Journal of Hydrology 375 (2009) 128–142

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Rainfall regime across the Sahel band in the Gourma region, Mali

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ARTICLE INFO

Keywords:
Precipitation
Gourma region
Sahel
Interannual variability
Diurnal cycle

SUMMARY

The Sahel is characterized by low and highly variable rainfall, which strongly affects the hydrology and the climate of the region and creates severe constraints for agriculture and water management. This study provides the first characterization of the rainfall regime for the Gourma region located in Mali, Central Sahel (14.5–17.5°N and 2–1°S). The rainfall regime is described using two datasets: the daily long term raingauge records covering the period 1950–2007, and the high frequency raingauge records collected under the African Monsoon Multidisciplinary Analysis (AMMA) project between 2005 and 2008. The first rainfall dataset was used to analyse the interannual variability and the spatial distribution of the precipitation. The second dataset is used to analyse the diurnal cycle of precipitation and the nature of the rainfall. This study is complementary to previous analyses conducted in Sahelian areas located further south, where the influence of the continental Sahara heat low is expected to be less pronounced in summer.

Rainfall regimes in the Gourma region present a succession of wet (1950–1969) and dry decades (1970–2007). The decrease of summer cumulative rainfall is explained by a reduction in the number of the rainy days in southern Gourma, and a decrease in both the number of rainy days and the daily rainfall in northern and central Gourma. This meridional difference may be related to the relative distances of the zones from the intertropical discontinuity, which is closer to the northern stations. The length of the rainy season has varied since the 1950s with two episodes of shorter rainy seasons: during the drought of the 1980s and also since 2000. However, this second episode is characterized by an increase in the daily rainfall, which suggests an intensification of rainfall events in the more recent years.

High-frequency data reveal that a large fraction of the rainfall is produced by intense rain events mostly occurring in late evenings and early mornings during the core of the rainy season (July–September). Conversely, rainfall amounts are less around noon, and this mid-day damping is more pronounced in northern Gourma. All these characteristics have strong implications for agriculture and water resources management.

Introduction

The arid and semi-arid regions of Africa are characterized by low and unreliable rainfall, which strongly affects water resources and food security (Nicholson, 1989). The largest of these regions, the Sahel, runs 3800 km from the Atlantic Ocean in the west to the Red Sea in the east, in a belt that varies from several 100–1000 km in width, covering an area of 3,053,200 km^2. This semi-arid area is bordered to the north by the Sahara Desert and to the south by Sudanian savannas. The Sahelian climate is characterized by a unimodal rainfall regime controlled by the west African Monsoon – WAM (Nicholson, 1981; Todorov, 1985; Morel, 1992; Hiernaux and Le Houérou, 2006). During the 20th century, the Sahel experienced a multidecennial drought that started at the end of 1960s, with two sequences of extremely dry years, in 1972–1974 and 1983–1985 (Hulme, 1992; Le Barbé and Lebel, 1997; D'Amato and Lebel, 1998; L'Hôte et al., 2002; Lebel et al., 2003). This is, indeed, the strongest measured climatic event of rainfall variability at these time and space scales (Hulme, 2001). The substantial changes in the climate conditions obliged Sahelian farmers and pastoralist communities to adapt to the decrease in water resources (Mortimore and Adams, 2001; Tarhule and Lamb, 2003; Pedersen and Benjaminsen, 2008).

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doi:10.1016/j.jhydrol.2009.03.007

The few recent studies of Sahelian rainfall regimes using raingauge data were carried out over large areas located further south (Le Barbé et al., 2002; Lebel et al., 2003; Bell and Lamb, 2006), whereas the rainfall regimes of the drier central and northern Sahel, which experience a strong climatic influence of the Sahara heat low in summer, remain poorly described.

This study is the first to focus on the rainfall regime of the northern AMMA–CATCH (African Monsoon Multidisciplinary Analysis–Couplage de l'Atmosphère Tropical et du Cycle Hydrologique) mesoscale site (14.5–17.5°N, 1–2°W), located in the Gourma region, in Mali. Ground-based measurements covering a range of complementary scales are used.

This study focuses on an analysis of rainfall variability over the Gourma region during the years 1950–2007, using time series of daily precipitation data. The rainy season is characterized in terms of length, distribution of precipitation, and number and intensity of rainy days. Historical trends affecting West Africa and the Sahel over the past century are presented and discussed for the Gourma region specifically.

Smaller scale modes of rainfall variability are investigated using high frequency measurements collected by the AMMA–CATCH raingauge network during the AMMA Enhanced Observations Period (EOP), 2005–2008. Over the Sahel, and in the Gourma region, rainfall is of convective origin and organized Mesoscale Convective Systems (MCS), which accounts for most of the rainfall as shown by Mathon et al. (2002). Therefore, the distribution of rainfall rates associated with rainfall events over the Gourma region is analysed and compared with existing studies. The diurnal cycle, a major

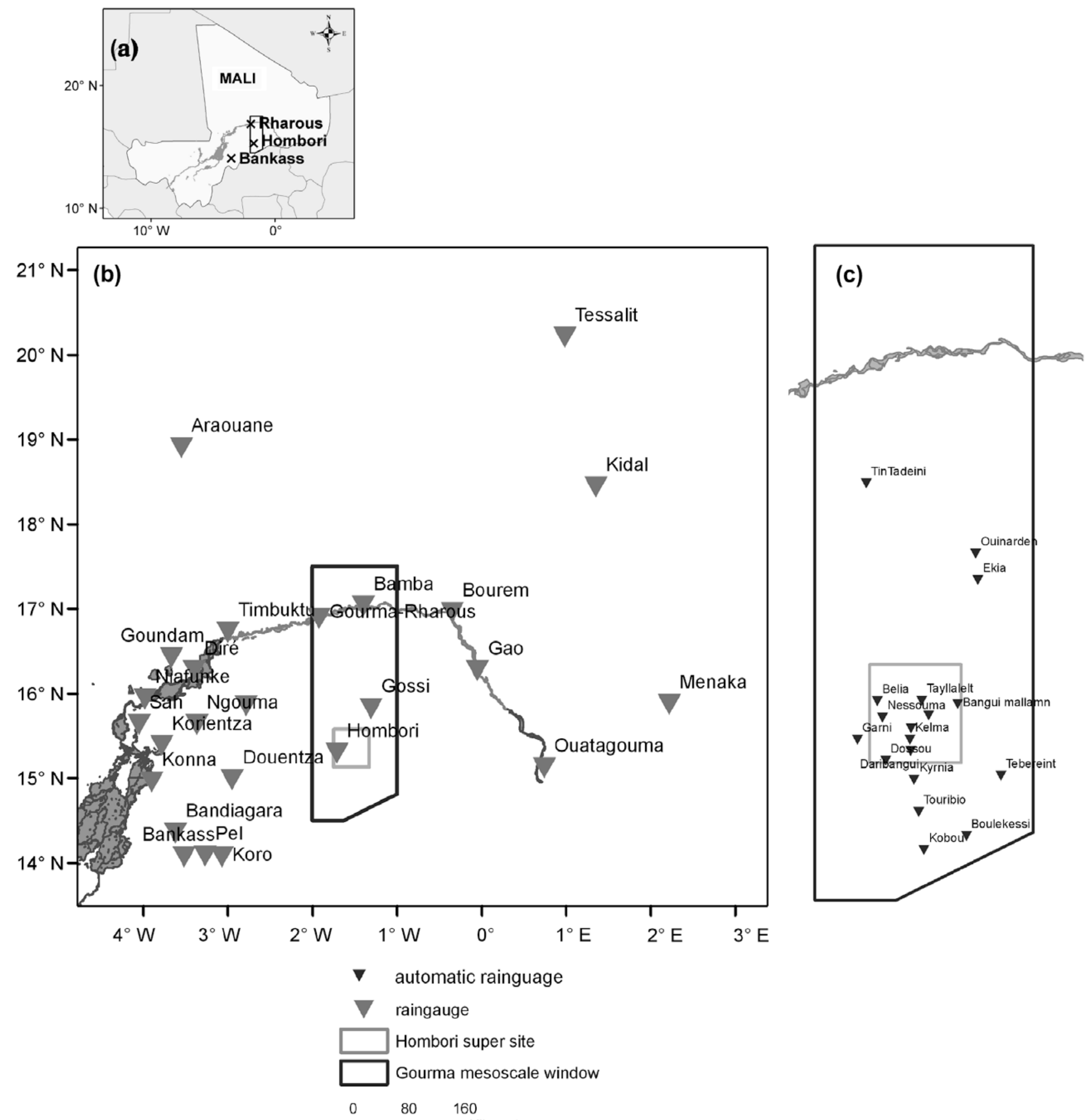

Fig. 1. (a) Location of the Gourma region, Mali, West Africa; (b) location of the historical rain gauges within and outside the Gourma region, Mali and (c) location of the automatic rain gauges in the AMMA mesoscale site.

feature of convection and of rainfall over land (Wallace, 1975; Yang and Slingo, 2001), is also analysed and discussed for the Gourma region.

Materials and methods

The study region

The Gourma region belongs entirely to the Sahel zone and extends over 90,000 km^2, from the south of the large loop made by the Niger River between Timbuktu and Gao – 17°N – down to the border with Burkina-Faso – ~14.5°N (Fig. 1). This region, mainly pastoral, is bracketed by the 150 and 500 mm annual isohyets, with interannual coefficients of variation of the mean annual rainfall ranging from 15% to 30% (Sivakumar, 1989). A comprehensive presentation of the Gourma AMMA mesoscale site can be found in Mougin et al. (2009).

