

Agroclimatological Characteristics of Rainy Seasons in Southwestern Burkina Faso during the 1970-2013 Period

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How to cite this paper: Ibrahim, B., Waongo, M., Sidibe, M., Sanfo, S. and Barry, B. (2022) Agroclimatological Characteristics of Rainy Seasons in Southwestern Burkina Faso during the 1970-2013 Period. *Atmospheric and Climate Sciences*, 12, 330-357.

<https://doi.org/10.4236/acs.2022.122021>

Received: January 5, 2022

Accepted: March 29, 2022

Published: April 1, 2022

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Abstract

The different drought phases observed during the 1970-2010 period have underlined important weaknesses of West African agricultural systems. The droughts resulted in important decreases in crop production, triggering a significant deficit in food availability. Many studies have identified changes in rain events seasonal patterns as the key drivers of agricultural production failure during these drought phases. In this study, seven agriculturally-relevant intra-seasonal rainfall characteristics (*i.e.*, annual rainfall amount, onset and cessation of the rainy season, dry spells, extreme rain events, hot spells, and strong winds) and associated constraints to crop growth are described for the main cereals (maize, millet, and sorghum) in southwestern Burkina Faso. These characteristics are calculated or determined using daily climate data from a local network of 16 weather stations spanning the 1970-2013 period. A computation of the intensity and the occurrence of these phenomena during the rainy seasons helped to draw the rainy seasons' nomenclature. Findings suggest that the rainy seasons during the drought phases are characterized by low annual rainfall amount, late onset, early cessation and more frequent long dry spells (>7 days). Furthermore, the long dry spells mostly occurred during the most sensitive phases of crop development: germination at the beginning of the rainy season and flowering at the end of the rainy season. Also, the intensity and the probability of occurrence of the other extreme events (hot spells and strong winds) during rainy seasons are very high in the establishment phase. Thus, adaptation strategies to mitigate these unfavorable climate conditions include a selection of short-cycle crop varieties combined with

supplementary irrigation systems during long dry spells.

Keywords

Climate Variability, Rainy Season, Dry Spell, Hot Spell, Burkina Faso

1. Introduction

The extreme drought events recorded across West Africa in the 1970s/80s have revealed important weaknesses of agricultural systems in the region [1] [2] [3] [4]. A number of several rainy seasons with important crop failure, resulting in significant decreases in food production were recorded [5] [6] [7]. As proposed by many studies [8] [9] [10] [11], this decrease in food production is mainly attributed to the deterioration of climatic conditions, *i.e.* significant changes in the regional rainfall regime [12]-[17]. More specifically, investigations pointed out climatic factors such as delayed rainy season onsets, a decrease in the annual rainfall amount, a decrease in the number of rain events, and long dry spells. Previous studies concluded that the timing of rain events during the rainy season significantly determines crop yield [17] [18] [19]. Comparing two rainy seasons (1991 and 1992) similar with respect to annual rainfall amount, [20] found from the observations within a dense rain gauge network in Niger, different timings of rain events resulting in different impacts on agricultural production. For instance, in 1992, the rainy season produced more dry spells of more than five days long, which led to reduced millet crop yields and very low development of grass cover. It is therefore critical to conduct an analysis of rainy season's governing characteristics of crop growth to help better describe the potentialities and constraints during the growing season. From the existing literature, dry spells are often listed as the most crucial characteristic of the West African rainy season that influences crop yield [17]. Depending on its duration and timing during the growing season, a dry spell of more than ten days can reduce maize yield by more than 70% [21]. Such a magnitude of crop production decrease is likely to result in a regional food shortage. Similarly, Waonga *et al.* [19] showed from an assessment of the impacts of the planting date on maize yield, that the planting date has a great impact on maize production during the rainy seasons in Burkina Faso. They found that with an optimized planting date (OPD), the potential maize yield would increase by 15%. Furthermore, other characteristics such as hot spells and strong winds could hamper crops development or damage crops at any development stage [11] [22] [23]. Importantly, these factors are being exacerbated by the observed global warming in the region, manifested through a significant increase in temperatures [24] [25]. In the context of global warming combined with increasing population pressure and frequent yield losses due to erratic rainfall in West Africa, there is a need to improve the stability and productivity of agricultural systems.

In this study, using only in-situ observation datasets (daily data), to avoid systematic biases that occur in some of the state-of-the-art climate products [26], data of three main climate variables (rainfall, temperature and wind velocity) are collected and analyzed to derive major agriculturally relevant rainfall characteristics in West Africa: annual rainfall amount, onset and cessation of the rainy season, dry spells length, heavy rain events, hot spells length, and strong wind velocity. The probability of occurrence, the detrimental threshold, the timing of the different climatological characteristics and their inter connections in southwestern Burkina Faso are investigated and the nomenclature of the rainy seasons is drawn for the 1970-2013 period, in relation to potentialities and constraints to crop growth. This represents an important contribution which complements existing studies with respect to the number of considered rainfall characteristics [26] [27] [28] [29]. In addition, the location of the study site is particularly relevant as Sudanian regions often serve as a buffer, alleviating the effects of crop failure across the Sahel [30]. Furthermore, many studies [1] [4] [31] on the characterization of the rainfall evolution in West Africa during the last century are based on annual rainfall amount which doesn't help to describe main features of the rainy seasons.

The present study which is a contribution to the characterization of climate conditions in WASCAL (West African Science Service Center on Climate Change and Adapted Land use) intervention zones in West Africa, is structured as follows: In Section 2, we describe the study area and datasets. In Section 3, we provide an overview of the different methods adopted. In Section 4, results are presented and conclusions are drawn in Section 5.

2. Study Area and Dataset

The study is carried out in southwestern Burkina Faso, around Dano (**Figure 1**), the main town of the Ioba province. In this area, the West African Science Service Center on Climate Change and Adapted Land use (WASCAL) is monitoring key components of climate and hydrologic systems through in-situ observations since 2012. The study area is located in the Sudanian climate zone, characterized by two distinct seasons: a dry season from November to April and, a rainy season from May to October, with a mean annual rainfall amount between 900 and 1200 mm/yr. The highest monthly rainfall (>200 mm/Month) is usually recorded in August. Regarding temperatures, daily minimum (<20°C) are recorded in December (the coldest month), while daily maximum (>35°C) are recorded in April (the hottest month).

The daily rainfall data used in the study was collected from 16 weather stations installed across the Ioba province, within a radius of 100 km from Dano. Among those stations, fourteen (14) provide only rainfall data and the other two (2) (Gaoua in the south and Boromo in the North) which are synoptic stations provide data for all major climate variables: rainfall, temperature, relative humidity, wind (speed and direction) and solar radiation. The data spans the 1970-2013

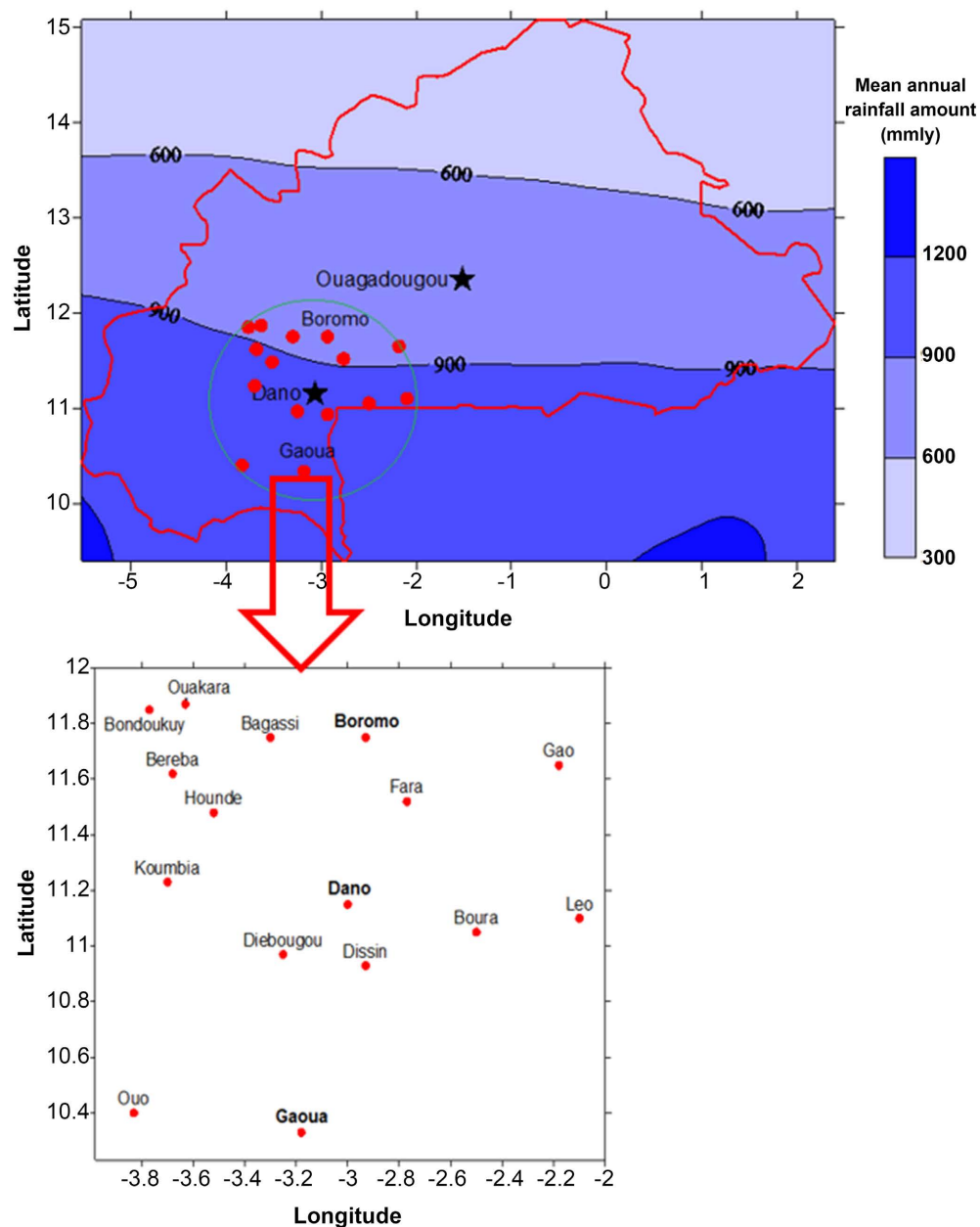


Figure 1. Location of the Study area and the observation network around Dano.

period and only four stations (Diebougou, Fara, Bagassi and Ouakara) present significant gaps with 16% (7 years), 36%, 16% and 40% (18 years) of missing data, respectively. Five stations (Gaoua, Ouo, Boura, Bereba and Boromo) do not present any gaps and the other stations have one or two years of missing data.

3. Methodology

Seven rainfall characteristics (annual rainfall amount, onset and cessation of the rainy season, dry spells, heavy rain events, hot spells, and strong winds) are computed from daily climate data recorded in the region from 1970 to 2013. This period (1970 to 2013, 44 years) of daily observations is particularly suitable

for the relevant statistical analyses. Furthermore, the considered timeframe includes two reference periods (1971-2000 and 1981-2010) defined by the World Meteorological Organization [32] for climate variability analysis.

