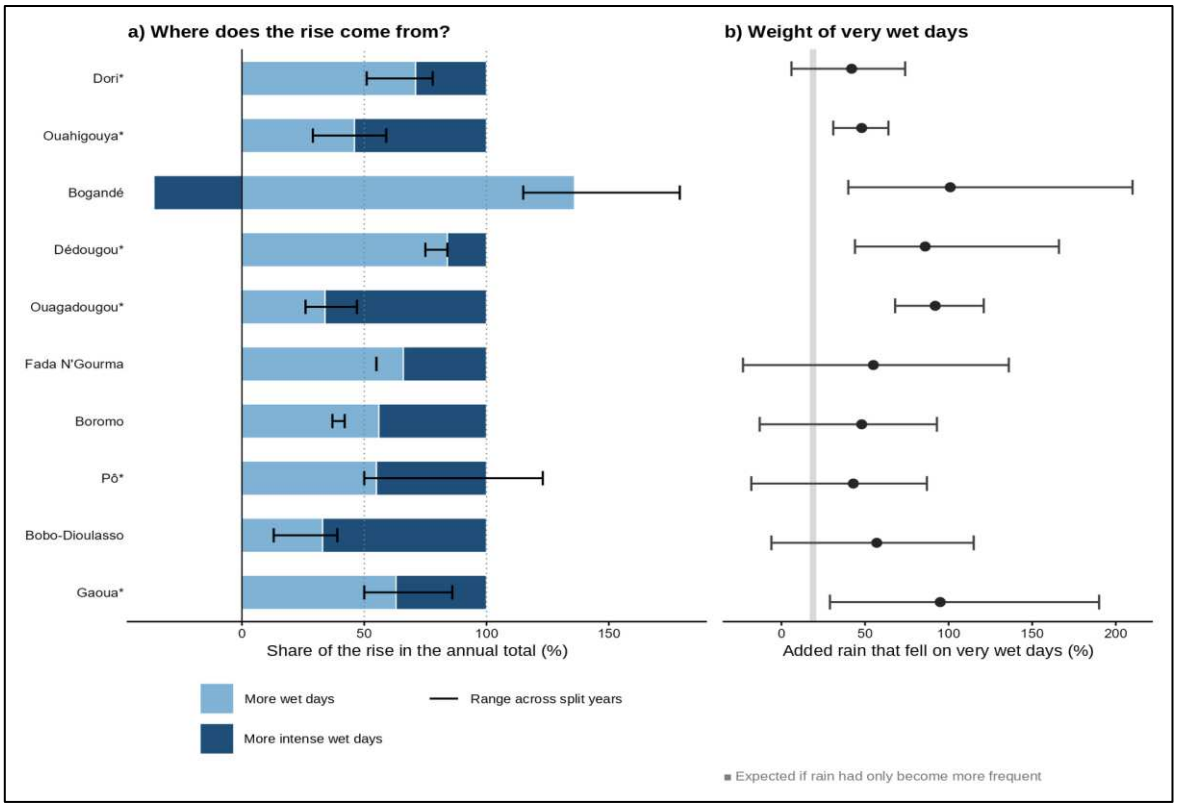


Fig. 8. Origin of the rise in the annual total at the ten stations; * *marks the six stations where the rise is significant at the 0.05 level, the only ones interpreted, because the shares are unstable where the total has varied little. (a) Contributions of more numerous wet days and of more intense wet days to the trend in the annual total; the whiskers give the range of the same share when the trend is replaced by the difference between the sub-periods before and after a split year (1995, 2002 or 2009; splits for which the total varies by less than 2% are omitted).*

(b) Share of the added rain (2003–2023 relative to 1981–2002) that fell on very wet days, with 90% bootstrap intervals; the gray band indicates the share expected if rain had only become more frequent.

According to Figure 8, rainfall frequency and intensity contribute in contrasting ways to the increase in annual rainfall at the six stations where this increase is statistically significant at the 5 per cent level. In Dédougou, Dori and Gaoua, the increase in the number of wet days is the predominant factor, accounting for approximately 84 per cent, 71 per cent and 63 per cent of this rise respectively, whilst in Pô the contributions are more evenly balanced, with approximately 55 per cent attributable to frequency and 45 per cent to intensity. In Ouagadougou and Ouahigouya, by contrast, the largest share is attributable to the increase in rainfall per wet day, accounting for approximately 66 per cent and 54 per cent of the increase respectively. Nevertheless, the extent of the whiskers indicates sensitivity to the time period considered, which is particularly marked in Pô.

