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Rainfall regime over the Sahelian climate gradient in the Gourma region, Mali

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Abstract

The Sahelian zone 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 in a poorly described region of Central Sahel, Gourma region (14.5° to 17.5° N and 2° to 1° S) in Mali, as obtained from long-term daily precipitation time series covering the period 1950-2007 and from high-frequency dataset between 2005 and 2008. First, raingauge data collected since the middle of the 20th century were analysed both in terms of interannual variability and spatial distribution. Second, we investigate the diurnal cycle of precipitation and the nature of the rainfall using automatic raingauges during the period 2005-2008. This study also completes previous analyses conducted in Sahelian areas located further South, where the direct continental influence of the Saharan heat low is expected to be less pronounced in summer.

The Gourma region rainfall presents a succession of wet (1950-1969) and dry decades (1970-2007). The decrease of the summer cumulative rainfall is explained by a reduction of the number of the rainy days in the southern Gourma region and by both a decrease of the number of rainy days and of the mean precipitation amount per rainy day in the North and the Centre. This difference may be related to their respective distances from the intertropical discontinuity, which is closer to 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 of the mean rainfall per rainy day, which suggests an intensification of the rain events in the more recent years.

High-frequency data reveal that most of the rainfall is produced by intense rain events occurring mostly in the late evening and the early morning during the rainy season

(July/August/September). Conversely, rainfall amounts are the weakest at noon, and this mid-day damping is more pronounced in the North. All these characteristics have strong implications for agriculture and water resources management.

Key words Precipitation, Gourma region, Sahel, interannual variability, diurnal cycle

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1. Introduction

The arid and semi-arid regions of Africa are characterized by low and unreliable rainfall, which strongly affects the continental water cycle, water resources and food security (Nicholson, 1989). The largest of these regions, the Sahel, extends across Africa along 6000 km from the Altlantic coasts of Senegal and Mauritania to the shores of the Red Sea in Sudan and from the Sudanian savannas in the South to the Sahara (14° N to 20° N in latitude). 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). Besides, the substantial changes in the climate conditions obliged Sahelian farmers and pastoralist communities to adapt in response to the decrease of the water resources (Mortimore and Adams, 2001; Tarhule and Lamb, 2003; Pedersen and Benjamisen, 2008).

The few recent studies of Sahelian rainfall regimes using raingauge data were mainly carried out over large areas located further South (Le Barbé et al., 2002; Lebel et al., 2003; Bell and Lamb, 2006) whereas rainfall regimes of drier North, which experiences a strong climatologic influence of the Sahara heat low in summer, and Centre Sahel 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) meso-scale site (14.5–17.5°N, 1–2°W), located in the Gourma region in Mali. It is based on ground-based measurements covering a range of complementary scales.

First, it aims to provide a climatology of rainfall over the Gourma region during the years 1950-2007 with time series of daily precipitation. Namely, the rainy season will be characterized in terms of length, distribution of precipitation, and number and intensity of rainy days. Historical trends which affected West Africa and the Sahel as a whole over the past century will be presented and discussed specifically for the Gourma region.

Second, smaller scale modes of rainfall variability will be investigated with high frequency measurements from the AMMA-CATCH raingauge network for the AMMA Enhanced Observations Period (EOP) 2005-2008. Over the Sahel, and in the Gourma region as well, rainfall is of convective origin, and organized Mesoscale Convective Systems (MCS) account for most of it as shown by Mathon et al. (2002). Therefore, we explore how the distribution of rainfall rates associated to rainfall events over the Gourma region comply to existing studies. The diurnal cycle is also a major feature of convection and rainfall over land (Wallace, 1975; Yang and Slingo, 2001) and is discussed here for the Gourma region.

2. Material and methods

2.1 The study region

The Gourma region, a region of 90,000 km^2, belongs entirely to the Sahel and extends from 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 is mainly pastoral bracketed by the annual isohyets of 150 and 500 mm with an interannual coefficient of variation of the total annual rainfall ranging from 15 to 30% (Sivakummar, 1989). A comprehensive presentation of the Gourma AMMA meso-scale site can be found in Mougin et al. (this issue).