The non-parametric variant of the Mann-Kendall test [33] is applied for linear trend detection in the considered rainfall characteristics time series. This method, which is less sensitive to the positive serial correlation, consists of detrending raw time series and extracting the lag-1 serial correlation from the detrended series (*i.e.* a trend-free pre-whitening procedure [TFPW] which should generate independent residuals series). Analyses are performed with the statistical tool R (<http://www.r-project.org/>) considering a significance level of 5% (*i.e.* a significant trend in a time series is testified by a p -value lower than 5%).

3.1. Description of the Rainy Season Characteristics

Over the region, the single rainy season from April to October is characterized by two phases: the first phase (establishment) called onset of the rainy season and the second phase (retreat) referred to as the cessation of the rainy season. Several methods were developed to determine onset and offset dates of rainy seasons in West Africa from daily rainfall amounts [9] [16] [34]. In this study, four different methods are used to determine the two main dates for each year. First, the agronomic method proposed by Balme *et al.* [35] from the original method developed by different research groups (e.g. [9] [16] [34]), identifies the two dates based on the following rules:

- The onset is defined by three days of a cumulative rainfall amount higher than 20 mm after April 1st, with no dry spell of more than seven days within the following 30 days (three dekads);
- The offset is defined by the last rainfall higher than 5 mm/day after September 1st and with no rainfall higher than 5 mm/day during the following 20 days (two dekads).

The three other methods used to identify rainy seasons onsets are defined by the amount of the daily rainfall events as proposed by [35] for the hydrology approach. The onset is defined by the first rainfall event in the year with an amount higher than a threshold without considering dry spells after the rainfall event. Three different threshold values were considered: 5 mm/day, 10 mm/d and 20 mm/d. The rainy season's offset remains the same as previously described because this characteristic is very stable from one method to another according to Ibrahim *et al.* [34].

The other characteristics of the rainy season are determined during the period defined by these two salient dates. Nonetheless, we consider the annual rainfall amount which includes rainfall events recorded outside the rainy season period instead of the seasonal rainfall. Though the two quantities present the same inter-annual variability and a difference in magnitude lower than 10% [36]. Dry spells during the rainy season are determined with the rainfall threshold of 1 mm/d. Thus, a day is considered dry if the recorded rainfall amount is less than

1 mm. Also, a dry spell is defined as a period of more than five consecutive dry days. Studies on dry spells effects on crop growth [17] [21] show that dry spells become harmful to crops when they last more than seven days. Temperature is the second climate parameter that influences crop development. Gourджи *et al.* [37] presented critical threshold values of high temperatures for crop growth: 34°C for wheat, 35°C for maize, 36°C for rice and 39°C for soybeans. The hot spells are defined by more than three consecutive days with daily maximum temperature higher than 35°C.

3.2. Statistical Distribution of Extreme Climate Events

Extreme climate events include unusual, severe or unseasonal weather; weather conditions at the extremes of the historical distributions—the range that was not observed in the past [38]. The designation of extreme climate events depends on the region and the objectives of the study [39] [40] [41]. Beniston and Stephenson [40] stated that “there is no single definition of what constitutes extreme events” and Stephenson [41] suggested that the main attributes of extreme events can be defined from the following:

- rate of occurrence (probability per time unit);
- magnitude (intensity);
- duration and timing;
- spatial scale (footprint);
- multivariate dependencies.

Extreme climate events are also characterized by their impact on human well-being as they generally entail important economic loss and mortality.

Three climate extreme events are considered in this study: heavy rain events, long dry spells and strong winds. The first extreme event often results in floods (drowned cropland); the second is the source of crop failure and the last extreme event is the source of important damages. The intensity and the occurrence of extreme events are described with the Gumbel distribution after the method by El Adlouni *et al.* [42]. This method helps to relate events' intensity to their frequency of occurrence and vice versa through the probability distribution. The intensity of extreme events is inversely proportional to the frequency:

$$\text{Intensity} \propto \frac{1}{\text{frequency of occurrence}}$$

The probability density function (pdf) of the Gumbel distribution is presented by:

$$f(x) = \frac{1}{\alpha} \exp\left[-\frac{x-\mu}{\alpha} - \exp\left(-\frac{x-\mu}{\alpha}\right)\right] \quad (1)$$

where $\alpha = \frac{\sqrt{6}s_x}{\pi}$, $\mu = \bar{x} - 0.5772\alpha$.

With x the intensity of the extreme event, \bar{x} is the observed average of the time series of extreme values, s_x the standard deviation of the time series.

Let y be the reduced variable with

$$y = \frac{x - \mu}{\alpha} \quad (2)$$

The cumulative distribution function (cdf), denoted $F(X < x)$, is the probability that the random variable X is less or equal to x (non-exceedance probability $F(x)$). The $100p$ percentile x_p is the value with cumulative probability of p . The $100p$ percentile is also called the $100(1 - p)$ percent exceedance event because it will be exceeded with probability $1 - p$. The corresponding return period T is:

$$T = \frac{1}{1 - p}.$$

$$F(x) = \exp[-\exp[-y]] \quad (3)$$

$$y = -\ln[-\ln(F(x))] = -\ln[-\ln(p)] \quad \text{Where } p = P(x \leq x_T)$$

$$y_T = -\ln\left[-\ln\left(1 - \frac{1}{T}\right)\right] \quad (4)$$

F cumulative distribution function and T the return period.

If T is known, y_T can be found from Equation (4), and once y_T is known, x_T can be computed by:

$$x_T = \mu + \alpha y_T \quad (5)$$

Thus, the intensity of x corresponding to different return periods T (and vice versa) can be computed from Equations (4) and (5).

4. Results

The seven rainfall characteristics (annual rainfall amount, onset and cessation of the rainy season, dry spells, heavy rain events, hot spells, and strong winds) are computed for each rainy season from 1970 to 2013. The inter-annual variability of each characteristic is analyzed at local and regional levels.

4.1. Description of the Different Phases of the Rainy Season

From the agronomic method of onset identification [16] [19] [34], rainy seasons in the study area begin, on average, by the end of April in the South (Gaoua), and by the end of May in the North (Ouakara) (Figure 1 & Figure 2). Thus, there is a significant lag time (one month) in the rainy season establishment between the southern part and the northern part of the study area (latitudinal extend of about 200 km). This lag time in the rainy season's onset appears over all the four criteria used to determine the rainy season's onset (Figure 3), with a seasonal standard deviation for onset of about three weeks. From West to East, however, onset occurred at the same dates along similar latitudes. Offsets are reported in the North at Ouakara at the end of September, and in Gaoua by the mid-October. A lower lag time (two weeks) in the rainy seasons' offsets (in comparison to the rainy season onset) between North and South was also noticed by Issa Lélé and Lamb [43] and Ibrahim *et al.* [34].

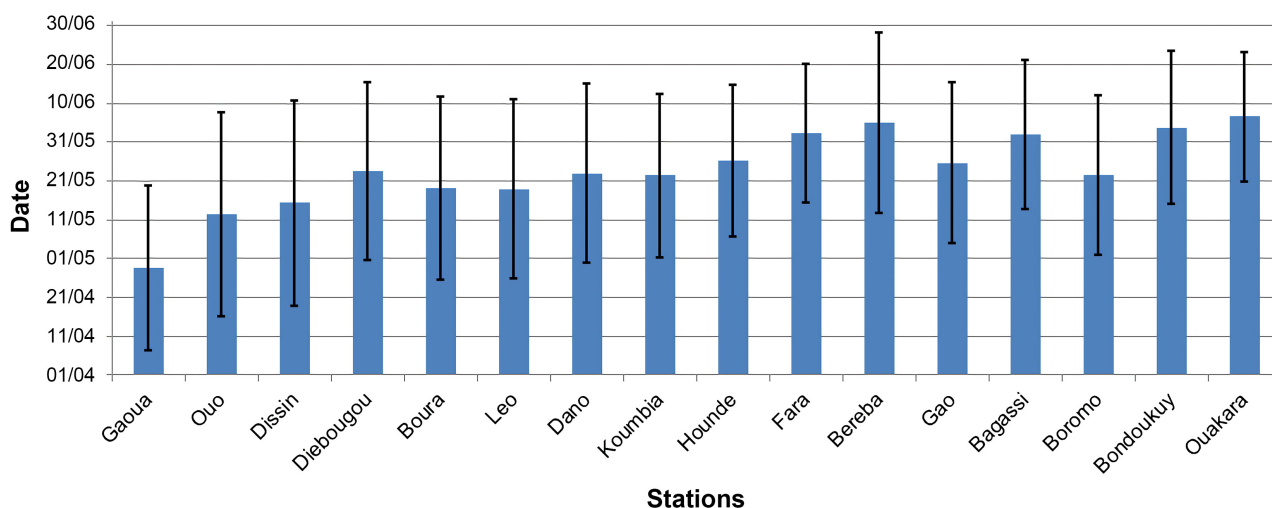


Figure 2. Average dates of the onset of the rainy season around Dano during the 1970-2013 period. The whiskers represent the standard deviation of the time series at each station for the whole period.

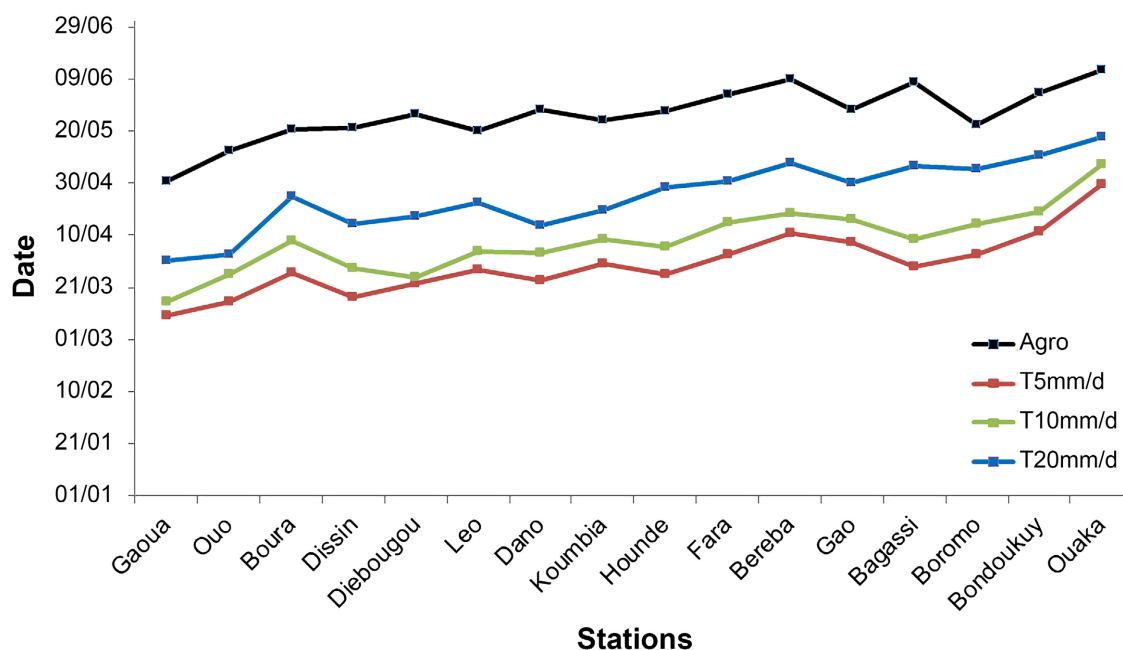


Figure 3. Mean date of the onset of the rainy season during the 1970-2013 period from four methods. Agro: Agronomy method dates, T5mm/d: first annual rainfall higher than 5 mm/d, T10mm/d: first annual rainfall higher than 10 mm/d, T20mm/d: first annual rainfall higher than 20 mm/d.