Between 1981–2002 and 2003–2023, approximately 86 per cent of the additional rainfall in Dédougou is attributable to very rainy days, 92 per cent in Ouagadougou and 95 per cent in Gaoua, whilst their contribution, which is more moderate, ranges from around 42 to 48 per cent in Dori, Pô and Ouahigouya. The 90 per cent bootstrap intervals lie entirely above the expected reference level for a simple increase in rainfall frequency in Ouahigouya, Dédougou, Ouagadougou and Gaoua; in Dori and Pô, they overlap with this reference level, meaning that an excess contribution from very rainy days is not established as clearly there. It appears that, in both Dédougou and Gaoua, an increase attributable mainly to the number of wet days does not rule out a high concentration of the additional rainfall on very wet days.

Precipitation on very rainy days has increased (Figure 4), with this rise occurring later in the north (Figure 6). It remains to be determined whether the rainiest days have become more intense or whether they have simply become more frequent; we examine this using return levels. However, these levels depend on the threshold above which a day is counted as a peak event; we therefore first verify this choice, station by station, in Figure 9, before presenting the curves. Plotted there, as a function of the threshold, are the average excess above the threshold (top) and the shape parameter of the fitted distribution (bottom), with the red dotted line marking the chosen threshold (95th percentile of rainy days). We consider a threshold to be appropriate as long as the shape parameter does not become erratic and the number of peaks remains sufficient.

