Chapter 2

The return of a wet period in the Sahel?

Observations and prospects

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Introduction

The question of the evolution of precipitations is of prime importance in the Sahel, a region where rainfall is at the heart of societal concerns. A deficit affects the availability of water resources and the yields of farming that is still mainly rainfed. Excess water can cause extreme hydrologic events that are harmful for populations increasingly exposed to flood risks. Precipitations are in fact the signature of the atmospheric and environmental processes that regulate the West African monsoon, which is in turn a component of the global climate system. The evolution of precipitations is thus at the hinge-point between climate variability and its impact on populations. Describing it is essential for learning about water-related risks and anticipating their future in a changing global climate.

Following the strong involvement of the international scientific community, especially at the end of the 1970s, major progress has been made in the understanding of the mechanisms of the West African monsoon, in particular thanks to an in-depth study of the rainfall regime in the Sahel. The simple description that long featured in climatological atlases of the rainy season lasting from June to September and the annual cumulated precipitation distributed along a latitudinal gradient from 200 mm in the north to 700 mm in the south (these isohyets are often put forward for the climatological delimitation of the Sahel) is now accompanied by in-depth knowledge of the long-term evolution of the rainfall regime from interannual to intraseasonal scales showing, in particular, disparities within the Sahel.

The evolution of cumulated annual rainfall figures has been studied by many scientists alerted by the drought peaks of 1972-1973 and the dramatic famines that accompanied them. The first work on the evolution of rainfall in the Sahel unsuccessfully sought signs of cyclicity in interannual variability (BUNTING *et al.*, 1976). Questions were then refocused on the establishment of the drought at the end of the 1960s and then on the signs and causes of its persistence (LAMB, 1982; HULME, 1992; FONTAINE and JANICOT, 1996; NICHOLSON, 2001; GRIST and NICHOLSON, 2001). The updating of rainfall data to the 1990s confirmed the strong contrast between a comparatively humid period until the end of the 1960s that was followed immediately by a sudden and persistent decrease in rainfall (LE BARBÉ and LEBEL, 1997). These studies show the regional character of drought at the scale of the Sahel, illustrated by a southward movement of the annual isohyets (decrease ranging from 20% in the south of the Sahel to 50% in the north) (LEBEL *et al.* 2003). Much work has shown the statistical significance of this sharp decrease in rainfall in different regions of the Sahel (HUBERT and CARBONNEL, 1987; DEMARÉE, 1990; TARHULE and WOO, 1998). Placing this evolution in perspective in a global context (RASMUSSON and ARKIN, 1993) now makes it possible to consider the great Sahelian drought as the most extensive and intense climate change ever measured in the world (HULME, 2001).

At the end of the 1990s, the question of a return to more humid conditions emerged and generated controversy (NICHOLSON, 2013). The demonstration of overall regreening of the plant cover in the Sahel region (see Chapter 6) also seemed to support the hypothesis of a recovery of precipitation. A major obstacle for the reliable quantitative documenting of the rainfall for the last two decades is on the one hand the difficult access to post-1990 data as the national meteorological networks are degraded (PANTHOU *et al.*, 2012) and on the other a certain reticence of the countries in West Africa to share their data (TARHULE and WOO, 1998). NICHOLSON (2013) considers that this difficulty is the initial reason for the small number of studies on the evolution of rainfall in the recent period and contributes to the blank zones that still weigh on our knowledge of climatology in the Sahel.

This chapter first sets out a synthesis of recent results concerning the evolution of precipitation in the Sahel, especially over the last 20 years. We first show that signs of return of rainfall do exist but are very relative and display regional disparities. It is shown in the second part that the notion of recovery is very dependent on the scale at which it is examined, especially when mesoscale convective systems are considered as these mark the key scale of the link between climate and impact. The evolution of rainfall is addressed at the scale of hydrologic and agronomic impacts in the third part. Information is provided on the evolution of the characteristics of rainfall events, and especially the most extreme ones that were long ignored in the literature and that provide a fresh view of the direction taken by rainfall climatology in the last two decades. A balance is drawn up in the last part, providing several lines of research to be emphasised.