Durations of rainy seasons computed from onset and cessation dates (**Figure 2 & Figure 4**) highlight longer rainy seasons at Gaoua in the South, with an average duration of 171 days, than Ouakara in the North with an average duration of 123 days.

The inter-annual variability of the first three characteristics of rainy seasons (onset, offset and duration) differs from one station to another. The only common aspects between the 16 stations are the mean standard deviations which are about three weeks for the onset rainy season (ORS) and about two weeks for

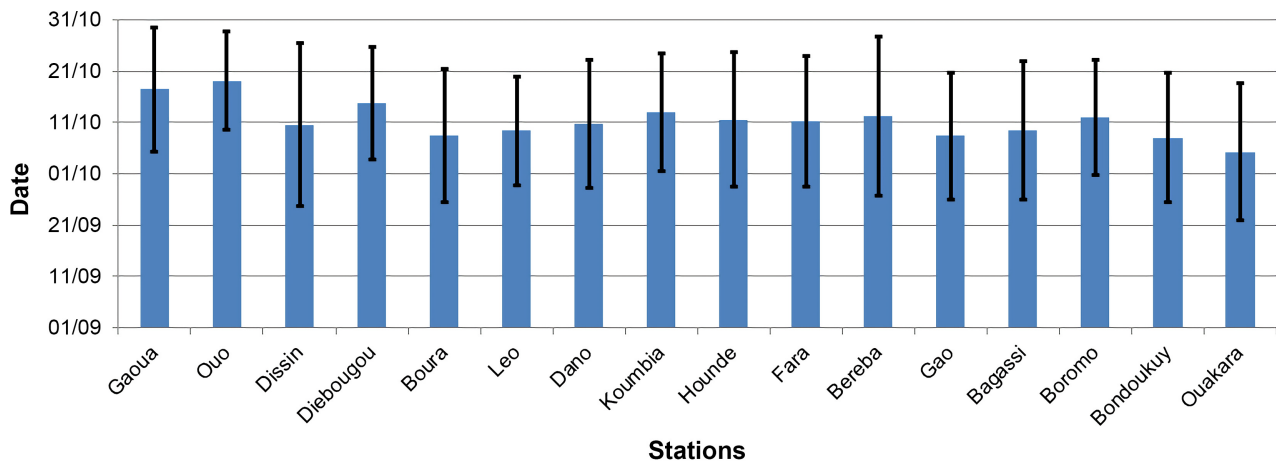


Figure 4. Average dates of the cessation of the rainy season around Dano over the 1970-2013 period. The whiskers represent the standard deviation of the time series at each station for the whole period.

cessation of the rainy season (CRS). The difference in the length of the mean standard deviations shows that the onset dates are more variable than the offset dates.

The Mann-Kendall test of general trend significance reveals no significant linear trend (p -values > 0.5) in the inter-annual variability of the rainy season's onsets over the 1970-2013 period (Figure 5). However, there is a significant increase in the number of delayed onsets between the 1970-1985 period and the 1986-2013 period. The two extreme curves of onset dates (lower curve, 5 mm/d threshold, and upper curve, agronomy method) show an increase in the number of delayed onsets since 1986. The differences, for both methods, between the two periods (1970-1985, 15 years, and 1986-2013, 27 years) for earliest, latest and mean dates of season's onset are about one week on average. For the 5 mm/d threshold method, onset occurred before April 4th during the 1970-1985 period, in contrast to the following period where ORS occur after April 10th for 9 out of 15 years. Using the agronomy criteria, ORS occurred before May 26th for 10 out of 15 years before 1985, and 15 out of 27 years after May 26th for the second period.

Delayed ORS and early CRS result in shorter rainy seasons. Between the two periods (1970-1985 and 1986-2013), the average rainy season duration in the study area has decreased by about two weeks. Table 1, displaying inter-annual correlations between onset and offset dates shows that the signs of correlation coefficients at 12 out of 16 stations are negative. Even though the correlation is not significant at most stations, their negative signs reflect a delayed onset followed by an early offset, thus a shorter rainy season.

4.2. Inter-Annual Evolution of the Annual Rainfall Amount

Figure 6 shows no significant linear trend in the evolution of the mean annual rainfall amount in the study area over the 1970-2013 period, as the Mann-Kendall p -values are higher than 0.7. However, significant wet and dry years can be identified for the 1970-2013 period from the mean annual rainfall. Considering only

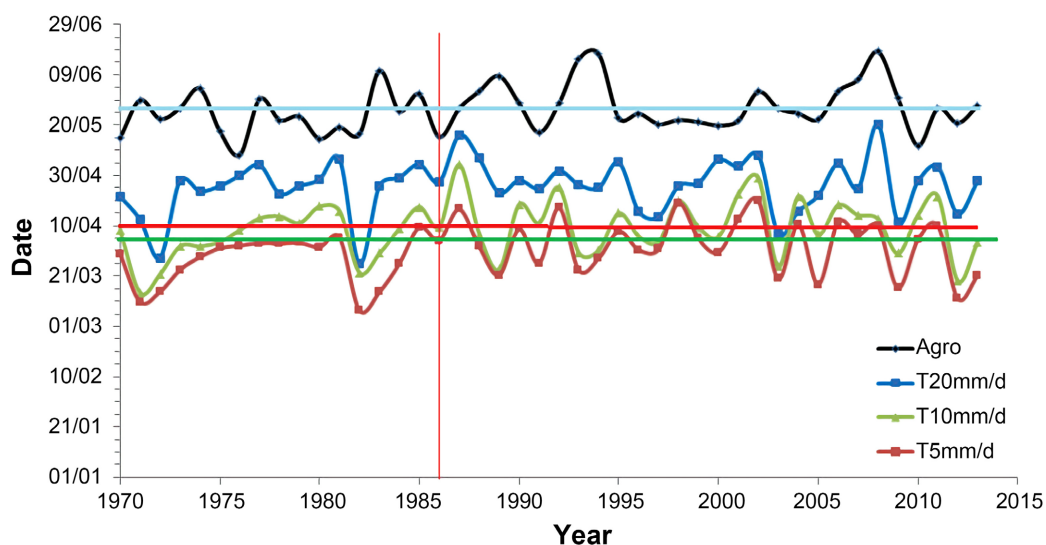


Figure 5. Inter-annual evolution of the mean date of the onset of the rainy season over the study area from four criteria. The vertical red line represents 1986; the bottom green horizontal line represents April 4th; the red horizontal line represents April 10th; and the horizontal light blue line represents May 26th.

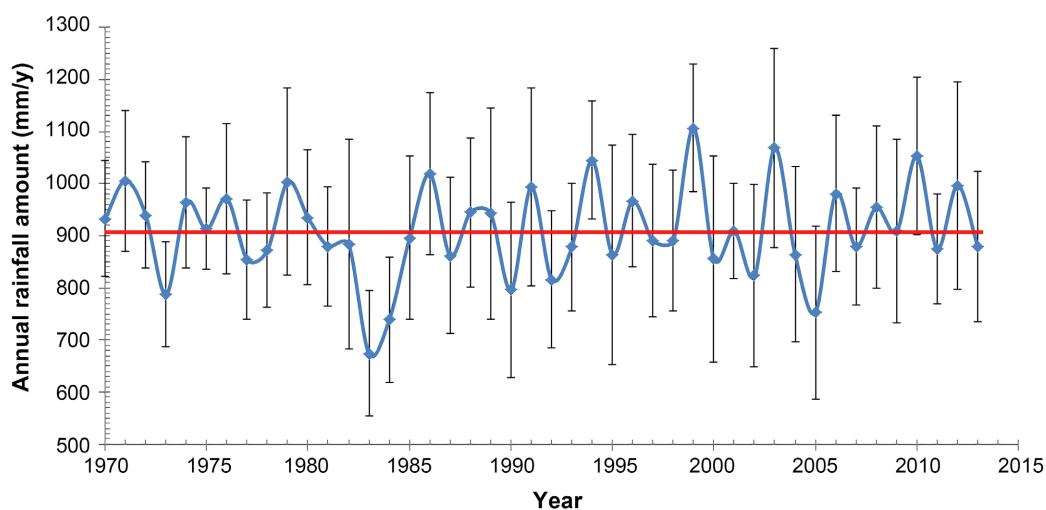


Figure 6. Inter-annual evolution of the mean annual rainfall amount over the 1970-2013 period. The whiskers represent the standard deviation within the 16 stations for each year and the horizontal red line represents the mean annual rainfall amount for the whole period.

Table 1. Inter-annual correlation between the rainy season's onset and offset.

Stations	Correlation	Stations	Correlation
Gaoua	-0.11	Houde	-0.05
Ouo	-0.04	Fara	0.07
Boura	-0.27	Bereba	0.06
Dissin	-0.55	Gao	0.06
Diebougou	0.34	Bagassi	-0.26
Leo	-0.08	Boromo	-0.16
Dano	-0.26	Bondoukuy	-0.23
Koumbia	-0.05	Ouaka	-0.31

the inter-annual average of 910 mm/y over the 1970-2013 period (Figure 6), six years (1973, 1983, 1984, 1990, 1992, and 2005) present significant low annual rainfall amount, and another six years (1971, 1986, 1994, 1999, 2003, and 2010) present significant high annual rainfall amount. Figure 7 presents the proportion of stations concerned by either a deficit or an excess in the annual rainfall amount with regard to the inter-annual average during the 1970-2013 period. This figure reveals 13 very dry years (with more than 60% of the network affected) and 15 very wet years. Nonetheless, all stations present a deficit in 1983 and in 1984, and an excess in 1999. Furthermore, the comparison between Figure 6 and Figure 7, *i.e.* considering magnitudes of the deficit or excess, and number of stations affected, shows that five years (1973, 1983, 1984, 1990, and 2005) are extremely dry (a shift of more than 10% and more than 80% of the network affected), and six years (1971, 1986, 1994, 1999, 2003, and 2010) are extremely wet (an increase of more than 10% and more than 80% of the network affected). Over the 1970-2013 period, 1983 is the driest year and 1999 is the wettest year.