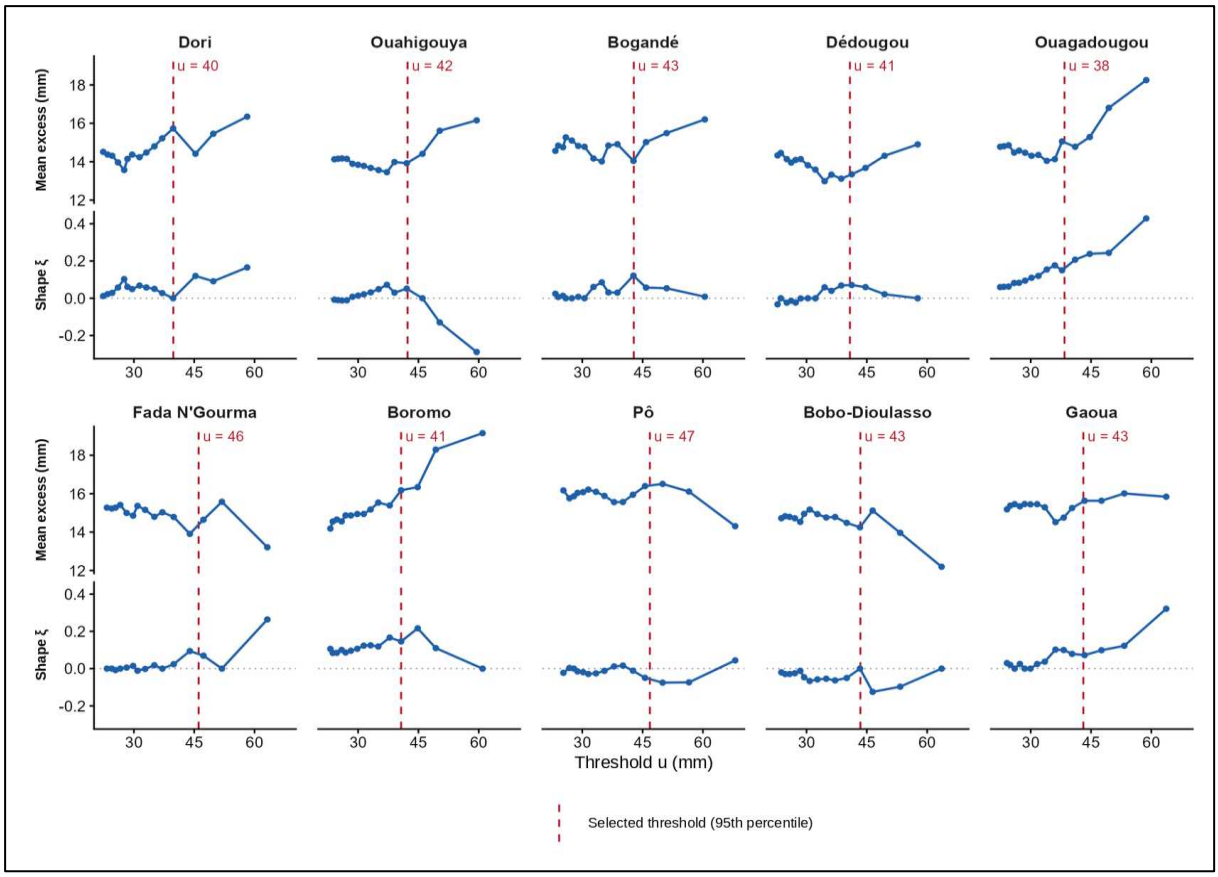


Fig. 9. Threshold diagnostics of the peaks-over-threshold model at the ten stations: mean excess above the threshold (upper row of each block) and shape parameter ξ of the generalized Pareto distribution (lower row of each block) as a function of the threshold u. The dashed red line marks the 95th percentile of wet days selected as the threshold, with its value in mm; the dotted gray line marks ξ = 0.

In Figure 9, the diagnostic results react differently to the choice of threshold across the ten stations. Set at the 95th percentile of rainfall on wet days, the threshold ranges from 38 mm in Ouagadougou to 47 mm in Pô, and the corresponding average excess is approximately between 13 and 16.5 mm. The shape parameter ξ is close to zero at several stations, moderately positive in Ouagadougou and Boromo in particular, and slightly negative in Pô. As the threshold rises, the trajectories diverge, since ξ increases in Ouagadougou whilst it decreases markedly in Ouahigouya, to the point of becoming negative. The mean excess curves also show inflections and fluctuations, particularly at Dori, Fada N'Gourma and Bobo-Dioulasso, meaning that the reliability of the assessments, both around the selected threshold and beyond it—varies from station to station. In the absence of confidence intervals and information on the number of instances where the threshold was exceeded, the figure alone is not sufficient to validate the choice of the 95th percentile at each of the ten stations.

Figure 10 then presents the return levels of daily rainfall for the ten stations, ordered from north to south, the return level being the rainfall depth exceeded on average once in a given number of years. In each panel, the points represent the observed peaks and the curve the distribution fitted to the independent peaks above the threshold, with its uncertainty band, which makes it possible to judge the quality of the fit. At the 25-year return period, two symbols set the first and second halves of the series side by side, these halves being the same as in Figure 8, and each panel also shows the trend in the annual number of heavy events. These two readings make it possible to distinguish a change in the magnitude of extremes from a change in their frequency.