2.2 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 available data, with only use records from 1950 to 2007. Nine of all the historical stations are located in the Gourma region, 13 are located around the Gourma region and are helpful to characterize the rainfall regime of this region and 3 are located North, in the transition zone between Sahel and Sahara. Nevertheless, data are often for a few years. This long term precipitation dataset mostly originates from Direction Nationale de la Météorologie (DNM), the Malian meteorological service. In order to place our results in the broader context of the West African Monsoon, daily rainfall data from 35 additional stations, provided by DNM too, and located further South in Mali have also been used.

In order to characterize the diurnal cycle and the nature of precipitation over the Gourma region, the dataset used comes from the records of the 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). In the following, we used the measurements recorded by the AR between June and September from 2005 to 2008.

2.2 Standardized rainfall anomaly index and standardized number days index

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

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

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 for the computation.

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

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

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.

2.3 Estimation 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). Following this criteria, for each raingauge and year, the beginning of the rainy season corresponds to an amount of rain of at least 20 mm in 3 days, after the 1st of May not followed by a drought longer than 7 days in the 30 following days. The end of the rainy season corresponds to 20 successive days without rain, after the 1st of September.

2.4 Dry spells 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 region climatic gradient.

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

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

where *N* is the number of year without missing days for a station, *p* is the rainfall and $\Omega = \begin{cases} 1 \text{ if } i \text{ is part of a dry spell of threshold } \tau \text{ for year } N \\ 0 \text{ if not} \end{cases}$.

3. Results and discussion

3.1 Major features of rainfall in the Gourma region

The mean annual rainfall over the Gourma region mesoscale site is characterized by a South to North decreasing gradient slightly larger than 1 mm km^{-1} (Fig. 2), a characteristic value found elsewhere in the Sahel (Lebel et al., 2003). It involves a gradation of bioclimatic zones distributed latitudinally with a slight southward inflexion from West to East (Hiernaux and Le Houérou, 2006). It should be mentioned here, however, that isohyets positions have varied considerably over the past 60 years in the Gourma region (Fig. 3) and more generally in the Sahel, as shown in Lebel and Ali (this issue). The dry years isohyets (1970-1989) are shifted about 100-150 km to the South by comparison to those of the preceding wet period, corresponding to a decrease of 100 mm per year in the North of the study zone and of 150 mm per year in the South. For comparison, a shift to the South of the isohyets of around 200 km is observed for the whole Sahel (Lebel and Ali, this issue). Their curvature also changed during this period, showing that a East-West variability is also present along with the North to South climatological gradient. This observation is in accordance with results from previous studies (Nicholson et al., 1980; Janicot, 1992; Nicholson and Palao, 1993; Moron, 1994; Nicholson, 2005; Lebel and Ali, this issue). Thus defining climatic zones remains a tricky 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 the 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 July August September (JJAS) number of rainy days (noted *Nd*) has been plotted either versus the JJAS cumulative rainfall (noted *R*) or the mean rain per rainy day (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 rainfalls.

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

Previous studies have highlighted the dominant role of *Nd* in the seasonal rainfall (Lebel et al., 1997; Le Barbé and Lebel, 1997; and Le Barbé et al., 2002). On the contrary, both the number of rainy days and the mean rainfall per rainy account for the annual rainfall in Gourma region.

Thus, our results depart from these studies which focused on more southern part of the Sahel. A possible reason for that is that the local atmospheric environment, in which convection occurs, may play a stronger role in explaining the annual rainfall amount in Gourma region than further South. It would be useful to explore how this result relates to interannual changes of atmospheric humidity, as this parameter exerts a significant control on evaporation of cloud water and rainfall and may control the amount of rainfall reaching the surface. More broadly, the Gourma region may be more directly under the influence of West African Heat Low (WAHL) circulations (which correspond to continental depression associated with an increase of the potential temperature and are a main component of the West African Monsoon likely to play a significant role in the rainfall variability over Sahel, see Janicot (1992) for more details) than Southern part of the Sahel. In this respect, it would be useful to assess the interannual variations of the location of the InterTropical 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 the winds (Ag Mahmoud, 1992), a view which is not inconsistent with an ITD located close to the Gourma region.