Dataset

Long daily rainfall series are available since 1897 for Timbuktu, and since the 1920s or the 1950s, for 25 stations over the Gourma region and the surroundings. The location of these stations is reported in Fig. 1b and Table 1, with corresponding data availability. To have a sufficient number of stations and data to analyse, only records from 1950 to 2007 were used. Nine of all the historical stations are located in the Gourma region, 13 are located in the surroundings and are helpful to characterize the rainfall regime of the region, and three others are located further north, in the transition zone between Sahel and Sahara but their data are incomplete. This long term precipitation dataset has been provided by the Malian meteorological service, Direction Nationale de la Météorologie (DNM). In order to place the results in the broader context of the west African Monsoon, daily rainfall data from 35 additional stations located further south in Mali, (also provided by DNM), have also been used.

The dataset used to characterize the diurnal cycle and the nature of precipitations is established from the records of 0.5 mm tipping bucket raingauges (AR for automatic raingauges) installed during the AMMA-EOP period 2005–2008 (see Fig. 1c and Table 1 for locations and period of data availability). Only AR records from June to September have been analysed in this study.

Standardized anomaly indices of rainfall and number of rainy days

The rainfall standardized anomaly index was defined by Lamb (1982) to study long term rainfall variations:

Table 1
Overview of available historical rain gauges (long term in the table) and automatic rain gauges (short term) within and outside the Gourma region.

Rain gauge	Type	Lon (°)	Lat (°)	Data availability	Climatic zone	Location
Tessalit	Long term	0.98	20.20	1950–2004	Sahara–Sahel	Sahara transition
Araouane	Long term	−3.55	18.90	1927–1987	Sahara–Sahel	Sahara transition
Kidal	Long term	1.35	18.43	1950–2004	Sahara–Sahel	Sahara transition
Bamba	Long term	−1.40	17.03	1920–1925 and 1950–2005	North Sahel	Gourma
Bourem	Long term	−0.35	16.95	1926–2007	North Sahel	Gourma
Gourma-Rharous	Long term	−1.92	16.88	1927–2006	North Sahel	Gourma
Timbuktu	Long term	−3.00	16.72	1897–1907 and 1915–1929 and 1949–2006	North Sahel	Gourma
Goundam	Long term	−3.67	16.42	1950–2001	North Sahel	Surroundings
Diré	Long term	−3.40	16.27	1950–2004	North Sahel	Surroundings
Gao	Long term	−0.05	16.27	1920–2007	North Sahel	Gourma
Niafunke	Long term	−3.98	15.93	1950–1990	Centre Sahel	Surroundings
Menaka	Long term	2.22	15.87	1950–2003	Centre Sahel	Surroundings
Bambara-Maoundé	Long term	−2.78	15.85	1953–1994	Centre Sahel	Gourma
Gossi	Long term	−1.31	15.82	1977–2007	Centre Sahel	Gourma
Sah	Long term	−4.05	15.63	1950–1989	Centre Sahel	Surroundings
Ngouma	Long term	−3.37	15.63	1950–1989	Centre Sahel	Surroundings
Korientzé	Long term	−3.78	15.38	1950–1999	Centre Sahel	Surroundings
Hombori	Long term	−1.71	15.29	1920–2007	Centre Sahel	Gourma
Ouatagouma	Long term	0.74	15.12	1950–1990	Centre Sahel	Surroundings
Douentza	Long term	−2.95	14.98	1926–2004	South Sahel	Gourma
Konna	Long term	−3.90	14.95	1950–1988	South Sahel	Surroundings
Bandiagara	Long term	−3.62	14.35	1950–2000	South Sahel	Surroundings
Pel	Long term	−3.27	14.08	1960–1995	South Sahel	Surroundings
Bankass	Long term	−3.52	14.07	1950–2003	South Sahel	Surroundings
Koro	Long term	−3.07	14.07	1950–1990	South Sahel	Surroundings
Tintadeini	Short term	−1.77	16.41	2005–2008	North Sahel	Gourma
Ouinarden	Short term	−1.26	16.09	2007–2008	North Sahel	Gourma
Ekia	Short term	−1.25	15.97	2006–2008	Centre Sahel	Gourma
Tayllaleit	Short term	−1.51	15.41	2007–2008	Centre Sahel	Gourma
Belia	Short term	−1.72	15.41	2007–2008	Centre Sahel	Gourma
Bangui-Mallamn	Short term	−1.35	15.40	2005–2008	Centre Sahel	Gourma
Agoufou	Short term	−1.48	15.34	2007–2008	Centre Sahel	Gourma
Nessouma	Short term	−1.69	15.34	2007–2008	Centre Sahel	Gourma
Bilantao	Short term	−1.56	15.29	2005–2006	Centre Sahel	Gourma
Kelma	Short term	−1.57	15.23	2005–2008	Centre Sahel	Gourma
Garni	Short term	−1.81	15.23	2007–2008	Centre Sahel	Gourma
Daribangui	Short term	−1.56	15.18	2006–2008	Centre Sahel	Gourma
Dossou	Short term	−1.68	15.14	2007–2008	Centre Sahel	Gourma
Tebereint	Short term	−1.15	15.07	2007–2008	Centre Sahel	Gourma
Kirnya	Short term	−1.55	15.05	2005–2008	Centre Sahel	Gourma
Touribio	Short term	−1.53	14.90	2007–2008	South Sahel	Gourma
Boulekessi	Short term	−1.31	14.79	2007	South Sahel	Gourma
Kobou	Short term	−1.50	14.73	2006–2008	South Sahel	Gourma

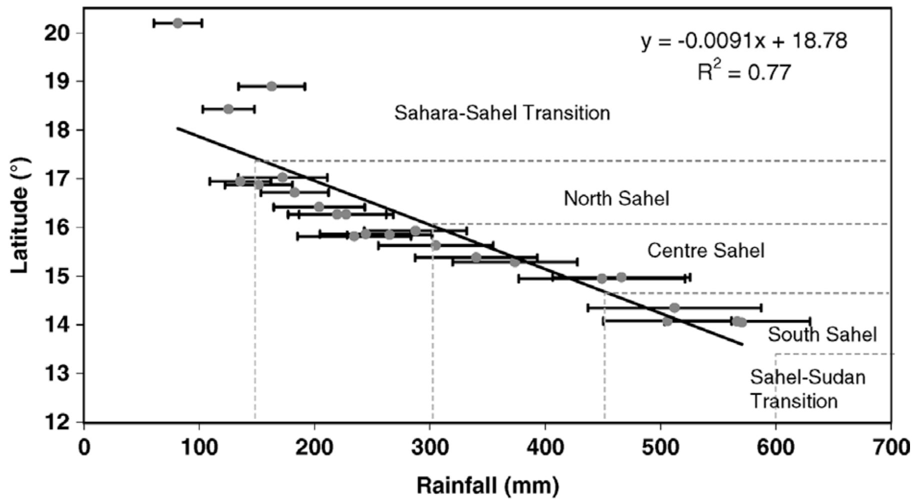

Fig. 2. Distribution of the mean annual rainfall and its standard deviation, from the origin to 2007, as a function of the latitude. The standard deviation of the measurement mean ranges from 42 mm in the north, to 139 mm in the south.

$$I_R(k) = \frac{1}{n}\sum_{i=1}^{n}\frac{R(i,k) - \overline{R(i)}}{\sigma(i)} \tag{1}$$

where $R(i,k)$ is the annual rainfall at station i for year k, $\overline{R(i)}$ and $\sigma(i)$ are the annual average and standard deviation over the reference period for station i, respectively, and n is the total number of stations used in the computation.

A similar standardized index is defined for the number of rainy days as follows:

$$I_N(k) = \frac{1}{n}\sum_{i=1}^{n}\frac{N(i,k) - \overline{N(i)}}{\sigma(i)} \tag{2}$$

where $N(i,k)$ is the number of rainy days during the rainy season at station i for year k, $\overline{N(i)}$ and $\sigma(i)$ the average and standard deviation over the reference period for station i, respectively, and n is the total number of stations used for the computation.

Estimates of timing and length of the rainy season

Several criteria, known as agronomical criteria, exist to define the beginning and the end of the rainy season using thresholds on the amount of precipitation fallen during consecutive days (Stern et al., 1981; Sivakumar et al., 1984). These criteria are very similar, and we decided to select the second one following Balme et al. (2005). The beginning of the rainy season is defined by the first occurrence of at least 20 mm cumulative rainfall in 3 days, after the 1st of May, and not followed by more than 7 successive days without rain within the 30 following days. The end of the rainy season is determined by the occurrence of 20 successive days without rain, after the 1st of September.

Dry spell length and probability of occurrence

The analysis of dry spells has been carried out using daily rainfall data between the 1st of May and the 30th of September. Years with missing days were excluded from the analysis. The length of dry spells (i.e., the number of days until the next day with rainfall greater than a given threshold value) and associated probability of dry spell occurrence have been estimated for different thresholds τ (1, 5, 10, 15, and 20 mm) at stations distributed along the Gourma climatic gradient.