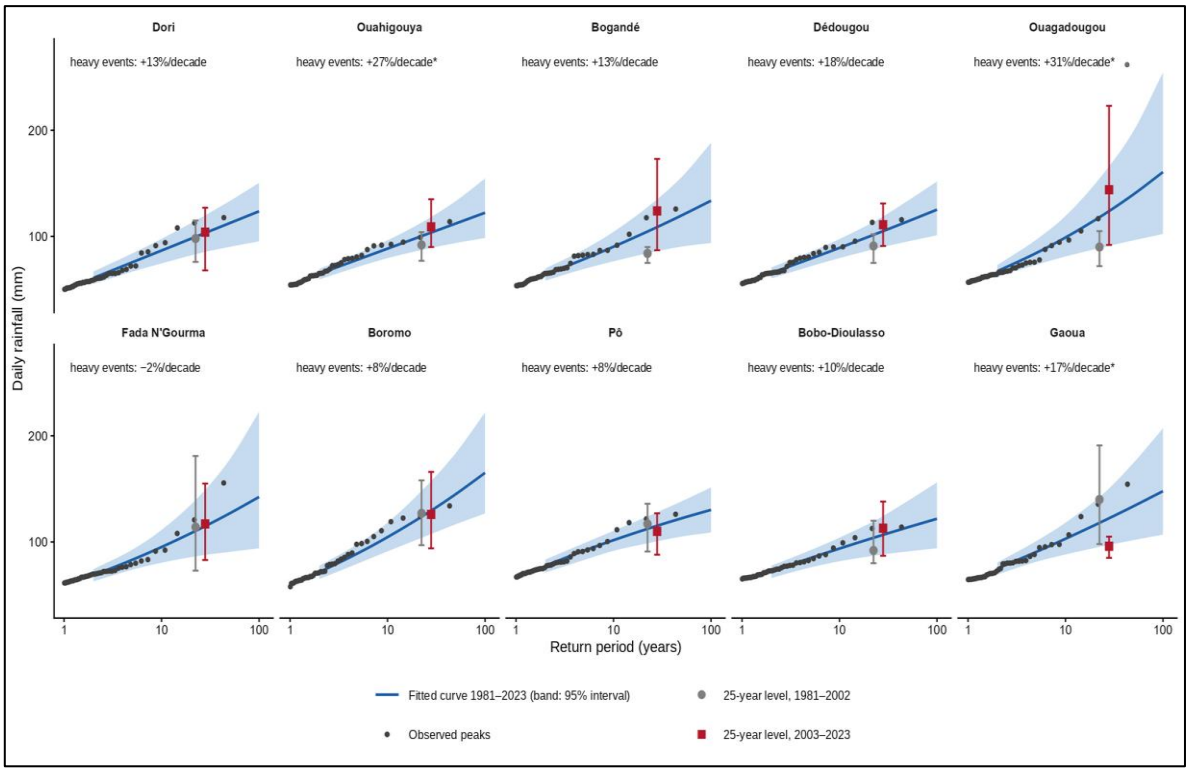


Fig. 10. Return levels of daily rainfall at the ten stations: generalized Pareto distribution fitted to the peaks above the 95th percentile, 1981–2023 (curve, with 95% bootstrap interval), observed peaks (points) and 25-year return levels for 1981–2002 and 2003–2023 (symbols, with 95% intervals). Each panel indicates the trend in the annual number of heavy events (* significant after FDR correction).

As shown in Figure 10, the frequency of heavy rainfall is increasing across the board, whilst 25-year return period levels are showing contrasting trends. The annual number of heavy rainfall events is indeed on an upward trend at nine out of ten stations, the sole exception being Fada N'Gourma (−2 per cent per decade); however, this increase is only statistically significant after FDR correction at Ouagadougou (+31 per cent per decade), Ouahigouya (+27 per cent) and Gaoua (+17 per cent); the estimated increases elsewhere, ranging from +8 per cent to +18 per cent, are not statistically significant.

When adjusted over the entire 1981-2023 period, the curves generally reflect the observed peaks, with the discrepancy being particularly marked for the maximum rainfall in Ouagadougou, which exceeds 250 mm; the influence of this episode on the adjustment warrants specific examination. The estimated 100-year return levels range approximately from 120 to 165 mm depending on the station, with no consistent north–south gradient emerging. As for the uncertainty intervals, they widen with the return period, particularly in Ouagadougou, Boromo and Fada N'Gourma, meaning that estimates are less precise for the rarest events.

It is at Bogandé (from approximately 85 to 125 mm) and Ouagadougou (from approximately 90 to 145 mm) that the 25-year return level increases most noticeably between 1981–2002 and 2003–2023, as can be seen from the graph. The increase is more modest in Dori, Ouahigouya, Dédougou and Bobo-Dioulasso, whilst the values for the two periods are similar in Fada N'Gourma and Boromo. By contrast, this level decreases slightly in Pô and more markedly in Gaoua, where it falls from approximately 140 to 95 mm.

However, the figure alone does not allow us to conclude that these differences between periods are significant, as the 95 per cent confidence intervals overlap; a direct test of the changes would require a bootstrap interval for the difference. Furthermore, the asterisks relate only to trends in the number of heavy events. In Gaoua, the frequency of exceedances increases whilst the estimated return level decreases, the latter depending on both their frequency and the distribution of their magnitude.

Discussion

Where rainfall has changed: spatial distribution of frequency, intensity and duration

Burkina Faso's return to wetter conditions is primarily due to the recovery of the rainy days lost during the drought. This finding is consistent with that of Lebel and Ali [4], who attribute most of the interannual variability in Sahelian rainfall between 1990 and 2007 to the number of significant rainy episodes rather than their intensity, and with that of Nicholson [5], who found that this recovery did not restore rainfall to the levels seen in the 1950s and 1960s. The signal is strongest in the north, precisely where the rainfall deficit had been most pronounced and where the most ground remained to be made up, which is consistent with the latitudinal contrasts in seasonal descriptors highlighted by Lodoun et al. [42]; by contrast, it is weakest in the east, around Fada N'Gourma.

In the south, Sougué et al. [20] found more evidence of a decrease than an increase in extreme events; yet rainfall on very wet days is rising sharply in Gaoua, whilst in Pô and Bobo-Dioulasso it remains at the detection limit.