The return of rainfall in the Sahel: regional disparities at the annual scale

Review of recent decadal variability

Cumulated annual precipitation is the most commonly used indicator for describing the long-term evolution of rainfall. In most studies, annual rainfall anomalies are estimated by calculating a standardised precipitation index (SPI) (ALI and LEBEL, 2009). The SPI is used to distinguish between the upper and lower years of the climatological average and to use interannual and decadal variability to show the main features of the evolution of rainfall (Figure 1).

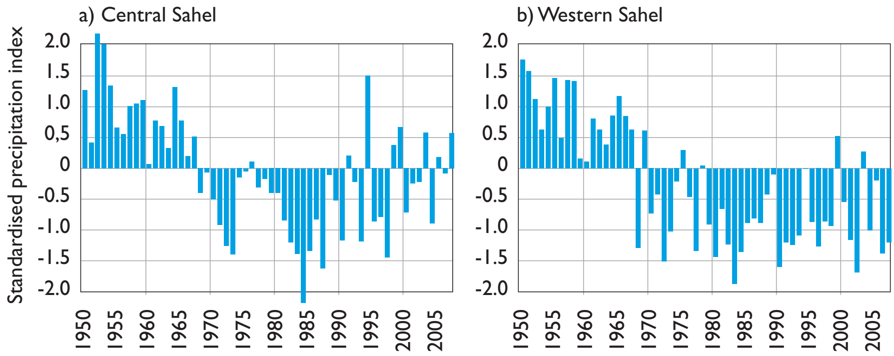

Figure 1.
Precipitation anomalies (standardised precipitation index)
calculated with reference to the 1950-1989 period in the central Sahel (left)
and the western Sahel (right).
After LEBEL and ALI (2009).

The question of the persistence or end of the drought was a subject for debate at the beginning of the 2000s. Analysing the SPI at the scale of annual rainfall in the Sahel until 2000, L'HOTE *et al*. (2002) held that dry conditions were still predominant at the end of the 1990s. OZER *et al*. (2003) refuted these conclusions, affirming that the drought ended in the mid-1990s. Extending the study period until 2003, DAI *et al*. (2004) and NICHOLSON (2005) did observe a tendency for rainfall to increase in the Sahel but stressed that average rainfall during the recent period was still much smaller than it had been during the 1950-1970 humid period. Using 1950-2007 information from network of rain gauges grouping a large number of national meteorological stations in the Sahel countries, ALI and LEBEL (2009) showed that the drought persisted after 1994 but there are differences in the recent evolution of rainfall in the Sahel. It can thus be seen in Figure 1a from LEBEL and ALI (2009) that although there was a decrease in rainfall deficits after 1990 in the central Sahel (defined in the window 11°N-17° N; 0°-5°E), this was marked by strong interannual variability and average rainfall remained well short of that of the 1950-1970 humid period. In contrast, in the western Sahel (defined in the window 11 N - 17°N; 15°W - 10°W) (Figure 1b), most of the years displayed a deficit whose average level was similar to that of the two preceding dry decades.

Several studies have since confirmed the evolution observed by LEBEL and ALI (2009). MAHÉ and PATUREL (2009) also propose a distinction between the evolution of rainfall between the eastern Sahel, where recovery is moderate, and the western Sahel, which has remained dry. IBRAHIM *et al*. (2012) and LODOUN *et al*. (2013) observed a gradual increase in annual rainfall in Burkina Faso from the end of the 1980s but the humid conditions of the 1950s and 1960s have not been matched. LODOUN *et al*. (2013) report very strong interannual variability, the sign of close alternation of dry and humid years that differ from the preceding periods. This feature is also observed in the Malian Gourma (FRAPPART *et al*., 2009) and more generally in the Sahelian part of the Niger River basin (TARHULE *et al*., 2014).

Variability of characteristics of the season

The decadal evolution of the seasonal precipitation cycle reveals other noteworthy differences between the central and western Sahel.