Following Sivakumar (1992), the probability for a day i to be part of a dry spell with a threshold τ is defined as

$$P(i,\tau) = \frac{\sum_{N\subset\{1950;\ldots;2007\}} \Omega(i,N,p<\tau)}{N} \tag{3}$$

where N is the number of years without missing days for a station, p is the rainfall and

$$\Omega = \begin{cases} 1 & \text{if } i \text{ is part of a dry spell of threshold } \tau \text{ for year } N \\ 0 & \text{if not} \end{cases}.$$

Results and discussion

Major features of rainfall in the Gourma region

The mean annual rainfall over the Gourma mesoscale site is characterized by a south–north decreasing gradient, at a rate slightly larger than 1 mm km^{-1} (Fig. 2), a characteristic value found elsewhere in Sahel (Lebel et al., 2003). It involves bioclimatic

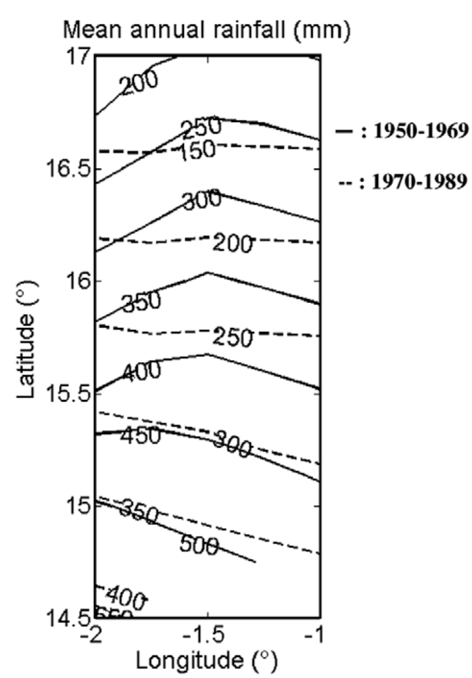

Fig. 3. Average annual rainfall (mm) over the Gourma region for the period 1950–1969 (wet – black line) and the period 1970–1989 (dry – dashed black line).

zones distributed latitudinally with a slight southward inflexion from west to east (Hiernaux and Le Houérou, 2006). However, isohyets positions have varied considerably over the past 60 years in the Gourma region (Fig. 3) and more generally in Sahel, as shown in Lebel and Ali (2009). The dry years isohyets (1970–1989) shifted about 100–150 km to the south compared to those of the preceding wet period. These shifts correspond to a 100 mm rainfall decrease per year, in northern Gourma, and 150 mm, in southern Gourma. This compares to a southern shift of the isohyets by around 200 km, observed in average over the whole Sahel (Lebel and Ali,

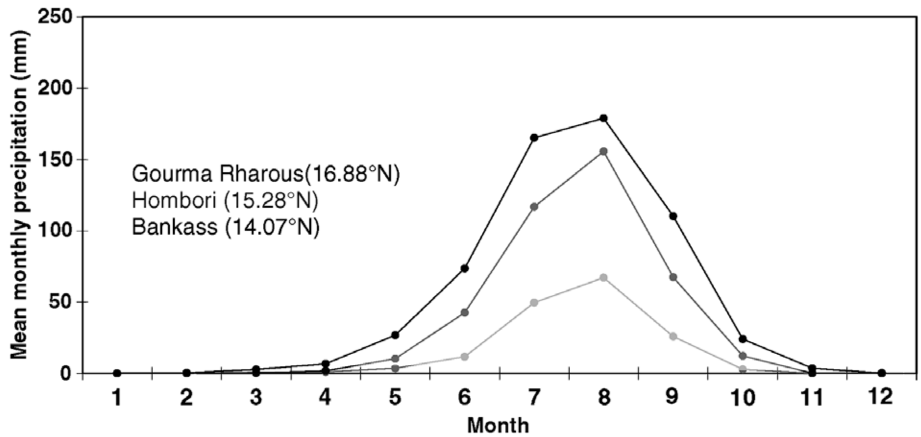

Fig. 4. Distribution of the mean monthly precipitation over the period 1950–2007 for Gourma-Rharous (north), Hombori (centre) and Bankass (south).

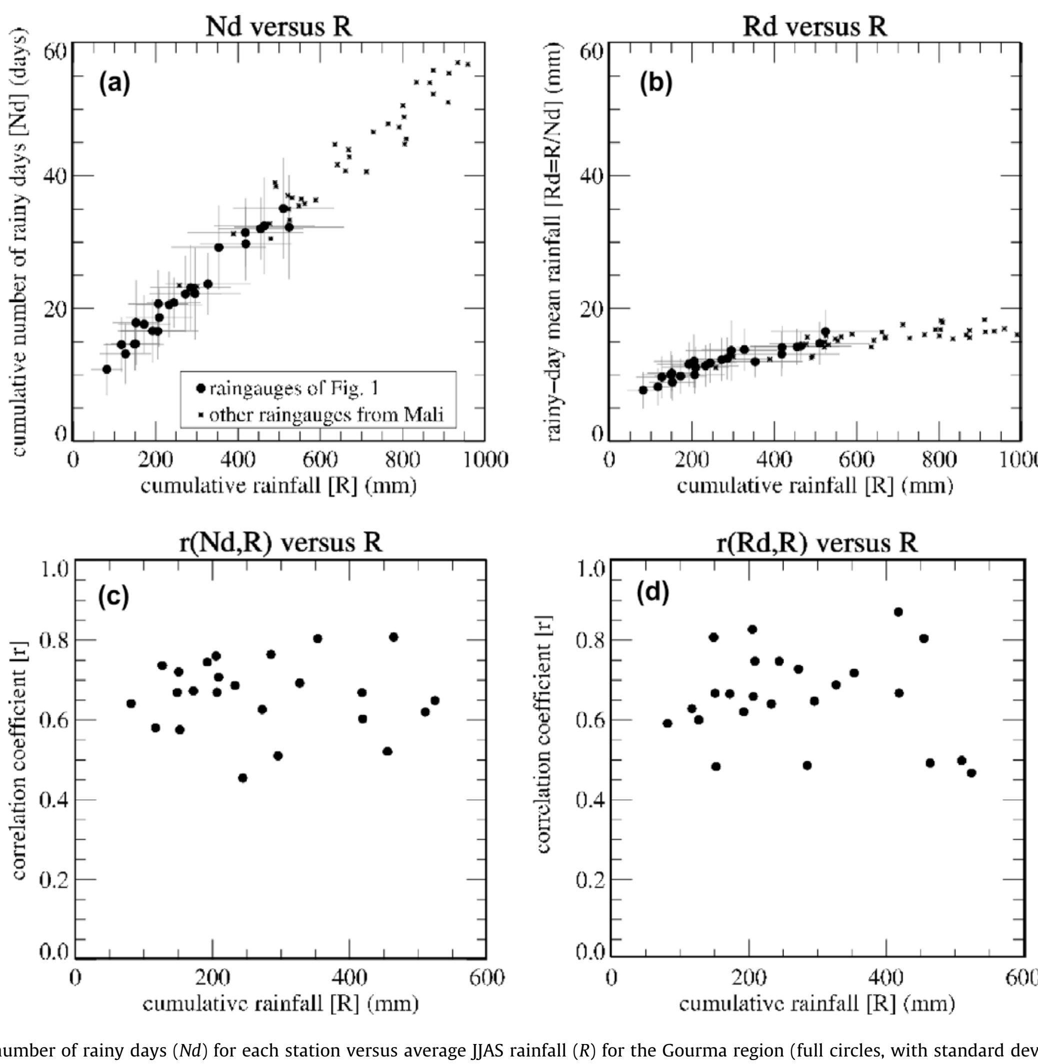

Fig. 5. (a) Average number of rainy days (*Nd*) for each station versus average JJAS rainfall (*R*) for the Gourma region (full circles, with standard deviation) and the Malian stations south of the Gourma region (dots); (b) mean rainfall per rainy day (*Rd*) for each station versus average JJAS rainfall (*R*) for the Gourma region (full circles, with standard deviation) and the Malian stations south of the Gourma region (dots); (c) correlation coefficient (*r*) between *R* and *Nd* for each Gourma station, characterizing the interannual variability and (d) correlation coefficient (*r*) between *R* and *Nd* for each Gourma station.

2009). The curvature of the isohyets also changed during this period, revealing some east–west dynamics in addition to the dynamics along the north–south climatic gradient. This observation is in accordance with results from previous studies (Nicholson, 1980; Janicot, 1992; Nicholson and Palao, 1993; Moron, 1994; Nicholson, 2005; Lebel and Ali, 2009). Thus, defining climatic zones remains a difficult task, especially in the northern part of the study domain where the mean rainfall over the wet period 1950–1969 was twice as high as during the dry period 1970–1989.

As in any other part of Sahel (Hiernaux and Le Houérou, 2006), the seasonal distribution of the mean monthly precipitation over the Gourma region presents a single peak. The rainfall occurs during the northern hemisphere summer, starting between May and July until September or October with a maximum in August (Fig. 4). Very few rainfall events are recorded before or after the rainy season.

For each station, the June to September (JJAS) number of rainy days (noted *Nd*) has been plotted, either versus the JJAS cumulative rainfall (noted *R*), or the daily rainfall (noted *Rd*), averaged over the period 1950–2007 (Fig. 5). Only rainfall of 1 mm or more have been retained to avoid biases from possible mis-reporting of small rain events.

The number of rainy days (*Nd*) increases with the JJAS cumulative rainfall (*R*) (Fig. 5a). Standard deviations of *Nd* slightly increase with *R*. In Fig. 5b, the daily rainfall (*Rd*) exhibits a saturation at the value of 20 mm per day for JJAS cumulative rainfall greater than 400 mm (southern Gourma). It clearly decreases for rainfall between 200 and 400 mm (central Gourma), and further decreases for rainfall lower than 200 mm (northern Sahel). The tiny variations of *Rd* over the 400–1000 mm range are consistent with the results from the previous studies by Le Barbé and Lebel (1997), and Le Barbé et al. (2002), for the same range of JJAS cumulative rainfall, even if daily rainfall are used here instead of rainfall per event. Correlations between *R* and *Nd*, and *R* and *Rd*, as a function of *R* are, respectively, presented in Fig. 5c and d. *R* and *Nd*, and *R* and *Rd* are both strongly correlated, with most of the correlation coefficients greater than 0.6.