Changes in intensity are more limited than is generally assumed, as the return of rainfall to the Sahel has been described as an intensification of the rainfall regime [6–8]. However, at the stations studied, the increase relates to rainfall on very rainy days, and not to that on ordinary rainy days, nor, at least not significantly, to that of the heaviest events. It is true that the wettest day of the year has increased at three stations and the five-day maximum at two, but only the latter remains significant after correction, at Ouagadougou. The fact that very wet days have become more prominent without the most intense events increasing in magnitude is consistent with the dominant role of frequency, which we shall return to below.

The duration of the season has remained virtually unchanged, and its start, which determines sowing has changed only at Ouahigouya; the longest dry spell has shortened only at Bogandé, whilst both these factors are crucial for farmers. In the Sahel, indeed, failed sowing is mainly due to dry spells lasting a week or more occurring after an initial light rainfall [29], and the start date of the season largely determines its duration [28]. The trend towards a later end corresponds to the 'hybrid' seasons described by Salack et al. [43], where late rains, false starts and showers coexist; however, this trend remains fragile, as it disappears when the time series begin in 1991.

It follows that the additional rainy days have, for the most part, fallen within the existing rainy season; it should also be noted that the longest dry spell does not account for shorter interruptions, which have become more frequent elsewhere in the Sahel [44].

When rainfall changed: a step in the 1990s, later changes in the north

A ten-year analysis suggests that these changes represent a recovery following the drought rather than a new trend. The bulk of the increase actually occurred between the 1980s and the 1990s, across all ten stations and in all three dimensions (more rainy days, more rainfall on very rainy days, shorter dry spells), and this timeline corresponds to the recovery in Sahelian rainfall described from the 1990s onwards [4, 5]. The frequency then levelled off in the 2000s, before rising again between 2011 and 2023; however, none of these differences exceeds interannual variability, with their 95 per cent confidence intervals containing zero, meaning that only the first phase can be considered statistically significant. It should be added that, over a longer observation period, Harrison et al. [14] note a decrease in the number of rainy days since 1950, which places the recovery described here at the lowest point of a longer-term decline.

This recovery has not followed the same pattern across all regions; the south and east returned to their average rainfall levels as early as the 1990s, with little change thereafter, which partly explains the weak trends calculated over the entire period at Fada N'Gourma, Pô and Bobo-Dioulasso. In the north and in Ouagadougou, by contrast, the increase is continuing or has only set in late, with the period 2011–2023 being the wettest there; indeed, it is here that the only significant breaks in the annual total occurred, in 2006 in Ouahigouya and in 2008 in Ouagadougou. These delayed changes differ from those observed in the first phase, as the average intensity and the maximum five-day total continued to increase in the

2000s whilst the frequency remained stable, and rainfall on very wet days reached its highest level between 2011 and 2023. Whilst these differences are arguably not significant, they are consistent with the intensification of Sahelian thunderstorms reported since the 1980s [6, 9]; however, the time series remain too short to distinguish a new phase from decadal variability.

This trend allows rainfall records to be reconciled with farmers' accounts. Farmers in the Central Plateau have perceived less rainfall and fewer 'heavy downpours' than thirty years ago [18], and ten-year totals did indeed remain below the long-term average until 2010 in Ouagadougou, whilst further south, perceptions showed little correlation with the recorded data [19]. If rainfall returns in the form of more frequent days of moderate rain, whilst the start of the season remains unchanged and dry spells persist, the risk faced at the time of sowing remains.

In the north, adaptation has, moreover, relied on the collection of runoff water and the construction of stone embankments, practices that respond as much to land-use pressures and market forces as to the climate [45].

Robust trends that nevertheless depend on the 1980s, a rise driven by frequency

Not all of these trends are equally robust, for whilst most frequency trends withstand correction for multiple testing, they depend on the inclusion of the 1980s – which were dry, as might be expected when the increase is concentrated between the 1980s and the 1990s. The ITA clarifies this point by showing that dry years have become less dry, whilst the increase in the number of rainy days and the shortening of dry spells mainly concern the most unfavourable years, which is consistent with the expected signature of a recovery from drought. The increase in rainfall on very rainy days, on the other hand, affects all years, and particularly the wettest ones. Less numerous, the trends in average intensity are also less sensitive to the starting year; the five-day maximum withstands the correction at only one station, whilst the wettest day of the year does not at any. The results based on a single period or on uncorrected tests should therefore be interpreted with caution.