Interesting findings are also derived from the analysis of the spatial distribution of annual rainfall during the driest year (1983) and the wettest year (1999). For instance, Figure 8 which presents the spatial distribution of annual rainfall deficit in 1983, highlights that this drought episode did not affect all the locations seamlessly. The highest deficit, more than 65%, is recorded around Leo in the East, while it is less than 25% in the West along the axis from Diebougou to Bondoukuy and around Gao in the Northeast. This spatial disparity also appears for the wettest year of 1999 (Figure 9): less than 20% along the axis from Bagassi to Boura, and higher than 40% around Gao. The two figures (Figure 8 & Figure 9) do not show any latitudinal organization in the annual rainfall amount distribution in the region in contrary to onset and cessation dates of the rainy season.

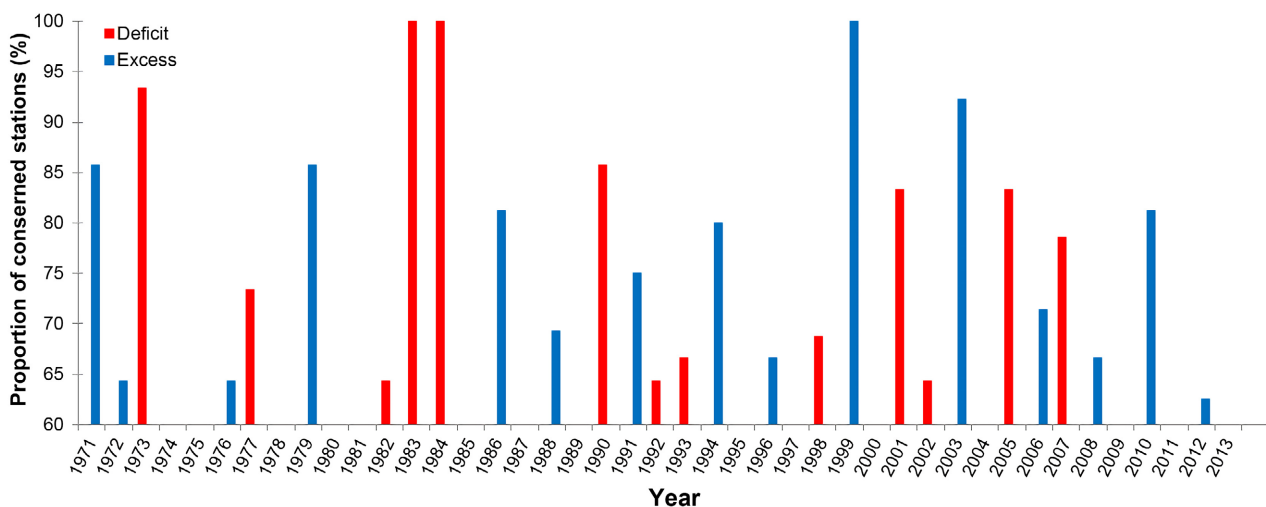


Figure 7. Proportion of stations concerned by significant wet (excess) and significant dry (deficit) years during the 1970-2013 period.

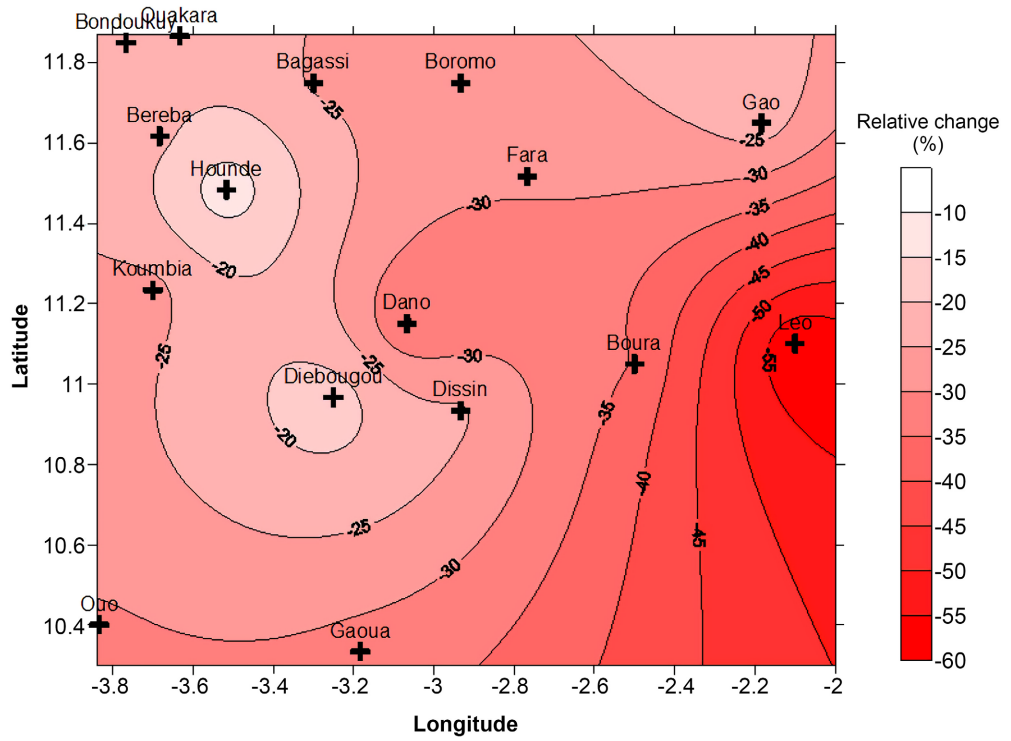


Figure 8. Spatial distribution of the deficit in the annual rainfall amount in 1983.

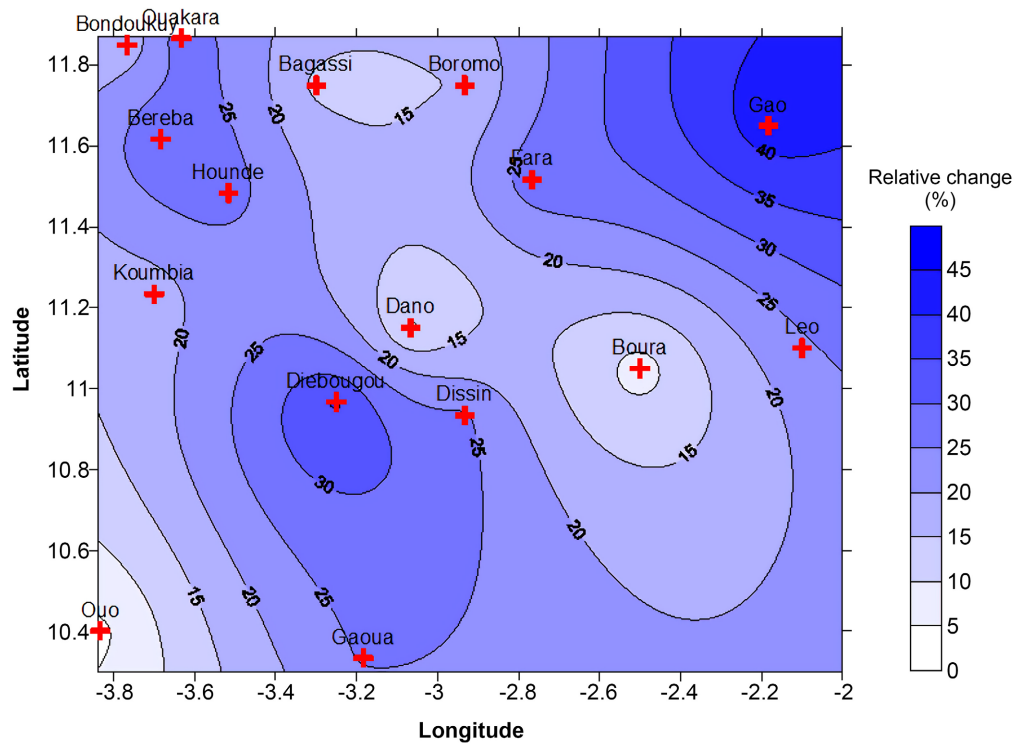


Figure 9. Spatial distribution of the excess in the annual rainfall amount in 1999.

4.3. Distribution and Evolution of Heavy Rainfall Events

The intensities of the annual maximum rainfall events in the study area vary

from 26 mm/d to 187.5 mm/d, with an average of about 70 mm/d for the region (Figure 10). The highest intensities for all the stations during the 1970-2013 period are higher than 120 mm/d (Table 2). Thus, the extreme intensity (with regard to flood) of 100 mm/d [44] can be exceeded in the study area. The annual heaviest rainfall events are mainly recorded in the heart of the rainy season: from mid-July to end of August. However, isolated intense rainfall events can occur outside this main period: rainfall amounts of 123 mm/d and 110 mm/d were recorded respectively on the 29/04/1998 at Boromo and on the 31/10/1974 at Gaoua. Furthermore, Figure 11 & Figure 12 show the high spatial disparity that characterizes extreme rainfall intensity distribution in the region during a rain event.

Table 2. Strongest rain events at the different stations over the 1970-2013 period.

Stations	Maximum intensity (mm/d)	Year of record	Stations	Maximum intensity (mm/d)	Year of record
Gaoua	154.4	1992	Hounde	100.8	1970
Ouo	137.4	1986	Fara	132	2012
Dissin	172	2008	Bereba	123	2007
Diebougou	149.5	1986	Gao	119.8	1982
Boura	136	1989	Bagassi	178.8	1971
Leo	187.5	2007	Boromo	134	2008
Dano	176.9	1981	Bondoukuy	145.6	1991
Koumbia	136.8	1978	Ouakara	161.5	1991

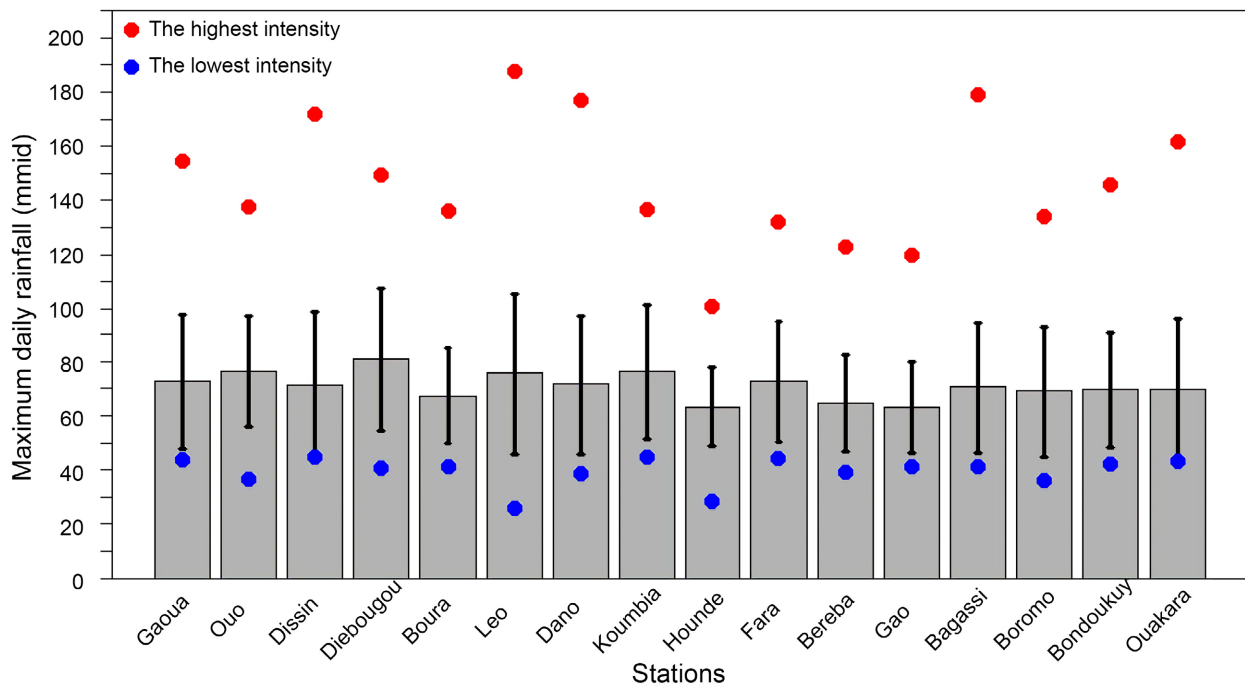


Figure 10. Intensity of annual maximum daily rainfall in the study area. The whiskers represent the standard deviation at each station over the whole period.