Previous studies have highlighted the dominant role of *Nd* in determining the annual rainfall (Lebel et al., 1997; Le Barbé and Lebel, 1997; Le Barbé et al., 2002). While in the Gourma region, both, the number of rainy days, and the mean rainfall per rainy day determine annual rainfall. This result departs from observations made further south in Sahel. A possible reason for this difference would be a stronger control of rainfall by the local atmospheric environment prevailing in the Gourma, than further south. It would be useful to explore how rainfall relates to interannual changes of atmospheric humidity, as this parameter exerts a significant control on the evaporation of cloud water and of rainfall, and

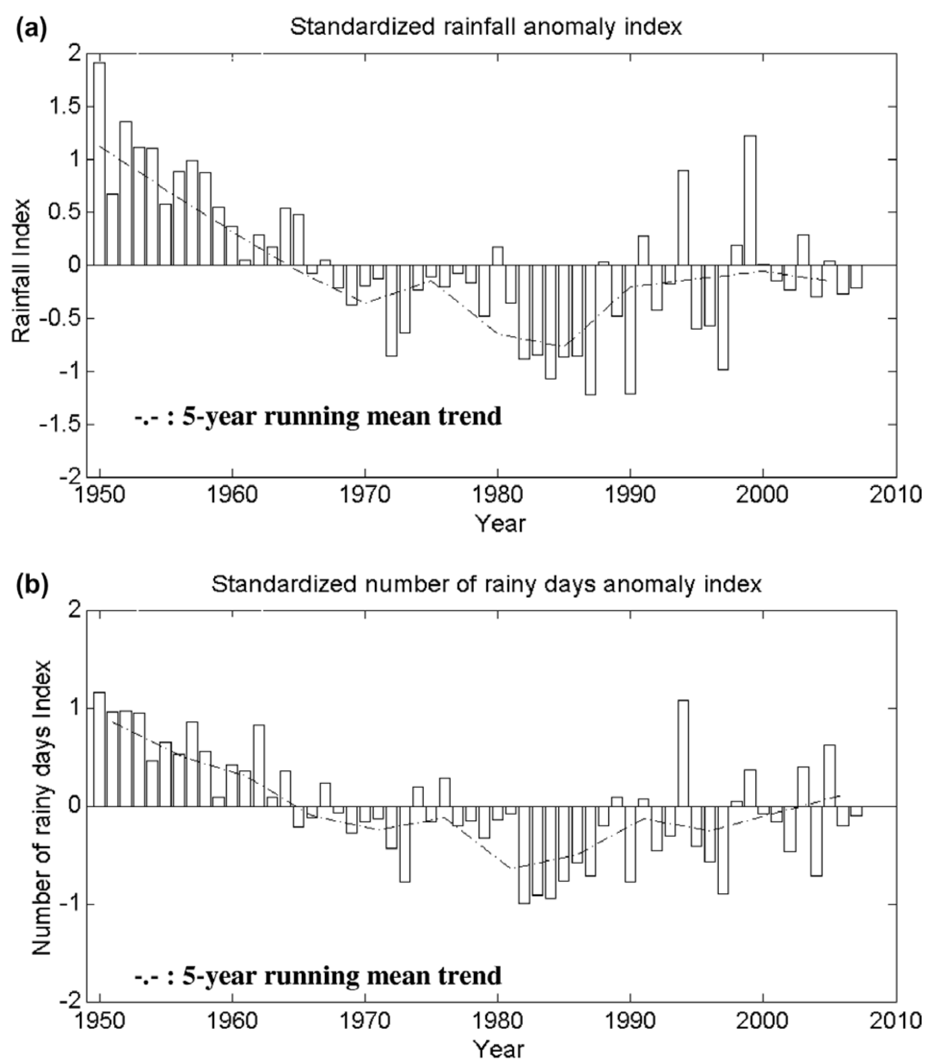

Fig. 6. (a) Evolution of the standardized rainfall index (I_R) over the Gourma region between 1950 and 2007. In dashed, the standardized rainfall index trend estimated between 1950 and 2007, using a 5 years running mean and (b) evolution of the standardized anomaly number of rainy days index (I_N) over the Gourma region between 1950 and 2007.

may thus control the amount of rain reaching the surface. More broadly, the Gourma region may be more directly under the influence of West African Heat Low (WAHL) circulations than southern Sahel. Yet, these circulations are generated by the continental depression associated with an increase in the potential temperature, and are the main components of the West African Monsoon likely to play a significant role in the rainfall variability over Sahel (see Janicot,1992, for more details). In this respect, it would be useful to assess the interannual variations of the location of the Inter Tropical Discontinuity (ITD) with respect to the Gourma region. Indeed, from a wider perspective, in the past, changes in rainfall amounts have been perceived by the local population as associated with, or even induced by changes in winds (Ag Mahmoud, 1992). And this view is consistent with the ITD being located close to the Gourma region.

Historical trend and variability of rainfall and number of rainy days over the Gourma region

Fluctuations of the standardized anomaly index for rainfall I_R (Eq. (1)) and for the number of rainy days I_N (Eq. (2)) have been calculated from 1950 to 2007 using daily rainfall collected at stations within and close to the Gourma region (Table 1). The number of available stations is not constant over the years, they are between 20 and 25 from 1950 to the late 1980s, 15 in the middle of the 1990s, 10 in 2003, and 6 in 2006.

The variation of the standardized rainfall index over the Gourma region from 1950 to 2007 presents a positive anomaly from the 1950s to the end of 1960s, and a long period of negative anomalies from the beginning of the 1970s until present (Fig. 6a). Three large negative precipitation anomalies can be observed: 1973–1974, 1982–1987 and 1995–1998. The two first correspond to the severe droughts that occurred in 1972–1974 and 1983–1985 in the whole Sahel. And the last one is in accordance with the study of L'Hôte et al. (2003), which considers that the 1990s were the driest decade since the beginning of the century in Sahel. Even if the results for the Gourma region present a larger variability, the trends observed are consistent with those found during previous climatological studies in Sahel (Le Barbé and Lebel, 1997; Hulme, 2001; Le Barbé et al., 2002; L'Hôte et al., 2002). Compared with the standard rainfall anomaly index calculated for the whole Sahel region between 1950 and 2002 (Balme et al., 2006), the 1990s and the beginning of the 2000s appear to be a little bit wetter in the Gourma region (five positive anomalies of I_R) than in the whole Sahel defined by the window 10–20°N, 20°W–20°E (two positive anomalies). The last 20 years present a succession of wet and dry

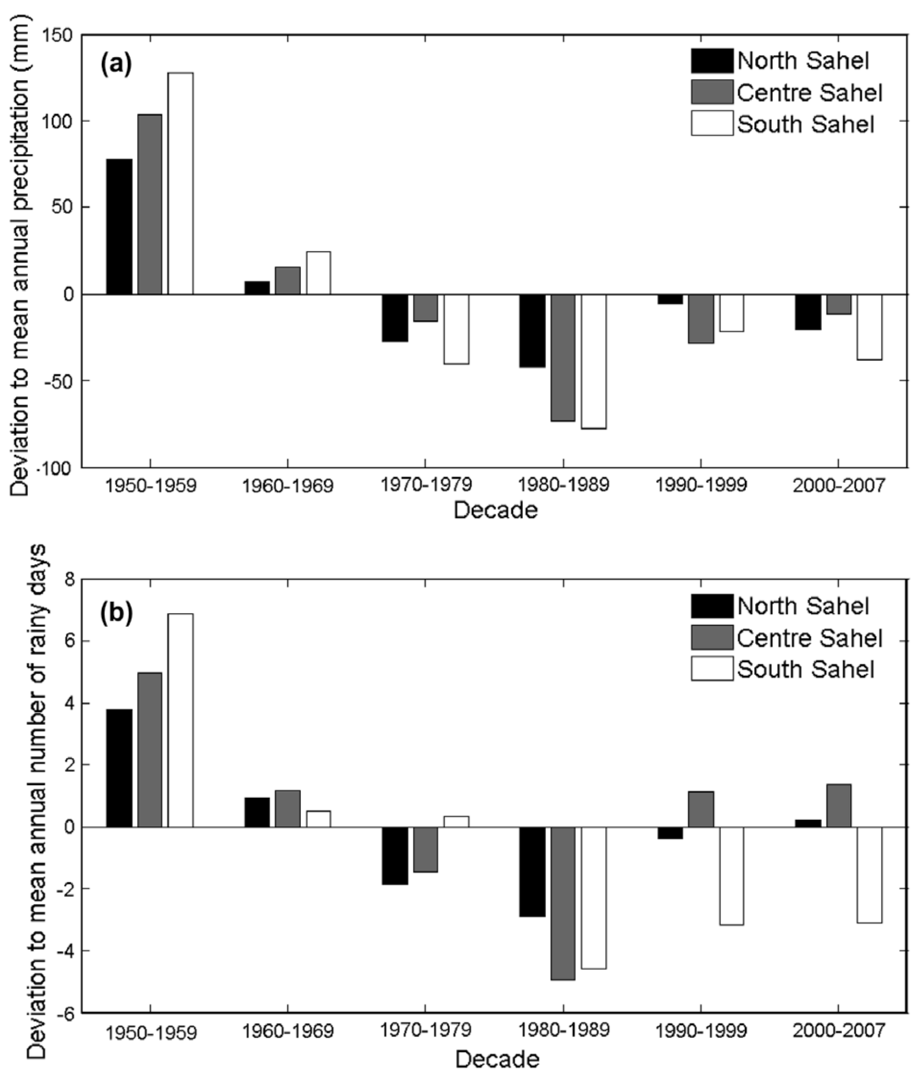

Fig. 7. (a) Deviations to the mean annual precipitation over each climatic zone (northern Sahel, 183 mm, central Sahel, 292 mm, southern Sahel, 504 mm) and (b) deviations to the mean annual number of rainy days during the rainy season over each climatic zone (northern Sahel, 21 rainy days, Central Sahel, 29 rainy days, southern Sahel, 37 rainy days).

years, with less dry conditions during the 1990s, and drier conditions from 2000 to 2007, as observed by Dai et al. (2004). Nevertheless, as the number of available station records declined from 24 to 15 by the end of the 1990s, and down to 6 or 7 for the last 3 years, the results for the 2000s have to be considered with caution.