The decomposition compares the two dimensions identified by the trend analysis and pinpoints the cause of the rise in annual totals, which is mainly due to a greater number of rainy days, with very rainy days also accounting for an increasing proportion. These two findings fit within the framework proposed by Pendergrass and Hartmann [46], according to which the distribution of precipitation changes in accordance with an 'augmentation' mode, which adds precipitation at all intensities, and a 'shift' mode, which shifts it towards higher intensities. The near-stability of the mean intensity is attributable to the former mode; the fact that very rainy days received more than their share of the additional rainfall at four of the six stations is attributable to the second mode. The slight increase in the concentration of rainfall observed at these same stations between 1993 and 2023 [25] provides a complementary finding, as it relates to the distribution of rainfall across months, whereas our finding relates to its distribution across rainy days.

Very rainy days have become more frequent without any detectable increase in their intensity. However, the thermodynamic argument, according to which atmospheric humidity increases by approximately 7 per cent per °C and is released predominantly during intense events [47], suggests that stronger extremes should be expected, a prediction confirmed, moreover, by global annual maxima [48]. It is true that we had only 40 to 80 peaks per half of the time series, meaning that only sharp increases in the intensity of extremes could be detected, and that their absence does not prove stability; over the period 1981–2023, however, changes in the frequency of rainfall systems appear to have predominated. In the Sahel, heavy rainfall stems mainly from mesoscale convective systems, the frequency of the most intense of which has tripled since 1982 [9], in connection with the warming of the Sahara [10]. Projections indicate a decrease in the number of rainy days but an increase in rainfall intensity [49], which suggests, without proving it, that this phase dominated by frequency could be transitory.

Geographical implications and limitations

As far as agriculture is concerned, the return of rainfall has resulted in more rainy days, but within a growing season whose start date has not changed and in which dry spells persist. It is true that water

availability has improved, particularly in the north; however, the risk of crop failure and water stress during the growing season has not diminished, meaning that adaptation remains necessary, whether through the collection of run-off water, staggered sowing or the use of drought-resistant varieties.

For small dams and soils, the key finding is the increasing impact of very rainy days. On cleared and encrusted soils, it is heavy rainfall that causes the runoff responsible for the Sahelian paradox [12, 15]; consequently, the increased frequency of very rainy days is likely to boost inflows into reservoirs, but also to exacerbate erosion, silting and the load on spillways. In urban areas, the risk of flooding stems from the frequency of days with heavy rainfall, combined with the development of flood-prone areas, rather than from any potential change in the hundred-year rainfall pattern. In both cases, monitoring should prioritise the frequency of very rainy days, which is already changing; the reference rainfall data, for its part, should be updated using regional or non-stationary analyses that group together stations, rather than based on sub-periods from a single station.

The national rainfall network, including its secondary stations, which reflect local variations [50], remains essential for monitoring the daily rainfall that causes flooding and erosion. This study has limitations, primarily due to the small number of stations – which leaves the north-west and the far east without observations – and the low statistical power for annual maximums. Furthermore, it cannot be ruled out that gaps in the time series may have been filled in; however, the absence of station metadata makes it impossible to verify this.

Conclusions

The aim of this study was to determine how the frequency, intensity and duration of rainfall have changed in Burkina Faso between 1981 and 2023, when this change occurred and how robust it is. It was the frequency of rainfall that changed the most, particularly in the north, whilst intensity changed more moderately, driven more by very rainy days than by average days or the most intense episodes, and the duration of the season varied the least, with only its end having been slightly delayed. The increase in annual total rainfall occurred mainly in a single phase, between the 1980s and the 1990s, at all stations; subsequent variations remained small and statistically indistinguishable from a stable situation; this represents a recovery following the drought rather than a new trend. However, this recovery was not uniform, as the south and east quickly returned to their average levels before stabilising, whilst rainfall continued to increase in the north and in Ouagadougou, with significant breaks in the annual total in 2006 in Ouahigouya and in 2008 in Ouagadougou. It is mainly due to frequency, for which the trends are the most robust but also the most dependent on the droughts of the 1980s, even though the increase in rainfall has been concentrated disproportionately on very rainy days, which have become more frequent without any detectable change in their intensity or return levels; Ouagadougou is an exception, as more intense rainfall predominates there.

For farmers, a greater number of rainy days in a season whose start date has not changed and in which dry spells persist does not reduce the risk faced at the time of sowing; consequently, the collection of run-off water, staggered sowing and drought-resistant varieties remain necessary. For small dams as well as for towns, the key variable to monitor is the frequency of very rainy days, which is expected to increase inflows but also erosion, silting and, with the occupation of flood-prone areas, the risk of flooding; such monitoring requires a well-maintained rainfall network, including secondary stations, as the ten stations studied do not cover either the north-west or the far east.

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