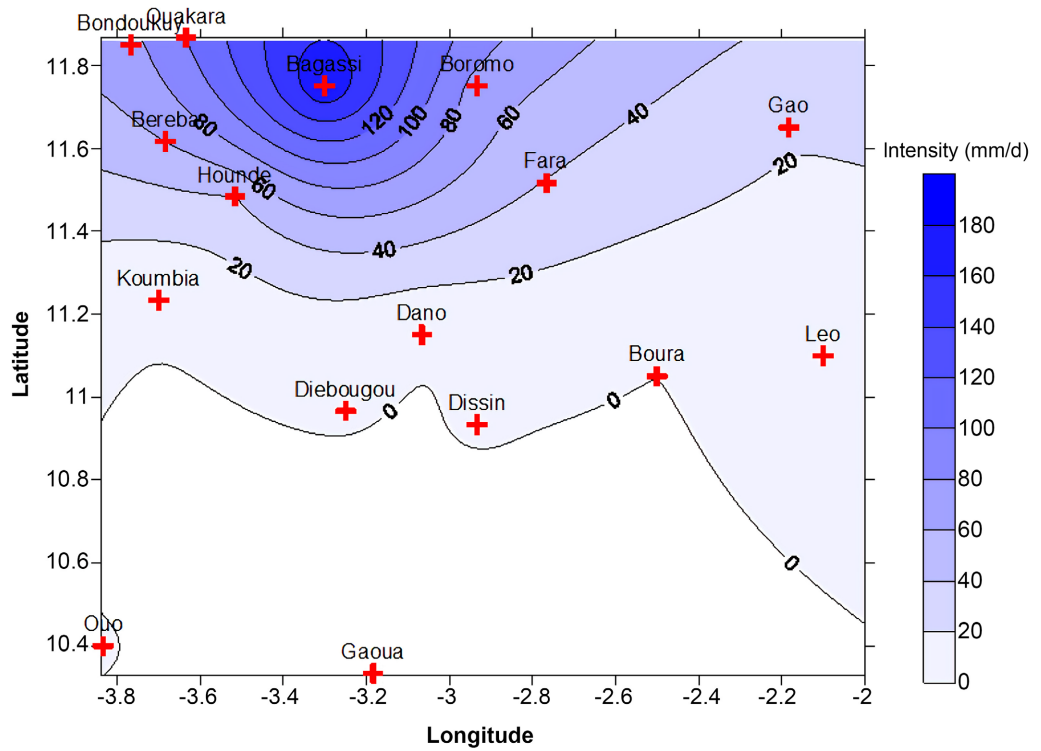


Figure 11. Spatial distribution of the rainfall intensity during the rain event on 17/08/1971.

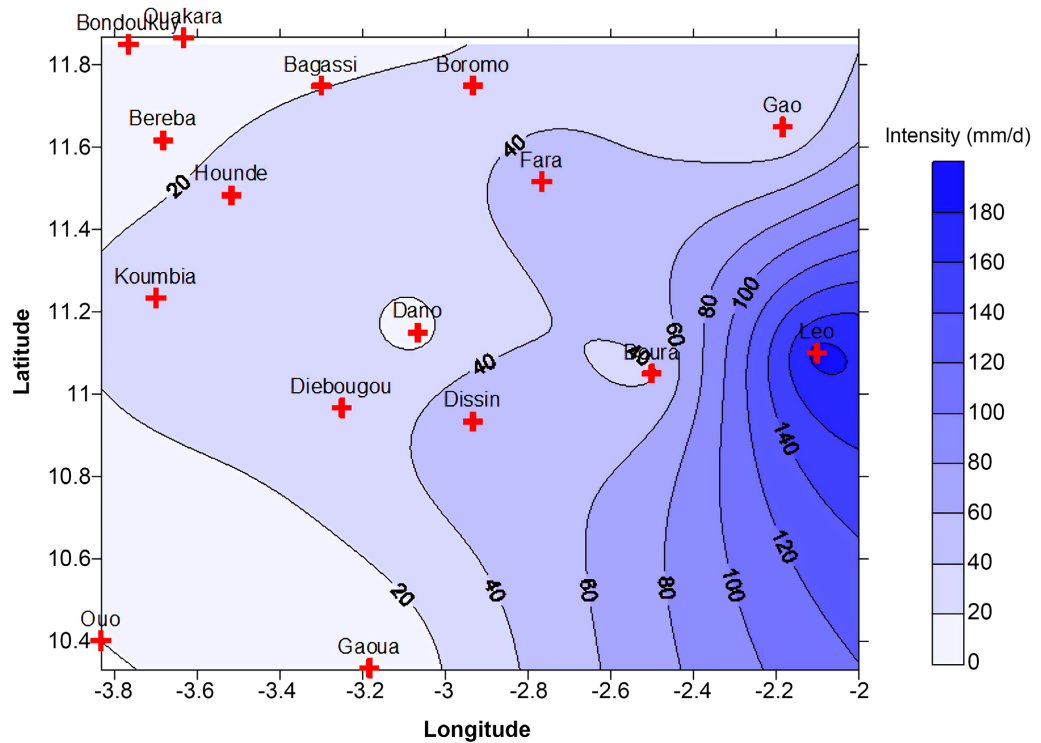


Figure 12. Spatial distribution of the rainfall intensity during the rain event on 28/07/2007.

Despite the important amount of rainfall at Bagassi (179 mm/d) during the rain event of 17/08/1971, Diebougou, 90 km to the South, recorded no rainfall. This

same spatial contrast appears for the heaviest event recorded on 28/07/2007 at Leo in the east with 187.5 mm/d, whereas the Ouo station, 210 km in the South-west received no rainfall. **Table 2** shows that the sixteen stations did not record the highest intensity in the same year during the 1970-2013 period; a maximum number of two stations recorded the same high intensities in 1986, 1989, 1991, 2007 and 2008. In the same way with the annual rainfall amount, the inter-annual evolution of the intensity of the annual heavy rain events presents no significant trend from 1970 to 2013 (p -values > 50%). There is only a slight increase in the mean intensity during the 1986-1999 period in comparison to the 1970-1985 period (figure not shown).

The cumulative density functions of the extreme events are very similar in the region (**Figure 13**). The cumulative density curves for the three main stations (Gaoua, Dano and Boromo) are very close for low frequency ($F > 0.97$) and high frequency ($F < 0.4$). **Figure 13** shows that the median intensity of the annual heaviest rain event in the region is about 80 mm/d. This intensity represents the highest intensity recorded in the study area at least once during two consecutive years. The probability that a rain event will not exceed 100 mm/d during the rainy season varies from 72% at Gaoua to 75% at Boromo (**Figure 13**). This probability means that this threshold could not be exceeded more than once within a period of five years. The one hundred-year and one thousand-year are about 184 mm/d and 250 mm/d, respectively. The recorded highest rainfall of 187.5 mm/d in the region corresponds to a return period of about 150 years.

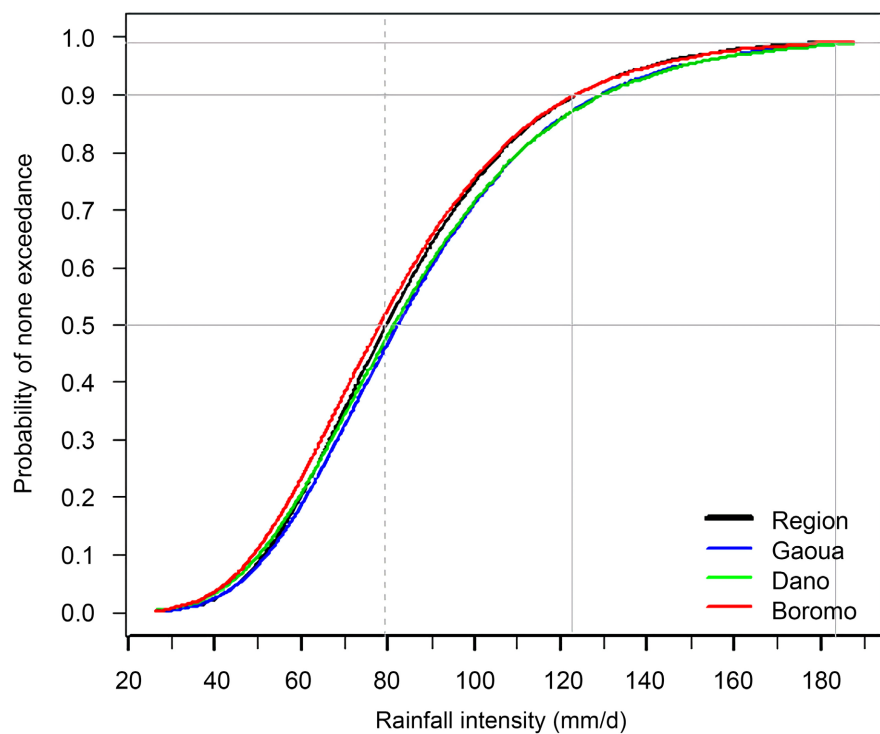


Figure 13. Cumulative probability of heavy rain events in the region. Horizontal lines represent the 0.5, 0.9 and 0.99 cumulative probabilities and the vertical lines represent the corresponding quantiles 79 mm/d, 122 mm/d and 183 mm/d.

4.4. Dry Spells Timing and Spatial Extension

Dry spells during the rainy season are mentioned in many studies [17] [21] [45] [46] as a key factor hindering crop growth in the Sudano-Sahelian zone. The impacts of dry spells on crops depend on the period of their occurrence during the growing season, as well as their duration and frequency [21]. The probability that a day (occurrence of dry spell divided by the 44 years of the whole period of observation) is part of a dry spell of more than five days is very large (>60%) at the beginning and at the end of the rainy season (Figure 14). A dry spell of more than two weeks can occur at any time during the season, the probability of their occurrence is higher than once in every ten years around the 1st of May, mid-July and at the end of September. Table 3, showing the mean number of dry spells during the rainy season, displays eight dry spells of 5 to 7 days, three dry spells of 8 to 13 days, and one dry spell longer than two weeks.