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

Fluctuations of the standardized rainfall anomaly index I_R (Eq. 1) and of the standardized number of rainy days anomaly index I_N (Eq. 2) have been calculated between 1950 and 2007 using daily rainfall collected at stations in and around Gourma region (Gourma region and surroundings in Table 1). The number of available stations is not constant for all years. Ranging between 20 and 25 from 1950 to the end of the 1980s, it decreases down to 15 in the middle of the 1990s, then down to 10 in 2003 and down to 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 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 the Sahel. Even if the results for the Gourma region present a larger variability, the trends are consistent with those found during previous climatological studies on 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 for the whole Sahel 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 (5 positive anomalies of I_R) than in whole Sahel, defined by the window 10°N-20°N, 20°W-20°E (2 positive anomalies). The last 20 years present a succession of wet and dry years with less dry conditions during the 1990s and drier 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.

Figure 6b presents the time variations of the standardized number of rainy days anomaly index between 1950 and 2007. The standardized number of rainy days anomaly index (Fig. 6b) and the standardized rainfall anomaly index (Fig. 6a) present a similar pattern. 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). Nevertheless, some differences appear. The major ones concern the drought of 1972-1974 where a positive anomaly is present in the standardized number of rainy days anomaly index (Fig. 6b) for 1974 and the drought of the 2000s where the standardized number of rainy days anomaly index is much more negative than the standardized rainfall anomaly index.

The decadal deviation to the mean annual rainfall (Fig. 7a) and to the mean number of rainy days (Fig. 7b) were computed for each climatic region (North, Centre, and South) to take into account the regional variability of the precipitation over Gourma region between 1950 and 2007.

Figures 7a and 7b exhibit differences especially for the period 1970 - present. During the 1970s, characterized by the drought of 1972-1974, the deviations from the mean number of rainy days are positive in the South of Gourma region, whereas the deviations from the mean annual rainfall are all negative. The opposite is observed during the 2000s (positive deviations in the North and Centre Gourma region and negative in the South), characterized by the drought of 1983-1985. Even for the southern part which is climatically close to the Niamey region (Niger) conditions, the deviations sometimes present an opposite sign (decades 1970-1979) or a more pronounced negative anomaly for the number of rainy days (~20% against ~10% for the normalized rainfall index). Similar results were obtained when thresholds of 1 and 3 mm were used to define a rainy day and to exclude potential bias coming from poor reporting of small rainfall amounts. These results suggest that both the number of rainy days and the amount of rain per rainy day control the annual rainfall in 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 the rainfall (negative anomalies of I_R and positive anomalies of I_N) in the North and the Centre of the Gourma region and an intensification of the 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 of the number of rainy days in the South of the Gourma region is 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).

3.3 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, defined with the criteria presented in section *Estimation of timing and length of the rainy season*, comprises 90% of the annual rainfall of Gourma region. 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 the Niger.

Figure 8a shows that 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), i.e., a northward delay of five days per degree of latitude for the beginning of the rainy season with a maximum standard deviation of 15 days for each location during the considered period. 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 7 days for each location during the considered period. Thus, the standard deviation is about twice smaller for the end date than for the start date. It means that there is more variability on the beginning of the rainy season than on the end. Along the South-North climatic gradient, the length of the rainy season varies from 120 days in the South of Gourma region to 60 days in the North, 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 on Fig. 9 and Table 2 for the 3 climatic zones of Gourma region. The average duration of the rainy season in the South of Gourma region (~110 days) and the beginning and ending days (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° to 14° N), i.e., 105 days, 21st of June and 4th of October. We notice a decrease of the mean length of the rainy season for each zone (North, Centre and South) during the 1950-2007 period of 13, 12, and 22 days respectively due to both a delay of the starting date (from the 1st of July to the 9th of July in the North, from the 22nd of June to the 27th of June in the Centre, from the 8th of June to the 21st of June in the South) and earlier ending (from the 17th of September to the 12th of September in the North, from the 24th of September to the 17th of September in the Centre, from the 5th of

October to the 26th of September in the South). The decrease started in the middle of the 1960s with a minimal length reached during the 1980s associated with the severe drought of 1983-1985. The length of the rainy season increased to the levels of the 1960s during the 1990s, especially due to a later ending.