Fig. 6b presents the variations of the number of rainy days standardized anomaly index between 1950 and 2007. The standardized anomaly indices for the number of rainy days (Fig. 6b) and for rainfall (Fig. 6a) present similar patterns. This confirms the strong link between the number of rainy days and the annual rainfall observed in Niger (Le Barbé and Lebel, 1997; Le Barbé et al., 2002; Balme et al., 2006). However, some differences appear. One major difference is the 1972–1974 drought, during which there is a positive anomaly for the number of rainy days (Fig. 6b). Another difference relates to the drought of the 2000s during which the number of rainy days index is much more negative than that of rainfall.

The decadal deviation to the mean annual rainfall (Fig. 7a) and to the mean number of rainy days (Fig. 7b) were computed separately for each climatic zone (north, centre, and south) to account for the regional variability of the precipitations over Gourma region between 1950 and 2007.

Fig. 7a and b exhibit differences especially for the period of 1970 to present. During the 1970s, marked by the 1972–1974 drought, the deviations from the mean number of rainy days are positive in the south, whereas the deviations from the mean annual rainfall are negative in the north and the centre. The opposite is observed during the 2000s: positive deviations in the north and centre, negative in the south. Even for the southern part which is climatically close to the Niamey (Niger) conditions, the rainfall and number of rainy days deviations sometimes present an opposite signs (1970–1979), or the negative anomaly of the number of rainy days (~20%) is more pronounced than that of rainfall (~10%). Similar results were obtained when thresholds of 1 and 3 mm were used to define rainy days, and to exclude potential bias coming from poor reporting of small rain events. These results suggest that both the number of rainy days and the daily rainfall control the annual rainfall in the Gourma region as observed in Fig. 5. Besides, the comparison of the mean annual rainfall and number of rainy days during the last 10 years shows a trend towards a decrease of rainfall (negative anomalies of I_R and positive anomalies of I_N) in northern and central Gourma, and an intensification of rainfall (negative anomaly of I_R and high negative anomaly of I_N) in the south. This intensification of the daily rainfall and the decrease in the number of rainy days in southern Gourma are in accordance with the recent increase in regionally averaged daily rainfall intensity and dry spell duration over southern and West Africa observed by New et al. (2006).

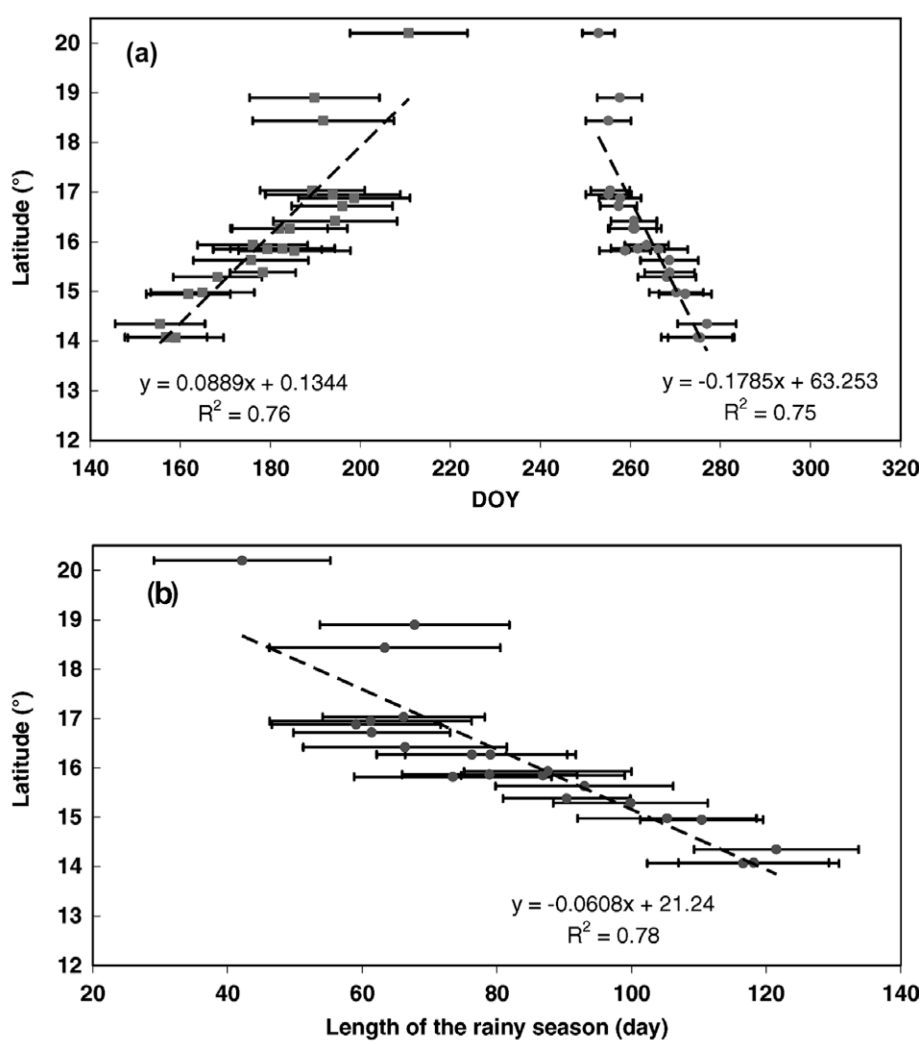

Fig. 8. (a) Starting and ending dates of the rainy season (grey squares and grey circles, respectively) in the Gourma region from 1950 to 2007 as a function of the latitude. The mean standard deviation on the start of the rainy season is 23 days and (b) length of the rainy season in the Gourma region from 1950 to 2007 as a function of the latitude. Standard deviation on the end of the rainy season ranges from 7 days in the north to 15 days in the south.

Timing and length of the rainy season

Daily time series of rainfall have been analysed to estimate the length and the timing of the rainy season over Gourma region. The rainy season, as defined in "*Estimates of timing and length of the rainy season*", comprises 90% of the annual rainfall. This result is in good agreement with those obtained by Sivakumar et al. (1984) for the whole Mali and by Balme et al. (2005) for Niger.

Fig. 8a shows that, depending on stations, the beginning of the rainy season ranges from the 5th of June (day 155) in the south to the 15th of July in the north (day 195), with a maximum standard deviation of the station mean of 15 days. Therefore, there is a northward lag of 5 days per degree of latitude for the onset of the rainy season. The end of the rainy season ranges from the 10th of September (day 253) in the north to the 1st of October (day 274) in the south with a maximum standard deviation of

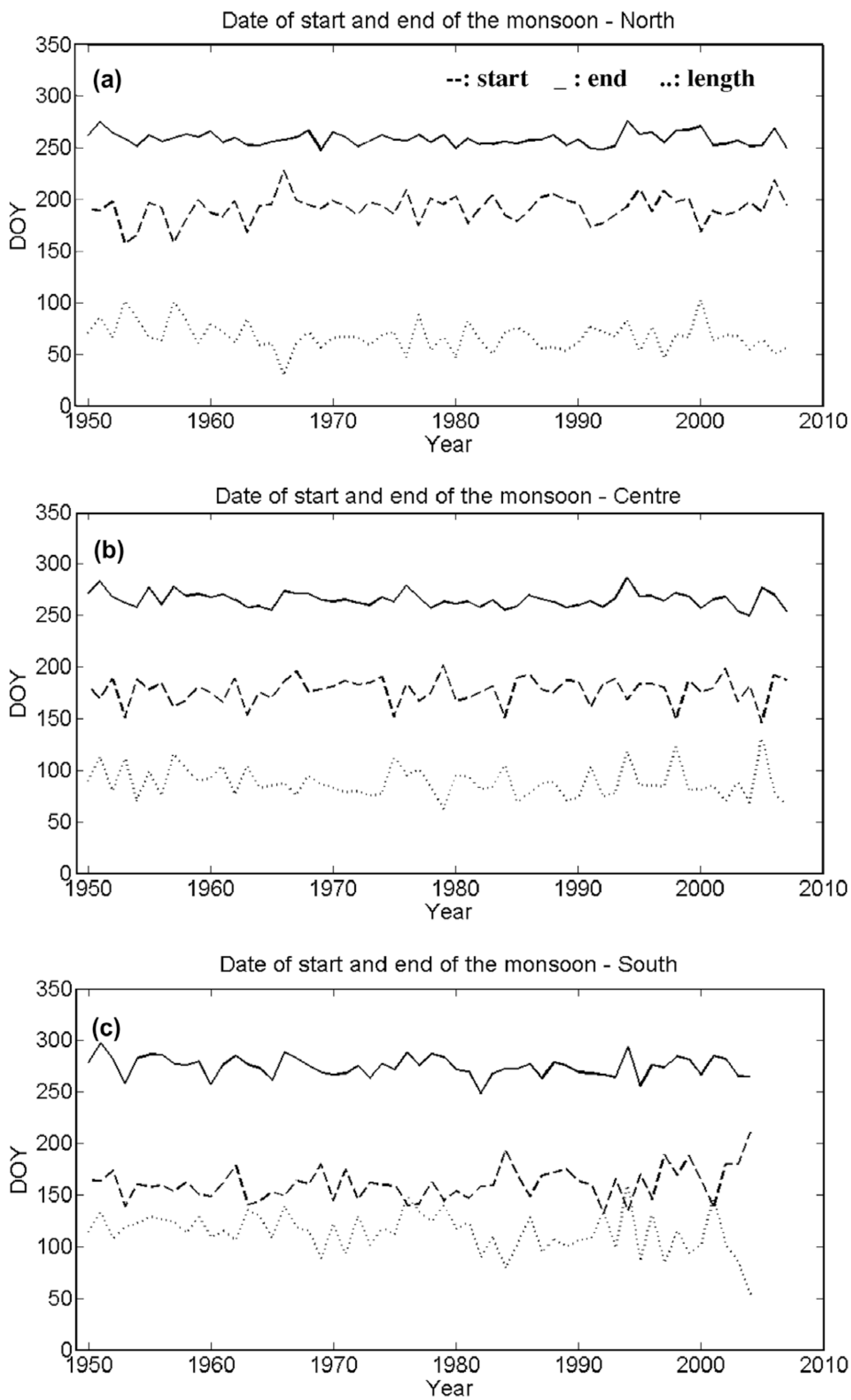

Fig. 9. Date of start (dashed line) and end (plain line), and length (dotted line) of the rainy season at three zones of the Gourma region: (a) north; (b) centre and (c) south.