Figure 15 presents the duration of seasonal longest dry spells underlines those dry spells can even exceed two weeks. Over the 16 stations, the maximum duration (red dots on Figure 15) at each station is higher than 15 days. This duration is reported to be prejudicial to all crops at any stage [21]. The inter-annual average for all 16 stations is about ten days (Figure 15), but the longest dry spells exceed two weeks in 27 out of the 44 years of observations (Figure 16). From a socio-economic and climatic survey made in the study area in May 2014 [30], majority of farmers emphasized that the tolerance level to dry spells for maize,

Table 3. Mean number of dry spells length per station over the 1970-2013 period.

	D5-7	D8-13	D ≥ 14
Average	8	3	1
Standard deviation	2	1	1

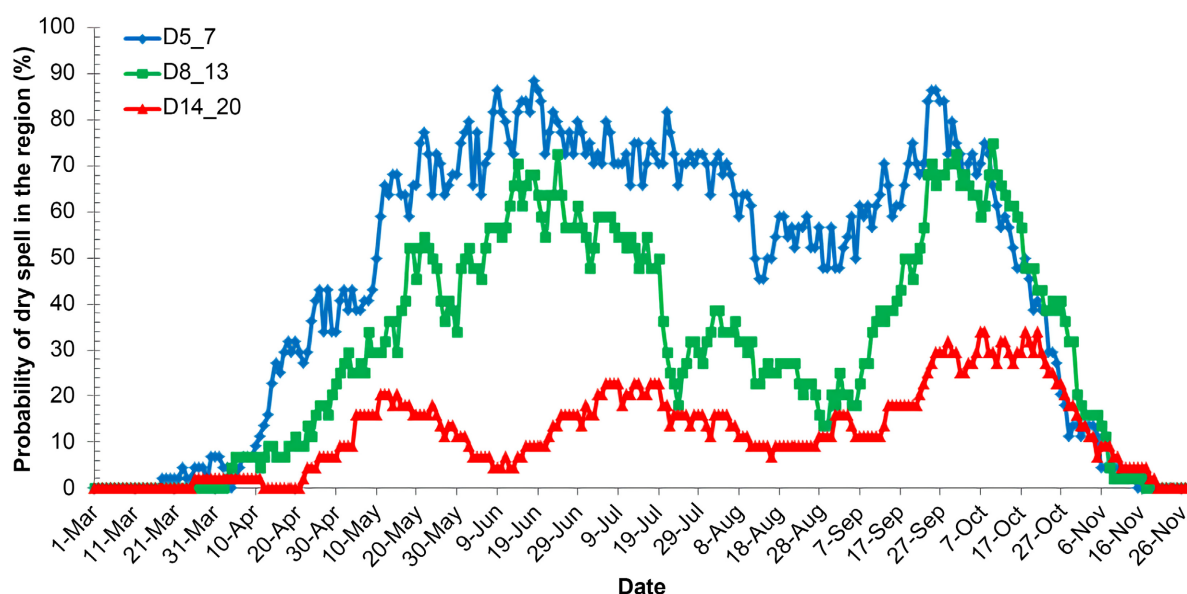


Figure 14. Probability in the study area of a day to be part of a dry spell period.

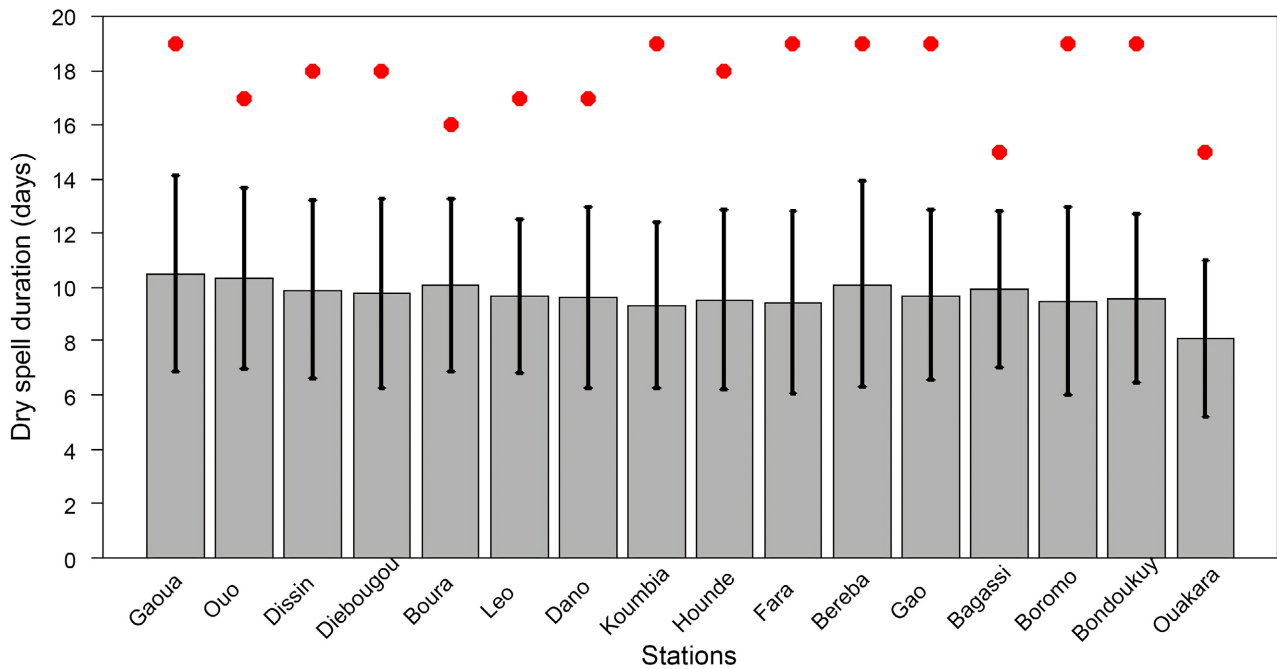


Figure 15. Mean duration of the seasonal longest dry spell in the study area during the 1970-2013 period. The whiskers represent the standard deviations at each station over the whole period. The red dots represent the maximum duration during the 1970-2013 period.

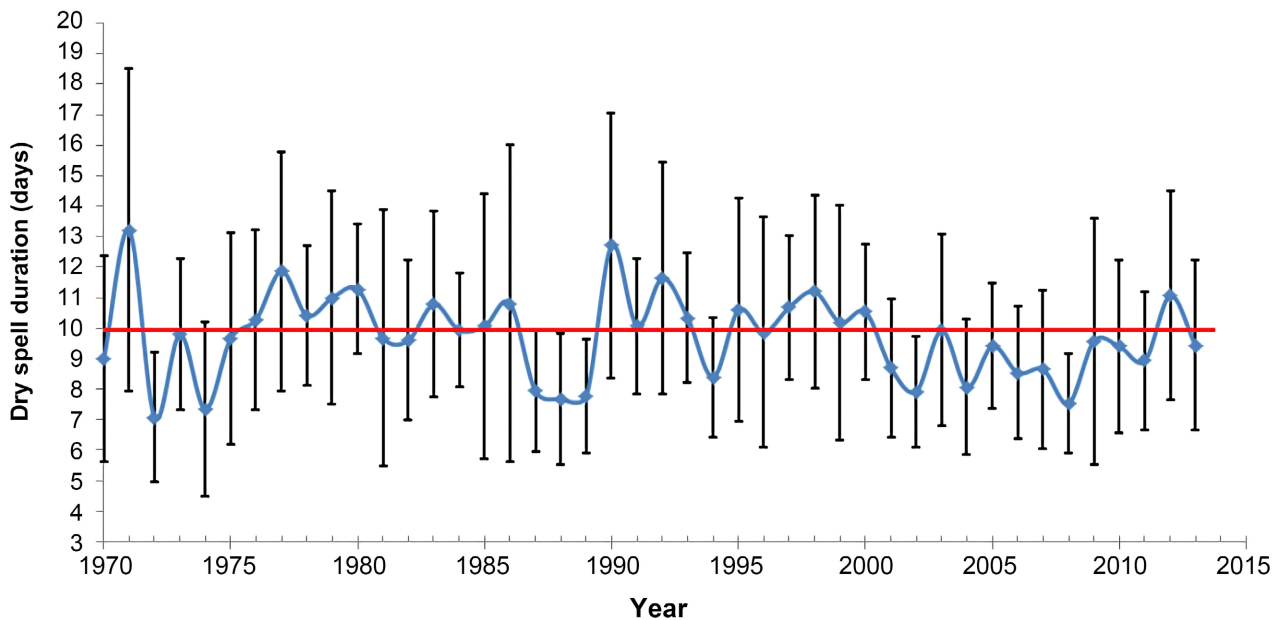


Figure 16. Inter-annual evolution of the mean longest dry spell over the 1970-2013 period. The whiskers represent the standard deviations for the 16 stations for each year, and the horizontal red line represents the mean dry spell duration for the whole period.

cotton, millet and sorghum during the critical phase of flowering are 10 days, 10 days, 13 days and 13 days, respectively. Thus, from 1970 to 2013, the critical level of dry spells for the main crops in the study area has been surpassed several times. **Figure 16** shows two years with very long dry spells (>12 days): in 1971

and in 1990. In 1971, seven stations recorded dry spells of more than 15 days, and in 1990, six stations recorded dry spells of more than 15 days.

Table 4 presents the main quantiles of dry spell duration for four return periods: 10, 20, and 50, 100 years. A Dry spell of two weeks duration corresponds to the decadal dry spell and the three weeks duration dry spell corresponds to one-hundred-year return period dry spell. From **Table 4** it appears that dry spells are much longer in the South than in the North: a difference of 3 to 4 days for the different quantiles between the South (Gaoua or Ouou) and the North (Bondokuy or Ouakara).

4.5. Description of Hot Spells Timing during the Rainy Season

Hot spells are also considered as an important climate risk for crop development [47]. In fact, long hot spells during the rainy season contribute to increasing crop evapotranspiration, drying out crops and therefore reducing significantly crop yields. In **Figure 17**, the representation of seasonal maximum temperatures at Gaoua and Boromo, indicates that maximum temperatures are always higher than 38.5°C. Thus, the critical temperatures for maize and rice were exceeded in

Table 4. Main quantiles of dry spell duration.