During the last 10 years, we observe a new decrease of the duration of the rainy season towards the values observed during the drought of 1972-1974 in the North, and towards the values observed during the severe drought of 1983-1985 in the Centre. Further South, the current length of the rainy season is the smallest of our period of study (Table 2). This decrease of length is caused by an earlier ending for the three zones and a later beginning (~10 days compared with the previous decade) in the South (Fig. 9).

3.4 Interannual variability of the rainfall

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

Previous studies in Niger showed that the diminishing of the number of events is the main factor explaining dry years in the Sahel (Le Barbé and Lebel, 1997; Le Barbé et al., 2002; Balme et al., 2006). In the Gourma region, at each station, the rainfall per rainy day is significantly larger during wet years compared with dry years, especially at the peak of the wet season. Three examples for the different climatic zones (North, Centre and South) of the Gourma region are presented in Fig. 10. These results confirm that the rainfall distribution is governed by both the number of rainy days and the rainfall by rainy day.

The rainy season in the Sahel is characterized by sequences of days without precipitation (or very low precipitation), known as dry spells. The length of a dry spell (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) are presented in Fig. 11 for different rainfall thresholds at three different locations: Gourma-Rharous (North Gourma), Hombori (Centre Gourma) and Bankass (South Gourma). These thresholds were selected following the study of Sivakummar (1992) on the impact of the dry spells for agriculture in the Sahel. The dry spell length presents a similar time variation for all the locations and the thresholds. Nevertheless, the length of the dry spells increases both with the increase of thresholds and the decrease of the annual rainfall amount (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 but less smoothed evolution with respect to time. The length of dry spells (Fig. 11) and the rainfall per rainy day (Fig. 10) over the Gourma region varies the opposite way with respect to time. We also observe that even during the core of the rainy season (DOY 180 to 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. This result stresses on the great variability of rainfall in Gourma region at intraseasonal scale.

3.5 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 this total (D'Amato et al., 1998; Laurent et al., 1998). Nevertheless, stratiform and convective precipitation both occur within the same complex of convection-generated cumulonimbus cloud. Convective rainfall refers to precipitation associated with young, active convection whereas stratiform rainfall refers to precipitation occurring in older, less active convection (Houze, 1997). In terms of rain rates, stratiform precipitation is defined as 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 precipitation of 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 minutes are considered stratiform, higher than 2 per 10 minutes purely convective. Normalized histogramm of 10-min summed rainfall over Gourma region between 2005 and 2008 is presented on Fig. 12a. Low and moderate rain rates, which correspond to stratiform precipitation, represent almost 63 % of total rainfall, whereas purely convective rainfall represents only 37 %. Low rain rates (≤ 0.5 mm per 10 mn, i.e., ≤ 3 mm h^{-1}) account for 43% of the total rainfall. Heavy rainfall (> 3 mm per 10 mn, i.e., > 18 mm h^{-1}), which are associated with the active core MCCs (Namchamkin 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, are ccount for relatively less rain during the day (33 % of the total rainfall for rain rates lower than 0.5 mm per 10 mn, i.e., 3 mm h^{-1}) than during the night (50 %).

3.6 Diurnal cycle of rainfall

Three AR located in Kobou (1.502° W, 14.727° N), Bangui Mallamn (1.346° W, 15.398° N) and Tintadeini (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 Gourma region.

The rainfall amounts recorded by the AR are accumulated every 2 hours in order to analyze 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 for 2005-2008, is presented in Fig. 13 for Tintadeini (North), Bangui Mallamn (Center) and Kobou (South). Tintadeini (North) rainfall distribution presents two pronounced peaks - a first peak centred in the early evening (18:00-20:00 LST – Local Standard Time) and a second peak centred in the early morning (0:00-4:00 LST). Minimum rainfall occurs in the late morning (10:00-12:00 LST). The Bangui-Mallamn (Centre) diurnal cycle presents two maxima, one during late afternoon and one during night-time - early morning (22:00-6:00 LST) as well as a minimum between 10:00-12:00 LST. As for Tintadeini, the June distribution is unimodal and centred in the early afternoon. Rainfall was very scarce in September (less than 5 mm).