Table 2
Dates of start and end, and length of the rainy season per decades, between 1950 and 2007 for the three bioclimatic zones. The associated uncertainties represent the half of the standard deviation.

Rainy season	North			Centre			South		
	Start	End	Length	Start	End	Length	Start	End	Length
1950–1959	183 ± 11	261 ± 5	78 ± 11	174 ± 9	268 ± 6	94 ± 12	160 ± 9	279 ± 7	120 ± 10
1960–1969	193 ± 13	257 ± 5	64 ± 13	180 ± 10	266 ± 6	86 ± 10	158 ± 10	273 ± 6	114 ± 11
1970–1979	194 ± 13	259 ± 4	65 ± 14	178 ± 13	266 ± 5	87 ± 14	154 ± 9	276 ± 7	122 ± 13
1980–1989	194 ± 13	256 ± 4	62 ± 13	180 ± 13	261 ± 5	81 ± 13	166 ± 9	268 ± 6	102 ± 10
1990–1999	192 ± 14	261 ± 7	68 ± 15	178 ± 13	266 ± 7	88 ± 15	162 ± 13	273 ± 7	110 ± 18
2000–2007	191 ± 12	256 ± 5	65 ± 14	179 ± 10	261 ± 7	82 ± 13	173 ± 15	270 ± 5	98 ± 18

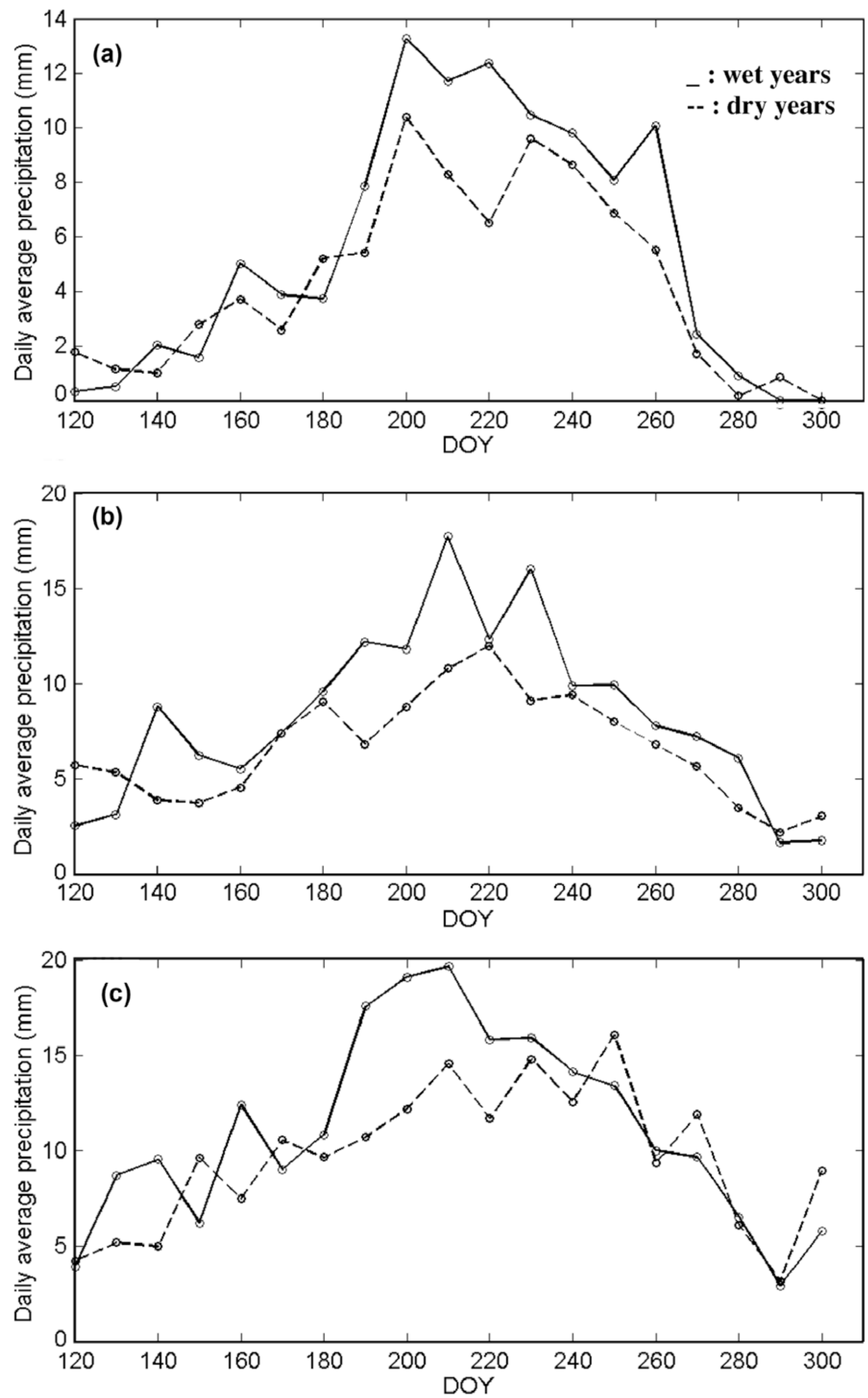

Fig. 10. Mean rainfall per rainy day on a 10-days period during the rainy season for dry (dashed line) and wet years (plain line) in Gourma-Rharous (north) (a), Hombori (centre) (b), and Bankass (south) (c), over the period 1950–2007. Dry and wet years, respectively, correspond to negative and positive values of the standardized anomaly index estimated by rain gauge.

the station mean of 7 days. Thus, the standard deviation of the station mean is about twice smaller for the ending date than for the starting date. It means that there is more variability at the onset of the rainy season than at its end. Along the south–north climatic gradient, the length of the rainy season varies from 120 days to 60 days, that is to say a decrease of 20 days per degree of latitude (Fig. 8b).

Moreover, the length of the rainy season, as well as its starting and ending dates, have varied over the last 60 years. This variation is presented in Fig. 9 and Table 2 for the three climatic zones in the Gourma region. The average duration of the rainy season in southern Gourma (~110 days), and the starting and ending dates (10th of June and 29th of September, respectively) are very similar to the results obtained by Balme et al. (2005) in Niger during the same period and for comparable latitudes (13–14°N): 105 days, 21st of June and 4th of October. The mean length of the rainy season decreased in all three zones during the 1950–2007 period by 13 days in the northern, 12 in central, and 22 in southern Gourma, respectively. This reduction is due to both, a delay of the starting date (from the 1st to the 9th of July in the north, the 22nd to the 27th of June in the centre, and from the 8th to the 21st of June in the south), and to an earlier ending (from the 17th to the 12th of September in the north, the 24th to the 17th of September in the centre and from the 5th of October to the 26th of September in the south). The length of the rainy season started to decrease in the middle of the 1960s and the minimal length was reached during the 1980s, in association with the severe drought of 1983–1985. In the 1990's the length of the rainy season widened back to the levels of the 1960s, due chiefly, to a later ending.

During the last 10 years, there is a new decrease of the duration of the rainy season back to values observed during the 1972–1974 drought in the north, and towards the values observed during the 1983–1985 drought in the centre. Further south, the current length of the rainy season is the shortest observed over the study period (Table 2). This recent shrinking of the rainy season is caused by an earlier ending observed in all three zones, and by a later start (~10 days compared with the previous decade) only observed in the south (Fig. 9).

Interannual variability of the rainfall

This sub-section deals with two aspects of the interannual variability of the rainfall: the distribution of daily rainfall, and the occurrence frequency of dry sequences during the rainy season.