Stations	Return periods (year)			
	10	20	50	100
Gaoua	15	17	20	22
Ouo	15	17	19	21
Dissin	14	16	18	20
Diebougou	14	16	19	21
Boura	14	16	18	20
Leo	13	15	17	19
Dano	14	16	18	20
Koumbia	13	15	17	19
Hounde	14	16	18	20
Fara	14	16	18	20
Bereba	15	17	20	22
Gao	14	16	18	20
Bagassi	14	15	17	19
Boromo	14	16	19	20
Bondokuy	14	15	18	19
Ouakara	12	14	16	17
Average	14	16	18	20
STD	1	1	1	1

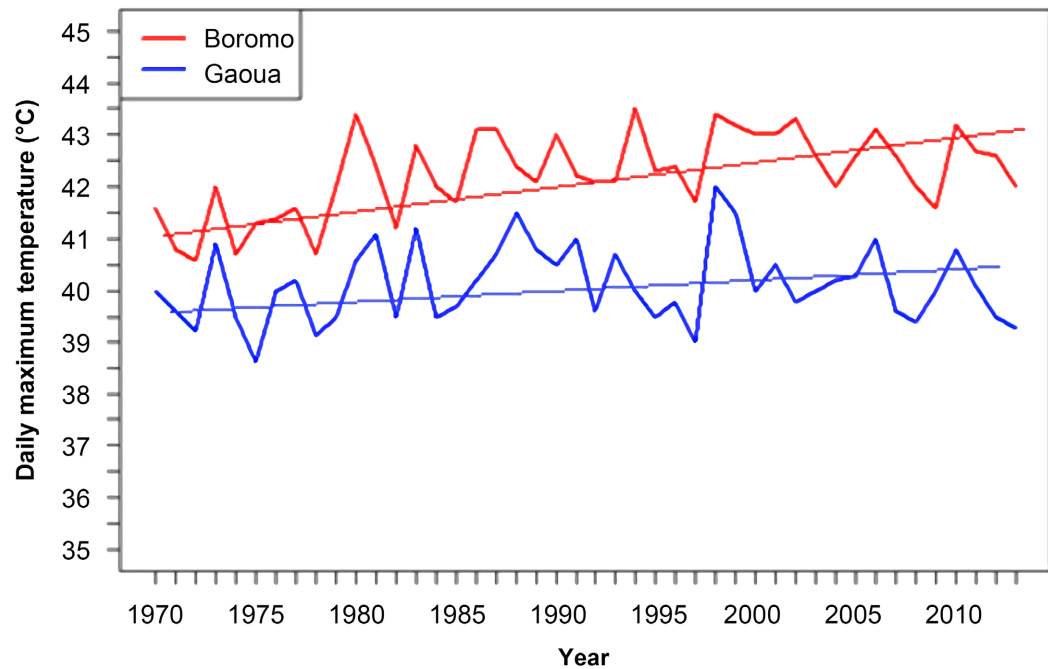


Figure 17. Evolution of the annual daily maximum temperature in the study area. Continuous lines represent linear trends.

all of the 44 rainy seasons of observation. This figure also shows an increasing trend in the daily maximum temperature from 1970 to 2013, the Mann-Kendall test p -values are lower than 1%. The difference between the average over the 1970-1979 period and the 2004-2013 period is about 0.5°C .

The extreme temperatures ($>35^{\circ}\text{C}$) occurring over more than three consecutive days (called hot spells in this study) during the rainy season are mostly recorded at onset and cessation periods (Figure 18). The probability that a day (occurrence of hot spell divided by the 44 years of the whole period of observation) is part of a hot spell increases from South (Gaoua) to North (Boromo). The hot spells probability of occurrence is nil at Gaoua from mid-July to the end of September and nil at Boromo from mid-July to mid-September. Moreover, the main period of hot spell ends in mid-June and begins again after the 7th of October at Gaoua, as opposed to ending in mid-July and starting again in mid-September at Boromo. This period of no hot spells is called thereafter, NilhotsPELL. Furthermore, this period would correspond to the heart of the rainy season. The lag time of the NilhotsPELL between the two stations is about one month for the beginning and two weeks for the ending. Thus, the length of the NilhotsPELL like the rainy season duration decreases from the North to the South of the region. Also, the difference in the two durations of the two lag times is similar to the difference in the lag times between the onset (from South to North) and the offset (from the North to the South) of the rainy season.

4.6. Description of Wind Speed during the Rainy Seasons

The mean wind speed in the region is about 1.5 m/s from the measurements at

the two synoptic stations (Gaoua and Boromo). The maximum values of wind speed recorded during the whole period from 1970 to 2013 are: 5.9 m/s at Gaoua and 6.1 m/s at Boromo. Two different trends appear in the evolution of the seasonal strong wind speed (Figure 19): a significant increase at Gaoua during the

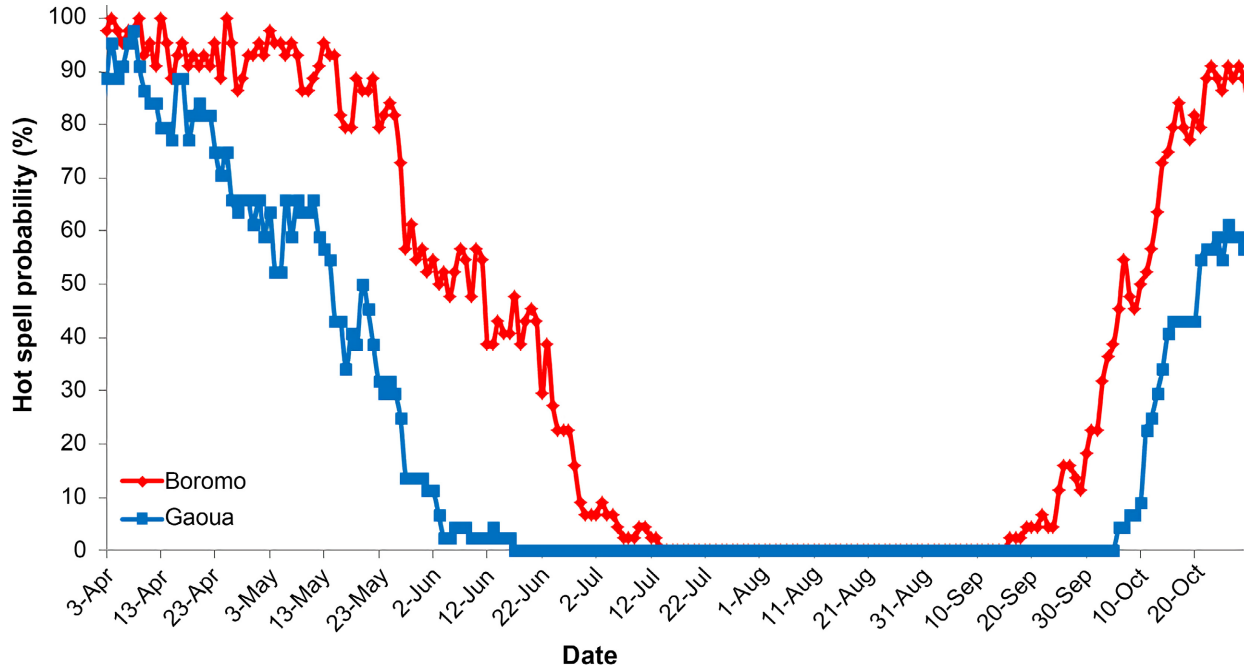


Figure 18. Probability of a day to be part of a hot spell (temperature ≥ 35 °C) during the different rainy seasons of the 1970-2013 period.

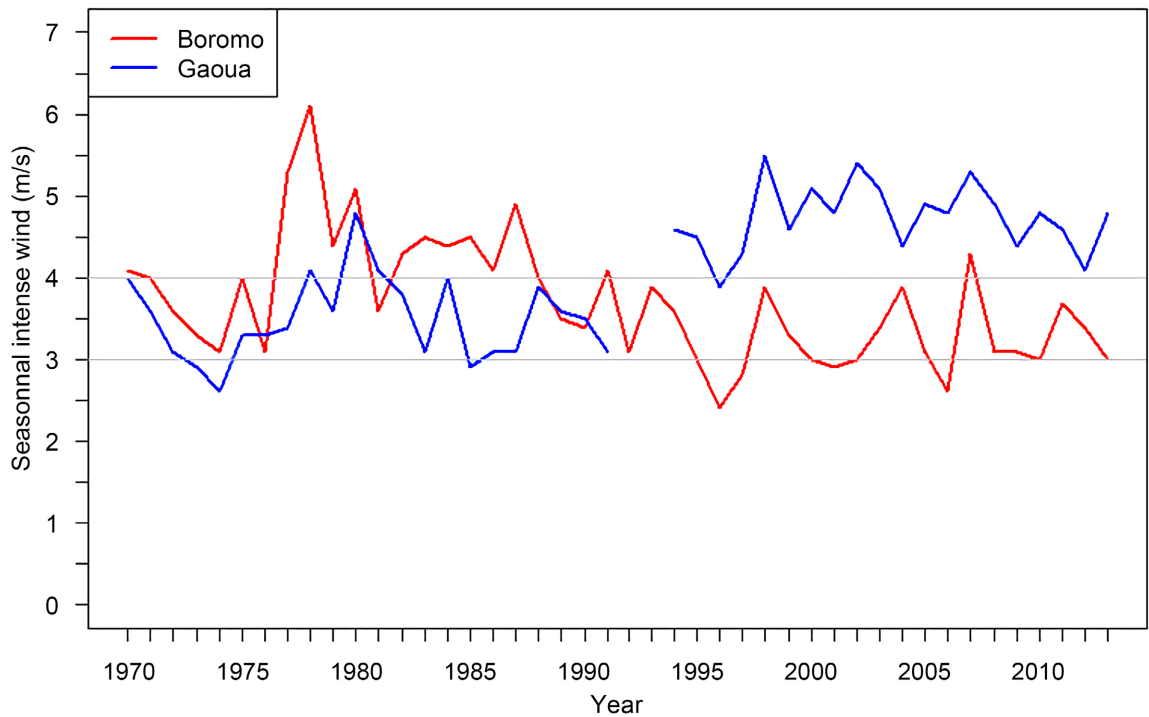


Figure 19. Seasonal maximum speed of wind at Boromo and Gaoua during the 1970-2013 period.

1996-2013 period (an average of 4.5 m/s) in comparison to the 1970-1990 period (an average of 3.5 m/s) and a decrease at Boromo during the 1996-2013 period (an average of 3.5 m/s) in comparison to the 1970-1990 period (an average of 4.2 m/s). An identification of period of high occurrence of strong winds (above 3 m/s) within the rainy season at Boromo and Gaoua (**Figure 20**), shows a high frequency of these winds at the beginning of the season: from April to the end of May. Youm *et al.* [48] investigating seasonal variation in wind speed over Senegal from a set of four stations. The frequency of strong winds is higher at Gaoua in comparison to Boromo. **Table 5**, displaying the classification of wind effects from their speeds, shows that the strong winds (above 3 m/s) recorded in the study area would certainly have negatively affected crops.

Table 5. Classification of wind speeds and effects on crops and trees.