The diurnal rainfall variations at Kobou (South) show a broad peak centred on the late evening/early morning (22:00-6:00 LST). The maximum present 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. Nevertheless, all AR in the South Gourma region shows that rainfall around noon are more common than for North and Centre regions. 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 Tintadeini (North) and Bangui-Mallamn (Centre), but with higher amounts. Large precipitation was also recorded in September with two-hour sum greater than 10 to 15 mm. September diurnal cycle is bimodal with primary and secondary peak observed in the afternoon (12:00-20:00 LST) and late evening/early morning (22:00-4:00 LST) respectively.

Results from other AR (including 5 years record at Agoufou, in the central part of the Gourma region) 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 the early morning or late in the afternoon. 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 afternoon. The September rainfall distribution is also bimodal whereas June distribution is unimodal and centred in the afternoon. Isolated convective cells can account for the low rainfall observed, as well as MCS passage when at their weakest in late morning.

4. CONCLUSION

This study provides the first characterization of the rainfall regime in Gourma region, Mali, since the 1950s. 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 sixty years, are essential for policy makers and government agencies 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 rainfall per rainy day which accounts for part of the annual rainfall. In the northern and driest part of the Gourma region, the amount of rain per rainy day is also an important factor. This may also be true for the rain events since the occurrence of more than one rain events 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 late start. However, it is associated with an increase of the mean rainfall per rainy day. This result 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 the South of the Gourma region, the rainy season is shorter now than in the 1980s and lost 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 investigated further.

Data acquired during the 4 years of the AMMA-EOP were used to characterize the diurnal cycle and the nature of precipitation at using data from AR installed in the Gourma region. Despite the relatively short duration of the sampled period, coherent features of the diurnal cycle of rainfall emerge from this dataset. The diurnal cycles of rainfall amount in the North and the Centre display a well-defined bimodal distribution with maxima registered in the late afternoon and the early morning 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 the organization of convection in the form of long-lived MCSs. In the South, the diurnal cycle presents the same maxima in the late evening and the morning 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, e.g.; in combination with colocated atmospheric analyses and MCS tracking products.

Thus, this study points to a significance of meridional gradients from the Central to Northern Sahel which are not only affecting the cumulative monsoon rainfall or the number of rainfall events, but also, the intensity of rainfall events and the diurnal cycle of rainfall amount.

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TABLES

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

Table 2. Dates of start and end, and length of the rainy season per decades, between 1950 and 2007 for the 3 bioclimatic zones. The associated uncertainties represent the half of the standard deviation.

FIGURES

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

Fig. 2. Distribution of the mean annual rainfall and standard deviation from the origin to 2007 as a function of the latitude. Standard deviation of the measurements ranges from 42 mm in the North to 139 mm in the South.

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

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 Gourma region (full circles, with standard deviation) and Malian stations south of Gourma region (dots). b) mean rainfall per rainy day (*Rd*) for each station versus average JJAS rainfall (*R*) for Gourma region (full circles, with standard deviation) and Malian stations south of Gourma region (dots). c) correlation coefficient (*r*) between *R* and *Nd* for each Gourma station, characterizing the inter-annual variability. d) correlation coefficient (*r*) between *R* and *Nd* for each Gourma station.

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. b) evolution of the standardized anomaly number of rainy days index (I_N) over the Gourma region between 1950 and 2007.

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

Fig. 8. a) start and end 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. 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.

Fig. 9. Date of start (dashed line) and end (plain line), and length (dotted line) of the rainy season at three different locations in the Gourma region: a) North, b) Centre and c) South.

Fig. 10. Mean rainfall per rainy day on a 10-day 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 at the raingauge.

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).

Fig. 12. a) normalized histogramm of 10-min rainfall accumulation for the period 2005-2008 over Gourma region. 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.).

Fig. 13. Rainfall distribution along the diurnal cycle by month from June to September for the 2005-2007 period in a) Tintadeini (North), b) Bangui Mallamn (Centre), and c) Kobou (South).