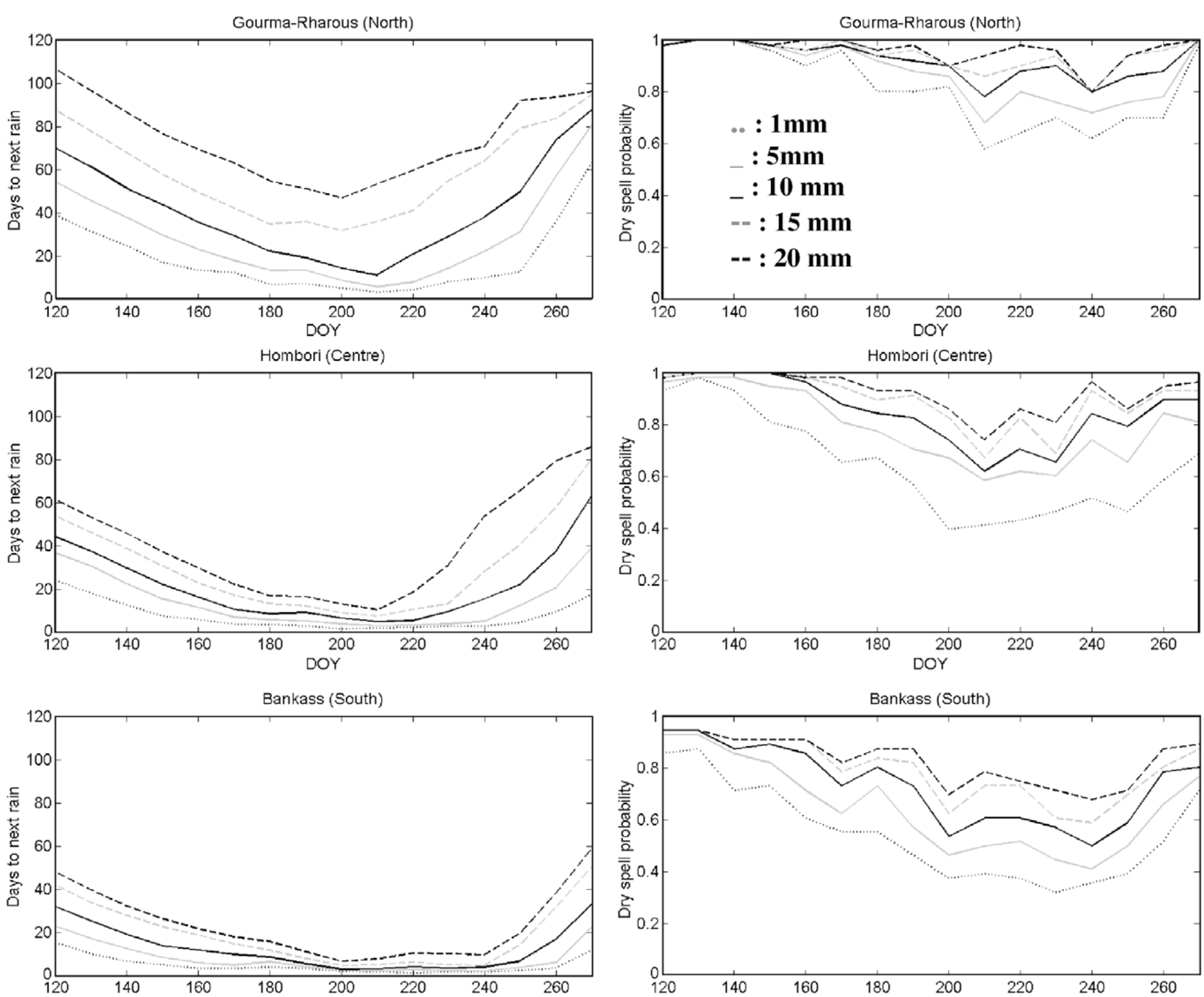

Fig. 11. Number of days until next rainfall greater than the threshold value (left column) – grey dotted line: 1 mm, grey line: 5 mm, black line: 10 mm, grey dashed line 15 mm, black dashed line: 20 mm, and associated probability of dry spell occurence (right column) at Gourma-Rharous (north), Hombori (centre) and Bankass (south).

Previous studies in Niger showed that reducing the number of events is the main factor explaining dry years in Sahel (Le Barbé and Lebel, 1997; Le Barbé et al., 2002; Balme et al., 2006). Yet in the Gourma region, the daily rainfall is significantly larger in wet years compared with dry years especially at the peak of the wet season, and this is observed in all stations. Examples for the three climatic zones are presented in Fig. 10.

The length of dry spells (as defined in "*Dry spell length and probability of occurrence*") and the probability of dry spell occurrence have been estimated for different thresholds τ (1, 5, 10, 15, and 20 mm). These thresholds were selected following the study of Sivakummar (1992) on the impact of dry spells on crops in Sahel. Examples are presented in Fig. 11 for three locations: Gourma-Rharous (northern Gourma), Hombori (central Gourma) and Bankass (southern Gourma). The dry spell length presents similar variations over time at all locations and for all thresholds. Nevertheless, the length of the dry spells increases both with the increase of thresholds, and the decrease of the mean annual rainfall levels (northward). The dry spell length drops down from day 120 (1st of May) to day 160 (10th of May) or 180 (1st of July), depending on the threshold value. It remains low until day 220 (1st of September), or 260 (20th of September), and then increases. The probability of dry spell occurrence presents a similar seasonal trend although more rugged. The length of dry spells (Fig. 11) and the daily rainfall (Fig. 10) vary over time in opposite directions. Even during the core of the rainy season (DOY 180–240), the probability of a dry spell greater than 5 days, for a threshold of 10 mm is always greater than 50% in Bankass, 60% in Hombori, and 80% in Gourma-Rharous. These statistics highlight the magnitude of rainfall variability at an intraseasonal scale over the Gourma region.

Nature of rainfall

Most of the Sahelian rainfall is of convective origin (Lebel et al., 2003). Indeed, more than 90% of the Sahelian rainfall is produced by MCS (Laurent et al., 1998). The more organized and efficient systems among the MCS, the Mesoscale Convective Complexes (MCC), account for more than 70% of MCS (D'Amato and Lebel, 1998; Laurent et al., 1998). Nevertheless, stratiform and convective precipitations both occur within the same complex of convection-generated cumulonimbus cloud. Convective rainfall refers to precipitations associated with young, active convections, whereas stratiform rainfall refers to precipitations occurring in older, less active convections (Houze, 1997). In terms of rain rates, stratiform precipitation is defined by rain rates lower than 12 mm h^{-1}, associated with non-convective structures (Nachamkin et al., 1994). This threshold is selected to discriminate between stratiform (purely stratiform, and stratiform precipitations within convective event), and purely convective rainfall. As the precipitation measured by the AR was summed by 10-min periods, the threshold of 12 mm h^{-1} becomes 2 mm per 10 min time period. As a consequence, rain rates lower than 2 mm per 10 min are considered

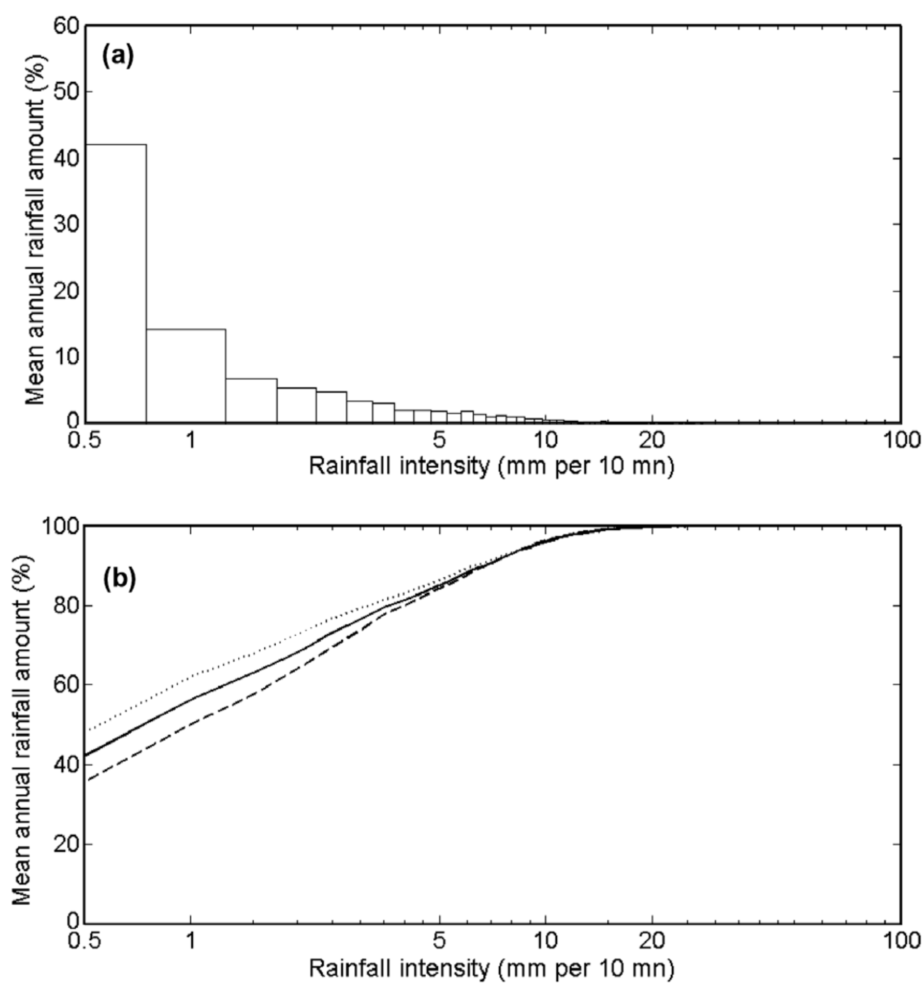

Fig. 12. (a) Normalized histogram of 10-min rainfall accumulation for the period 2005–2008 over Gourma region and (b) normalized 10-min rainfall accumulation for the period 2005–2008 over Gourma region. In black, the total distribution, in dashed black, the distribution during the day (9 a.m. to 9 p.m.), in dotted black, the distribution during the night (9 p.m. to 9 a.m.).

stratiform, and higher than 2 mm per 10 min, purely convective. Normalized histogram of 10-min summed rainfall is presented in Fig. 12a for Gourma stations, over the 2005–2008 period. Low and moderate rain rates, which correspond to stratiform precipitation, represent almost 63% of total rainfall, whereas purely convective rainfall represents only 37%. The lowest rain rates ($\leqslant$0.5 mm per 10 min, i.e., $\leqslant$3 mm h^{-1}) account for 43% of the total rainfall. The heaviest rain rates (>3 mm per 10 min, i.e., >18 mm h^{-1}), which are associated with the active core MCCs (Nachamkin et al., 1994), represents 27% of the total rainfall (and 73% of the purely convective rainfall).

An important contrast can be observed in the stratiform/convective distribution of rainfall between day (9 a.m. to 9 p.m.) and night (9 p.m. to 9 a.m.). In Fig. 12b, the low rain rates, which are associated with stratiform, account for relatively less rain during the day (33% of the total rainfall for rain rates lower than 0.5 mm per 10 min, i.e., 3 mm h^{-1}) than during the night (50%).