Type of wind	Description	Visible signs
0—Calm	less than 1 mph (0 m/s)	Smoke rises vertically
1—Light air	1 - 3 mph 0.5-1.5 m/s	Smoke drifts with air, weather vanes inactive
2—Light breeze	4 - 7 mph 2-3 m/s	Weather vanes active, wind felt on face, leaves rustle
3—Gentle breeze	8 - 12 mph 3.5-5 m/s	Leaves & small twigs move, light flags extend
4—Moderate breeze	13 - 18 mph 5.5-8 m/s	Small branches sway, dust & loose paper blows about
5—Fresh breeze	19 - 24 mph 8.5-10.5 m/s	Small trees sway, waves break on inland waters
6—Strong breeze	25 - 31 mph 11-13.5 m/s	Large branches sway, umbrellas difficult to use
7—Moderate gale	32 - 38 mph 14-16.5 m/s	Whole trees sway, difficult to walk against wind
8—Fresh gale	39 - 46 mph 17-20 m/s	Twigs broken off trees, walking against wind very difficult
9—Strong gale	47 - 54 mph 20.5-23.5 m/s	Slight damage to buildings, shingles blown off roof
10—Whole gale	55 - 63 mph 24-27.5 m/s	Trees uprooted, considerable damage to buildings
11—Storm	64 - 73 mph 28-31.5 m/s	Widespread damage, very rare occurrence
12—Hurricane	over 73 mph over 32 m/s	Violent destruction

Source:

http://gyre.umeoce.maine.edu/data/gomoos/buoy/php/variable_description.php?variable=wind_2_speed.

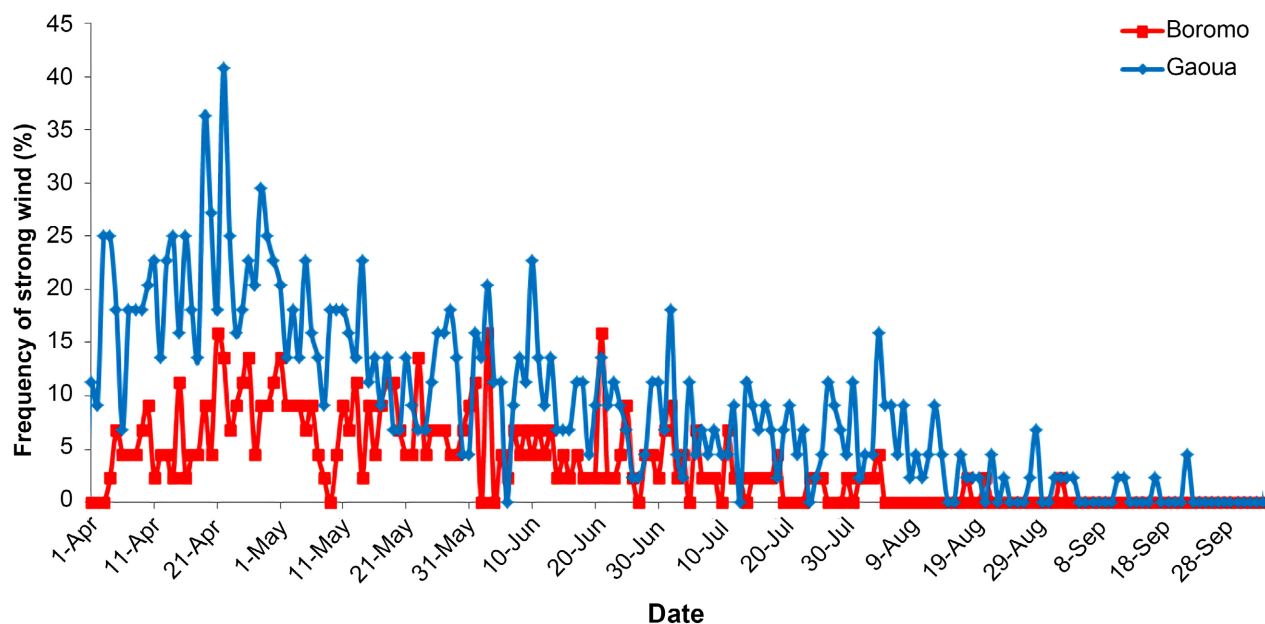


Figure 20. Frequency of intense wind (speed ≥ 3 m/s) over the study area during the 1970-2013 period.

5. Summary and Discussions

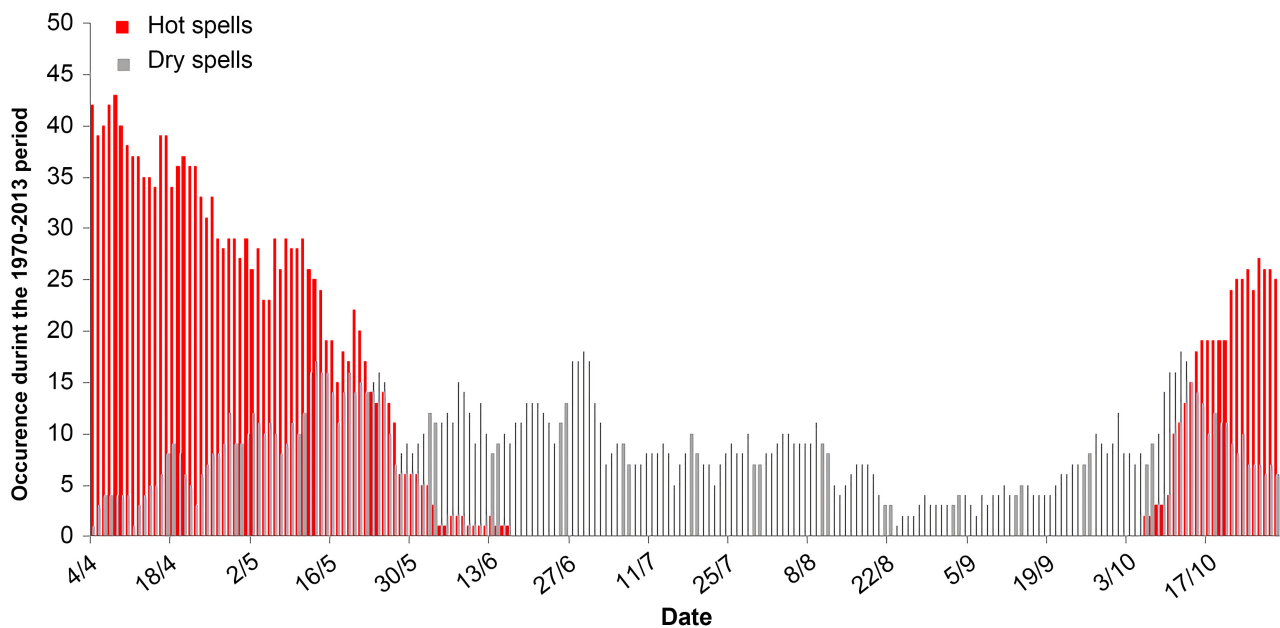
The southwestern part of Burkina Faso, like all of West Africa [1] [49], has recorded a high inter-annual variability in the annual rainfall amount during the 1970-2013 period. Even if no significant linear trend appears in the annual rainfall time series from 1970 to 2013, significant dry/wet years have been recorded in the region. These extreme years appear along the whole period and there is no decade with only one type of extreme year (dry or wet). Investigation of these extreme years revealed that 1983 and 1984 are the driest consecutive years with -27% and -18% decrease in the annual rainfall amounts, respectively. In contrast, 1999 recorded the highest annual rainfall amount with an increase of $+22\%$. The comparison of rainy season characteristics during dry and wet years (Table 6) indicated later onsets and earlier cessations in dry years relatively to wet years, resulting in shorter rainy seasons for dry years: about one month of lag difference between the dry years of 1983 and the wet year of 1999 (Table 6). The number of rainy days in 1983 is also about half the number of rainy days in 1999. Furthermore, there is a lengthening of dry spells and an increase in their frequency during the dry years. However, there is no significant change in the mean amount of daily rainfall despite an increase in the maximum daily rainfall amount for wet years. The seasonal maximum daily amount of rainfall is also not linked to the wetness or dryness of the season: the correlation coefficient between the annual rainfall amounts and the annual maximum daily rainfall amounts is less than 0.3 at all the stations. These results correspond to the findings of Ibrahim *et al.* (2014) for the whole country from the synoptic network data on the decrease of the annual rainfall amount between the wet period of 1961-1970 and the dry period of 1971-1990.

The rainy seasons in the southwestern part of Burkina Faso are also characterized

Table 6. Rainy season's characteristics for the two extreme years (driest and wettest) at the three main stations.

Characteristics	Gaoua		Boromo		Regional*	
	1983	1999	1983	1999	1983	1999
Rainy season onset	7-May	17-May	11-Jun	5-May	29-May	21-May
Rainy season offset	22-Sep	18-Nov	22-Sep	7-Oct	27-Sep	18-Oct
Season duration	139	186	104	156	122	151
Number of rain days	38	75	38	61	30	58
Mean daily rainfall (mm/d)	12	13	12	12	17	17
Maximum rainfall event (mm/d)	71	49	55	119	60	83
Number of dry spells	6	4	4	8	6	5
Mean dry spell duration (days)	9	8	8	7	7	8

*Regional represent the average from the 16 stations.

**Figure 21.** Occurrence of hot and dry spells at Gaoua during the 1970-2013 period.

by the occurrence of dry spells (more than five consecutive days with rainfall amount lower than 1 mm) and hot spells (more than three consecutive days with maximum temperature higher than 35°C). Both characteristics present high probability at the starting and the ending of the rainy season. However, the correlation between the two characteristics with regard to their daily occurrence is very weak (less than 0.1 at Gaoua and Boromo). **Figure 21** shows different trends between the daily occurrence of dry spells and the daily occurrence of hot spell at Gaoua during the 1970-2013 period. Unlike dry spells which can occur along the whole rainy season, hot spells do not occur from mid-June to end of September at Gaoua. The same relationship between dry spells and hot spells ap-

pears at the second synoptic station of Boromo in the North.

Furthermore, the southwestern part of Burkina Faso records strong winds (which could make large tree branches motion) with speeds higher than 5 m/s. Strong winds which usually precede storms in the Sudano-Sahelian zone are mainly recorded during the establishment phase of the rainy season. These windstorms are sources of important damages such as detachment of roofs, trees and crops falling, and soil erosion in the region [50] [51] [52].

6. Conclusions

During the last four decades (1970-2010), the rainy seasons in West Africa were characterized by high inter-annual variability. This study on the description of agriculturally relevant rainfall characteristics in southwestern Burkina Faso, during the 1970-2013 period, reveals five extremely dry years (1973, 1983, 1984, 1990, and 2005) and six extremely wet years (1971, 1986, 1994, 1999, 2003, and 2010). Our findings indicate that during dry years, very late onsets and very early offsets, contribute towards lowering their agricultural potentialities through a significant decrease in the amount of rain events and a lengthening of dry spells. The duration and probability of occurrence of the other extreme events (hot spells and strong winds) in the rainy season are very high in the study area at the beginning of the rainy season.

The results presented in this study show that rainy season potentialities and constraints could be understood from the daily climate information. Thus, the prediction of the different characteristics of the rainy season (annual rainfall amount, onset and cessation of the rainy season, dry spells, heavy rain events, hot spells, and strong winds) in the region from climate models would help local farmers plan and adequately organize their field activities. Such strategies, developed through national frameworks would then ensure food security at the local level, but most importantly address issues of crop failure across Sahelian regions.

Acknowledgements

This work has been funded by the German Federal Ministry of Education and Research (BMBF) through the West African Science Service Center on Climate Change and Adapted Land Use (WASCAL). The authors thank the Burkina Faso National Meteorological Agency (ANAM-BF), which provided the climate data.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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