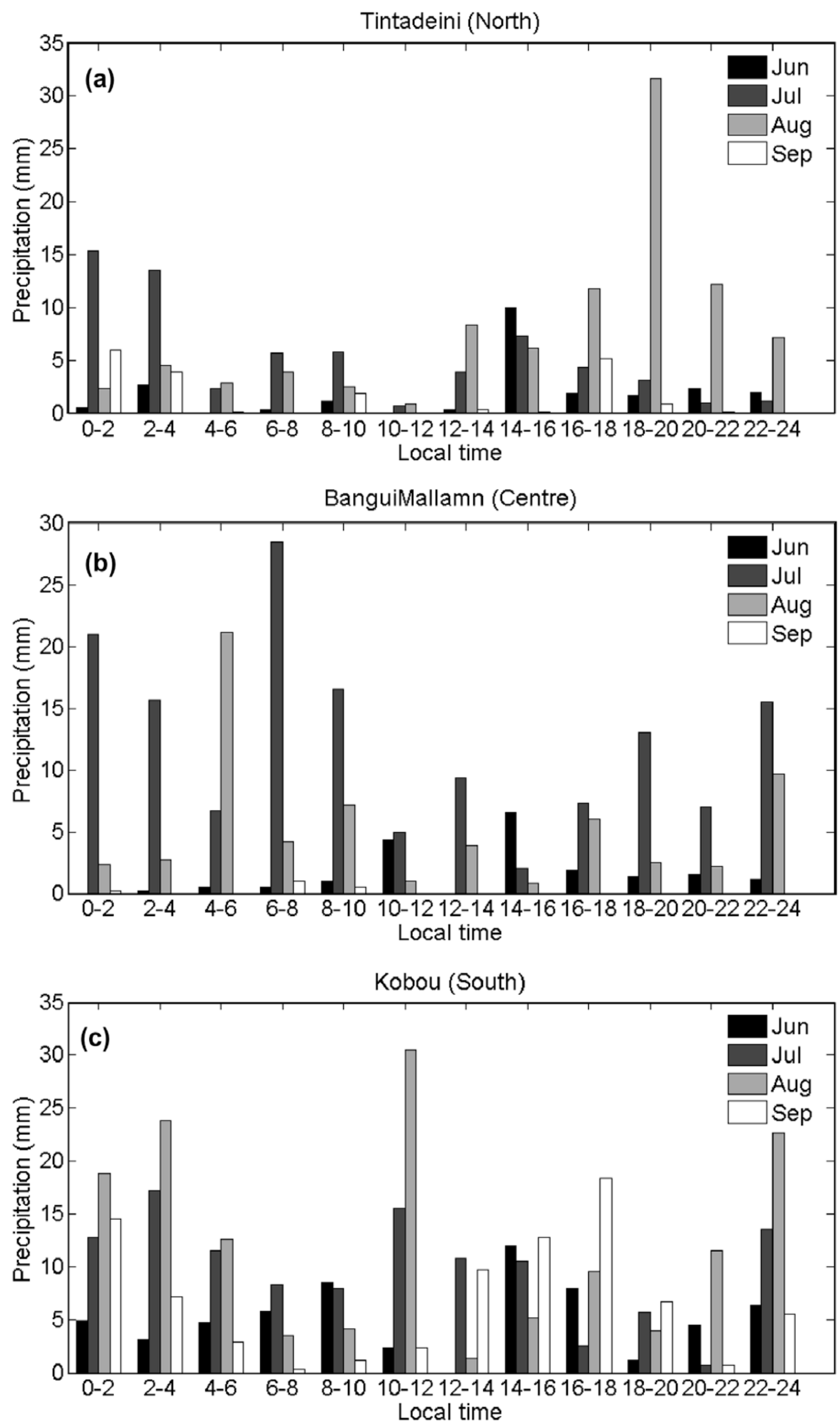

Fig. 13. Rainfall distribution along the diurnal cycle, by month, from June to September, for the 2005–2007 period in: (a) Tin Tadeini (north); (b) Bangui-Mallam (centre) and (c) Kobou (south).

Diurnal cycle of rainfall

Three AR located in Kobou (1.502°W, 14.727°N), Bangui-Mallamn (1.346°W, 15.398°N) and Tin Tadeini (1.766°W, 16.409°N) have been selected from the denser network presented above because their location along the latitudinal gradient is representative of the three rainfall regimes identified in the Gourma region.

The rainfall amounts recorded by the AR are accumulated every 2 h in order to analyse the average diurnal cycle. Due to the relatively short length of the record, it is difficult to obtain very robust statistics. Nevertheless, the basic features, which emerge from the analysis, are consistent with the existing literature. The diurnal cycle of precipitation, composed over 2005–2008, is presented in Fig. 13 for Tin Tadeini (north), Bangui-Mallam (centre) and Kobou (south). Tin Tadeini rainfall distribution presents two pronounced peaks – a first peak centred in early evenings (18:00–20:00 LST – Local Standard Time) and a second peak centred in early mornings (0:00–4:00 LST). Minimum rainfall occurs in late mornings (10:00–12:00 LST). The Bangui-Mallam diurnal cycle presents two maxima, one during late afternoons and one during nights – early mornings (22:00–6:00 LST), as well as a minimum between 10:00 and 12:00 LST. As for Tin Tadeini, the June distribution is unimodal and centred in early afternoons. Rainfall was very scarce in September (less than 5 mm).

The diurnal rainfall variations at Kobou show a broad peak centred on late evenings/early mornings (22:00–6:00 LST). The maximum observed between 10:00 and 12:00 LST is caused by one single event of 80 mm in August which is not smoothed because of the relatively short 3 years period of observation. Nevertheless, all AR from southern Gourma shows that rainfall around noon are more common than in northern and central Gourma. Rain distribution presents large variations between months. Rainfall amounts are higher in August than in July, with the same timing. Rain distribution in June is very similar to those observed in Tin Tadeini and Bangui-Mallam, but with higher amounts. Large precipitations were also recorded in September with 2-h sums greater than 10–15 mm. September diurnal cycle is bimodal, with primary and secondary peaks observed in afternoons (12:00–20:00 LST) and late evenings/early mornings (22:00–4:00 LST), respectively.

Results from other AR (including 5 year records at Agoufou, in central Gourma) strengthen both the bimodal distribution (late afternoon and early morning maxima) and the seasonal pattern (more early afternoon rainfall in June).

Two-peaked rainfall distributions were also observed by Shinoda et al. (1999) and Mathon et al. (2002), in Niger. They are typical of semi-desert and savanna regions of sub-Saharan Africa (Mohr, 2004). Here, the recorded late afternoon and evening maxima are consistent with afternoon convective triggering, while the morning maximum likely involves MCS life cycle. Differences in the diurnal cycle are noticed along the season. In July and August, the months with the largest amount of rainfall, precipitation mainly occurred, either in early mornings, or late in afternoons. This is in accordance with Mohr (2004), who showed that August rainfall can be explained, either by a greater concentration from shorter-lived organized convective systems, and/or by convective systems originated in late afternoons. The September rainfall distribution is also bimodal, whereas June distribution is unimodal and centred in afternoons. Isolated convective cells, as well as MCS passage when they are at their weakest activity, can account for the low rainfall observed in late mornings.

Conclusion

This study provides the first characterization of the rainfall regime since the 1950s in Gourma region, Mali. Common features and differences from studies undertaken in other Sahelian regions have also been underlined. The results of this study concerning the nature of rainfall, rainfall patterns and their changes during the last 60 years, are essential for policy makers and government agencies in order to manage water resources, and to elaborate agricultural policies.

The rainfall regime in the Gourma region presented wet (1950–1969) and dry decades (1970–1999) as observed in other studies on Sahelian rainfall but differences were observed along the climatic gradient. Since 2000, the Gourma region still exhibits dry conditions. As observed for other Sahelian locations, the annual precipitation amount in Gourma region is mainly controlled by the number of rainy days, but also by the mean amount of rainfall per rainy day. In the northern and driest part of the Gourma region, the amount of rain per rainy day is also an important factor. This statement may also be valid for the rain events, since the occurrence of more than one rain event per day is very rare. The length of the rainy season has been varying since the 1950s. It shortened significantly during the 1980s due to a later start. However, it is associated with an increase of the mean rainfall per rainy day, which suggests an intensification of the rain events in more recent years. Since 2000, a new decrease in the length of the rainy season was observed. In southern Gourma, the rainy season is shorter now than in the 1980s, and shorter of more than 20 days in comparison with the 1950s. The significance of these recent trends, and how they may be related to changes in the hydrological cycle over land (Lau and Wu, 2007; Wild et al., 2008), needs to be further investigated.

Data acquired during the 4 years of the AMMA-EOP from AR installed in the Gourma region were used to characterize the diurnal cycle and the nature of precipitations. Despite the relatively short duration of the measurement period, coherent features of the diurnal cycle of rainfall emerge from this dataset. The diurnal cycles of rainfall amount in northern and central Gourma display a well-defined bimodal distribution, with maxima registered in late afternoons and early mornings, and minima around noon. The late afternoon maximum is consistent with the daytime growth of convection over land, while the early morning maximum likely involves long-lived MCSs. In the south, the diurnal cycle presents the same maxima in late evenings and early mornings, but not a sharp damping around noon. The factors modulating this damping are yet to be determined, but these rainfall data offer a way to explore this issue further, if combined with colocated atmospheric analyses and MCS tracking products.

Thus, this study points to a significance of latitudinal gradients from the central to northern Sahel, which are not only affecting the cumulative rainfall or the number of rainfall events, but also, the intensity and the diurnal cycle of rainfall events.

Acknowledgements

This work was performed within the framework of the AMMA project. Based on a French initiative, AMMA has been constructed by an international group and is currently funded by large number of agencies, especially from France, the UK, the US and Africa. It has been the beneficiary of a major financial contribution from the European Community's Sixth Framework Research Programme. Detailed information on the scientific coordination and funding is available on the AMMA international web site (http://www.amma-eu.org/). The authors want to thank Dr. Manuela Grippa from CESBIO for Fig. 1. They are also very thankful to Pr. Baxter Vieux from University of Oklahoma (USA), Dr. Marc Leblanc and Dr. Sarah Tweed from James Cook University (Australia) for helping us improving the quality of the manuscript. FF is funded by a CNRS Research Grant. Longterm rainfall data were kindly provided by the DNM of Bamako.

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