In the central Sahel, distinction is generally made between five phases in the seasonal precipitation cycle (LEBEL *et al*., 2003; SULTAN *et al*., 2003); these are traced clearly in Figure 2a for 1950-1969: (1) the establishment of the ocean phase of the monsoon causes a steady increase in rainfall from the beginning of April to the end of May; (2) rainfall stabilises in June; (3) cumulated precipitation increases rapidly at the end of June with the onset of the monsoon; (4) the continental phase of the monsoon is accompanied by a steady increase to a maximum in August after slight stabilisation in July; (5) rainfall then decreases steadily until the end of October with the withdrawal of the monsoon. In the western Sahel (Figure 2b), the seasonal signal is not marked by the onset of the monsoon and thus features three phases with the start of the monsoon followed by a steady increase in rainfall until the beginning of September and then a rapid decrease.

Analysis of the decadal evolution of the seasonal signal (Figure 2) shows that these phases are visible during all periods except for the dry years (1970-1989) in central Sahel, with (1) smoothing of the June and July peaks, thus masking the influence of the onset of the monsoon, (2) peak rainfall distinctly less than during the humid period (1950-1969) and occurring 20 days earlier. However, the decrease in rainfall in the western Sahel during the dry period is distributed much more evenly throughout the season.

It can be seen in Figure 2 that the seasonal signal for the recent period (1990-2007) is closer to that of the dry period (1970-1989) than to that of the humid period (1950-1969). In particular, the strong decrease in rainfall in the central Sahel in August and the shift in the peak season observed for 1970-1989 continued in recent years. This confirms the results reported by NICHOLSON (2005) and underlines the very relative nature of the recovery.

Three peaks can be seen—in June, July and August—in the central Sahel. These reach the level of the 1950-1969 signal but do not last as they did in the humid

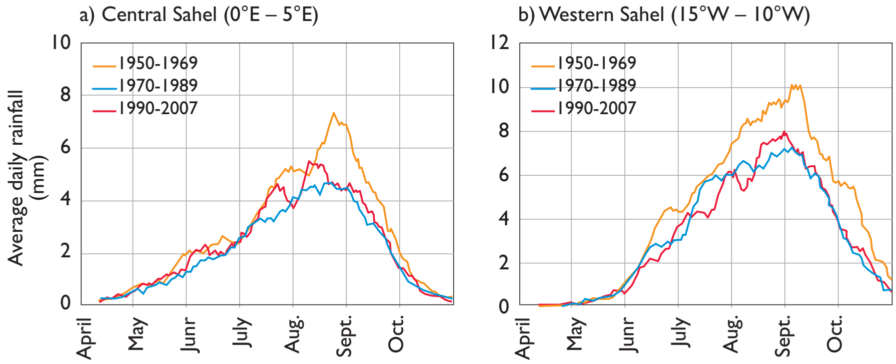

Figure 2.
Decadal evolution of the seasonal signal in central Sahel (a) and western Sahel (b).
After LEBEL *et* ALI *(2009).*

period. An interesting feature is the contrast in phase between the three peaks and those observed in the western Sahel during the same period; this may suggest the establishment of an east-west dipole during the continental phase of the monsoon.

Finally LEBEL and ALI (2009) note that the duration of the rainy season (defined by days with rainfall of more than 1 mm) is practically identical in all the periods. This observation is shared by IBRAHIM *et al*. (2012) in Burkina Faso and confirms the results of BALME *et al*. (2005) in Niger which show that there is no significant correlation between cumulated annual depth and the duration of the rainy season.

The recovery of rainfall in the Sahel: a question of scale

Mesoscale convective systems: a key scale in the link between climate and impact

Rainfall in the Sahel is caused by broad storm systems that spread from east to west at several tens of kilometres per hour and are referred to as mesoscale convective systems (MCSs). These account for 80% of annual rainfall, with the remaining 20% occurring during more local rainstorms (MATHON *et al*., 2002). A rainy season in the Sahel involves the passage of about 40 of these systems, making rainfall very intermittent and extremely variable in time and space. BALME *et al*. (2006 b) show that 50% of annual rainfall takes place in less than 4 hours.

The genesis and life cycle of the precipitation systems in the Sahel result from the interaction of meteorological processes across a scale continuum ranging from the synoptic to the mesoscale (REDELSPERGER *et al*., 2006). Furthermore as is seen below, the occurrence, intensity and spatial extension of MCSs modulate the internannual variability of precipitation in the long term (Le Barbé *et al.*, 2002; Lebel *et al.*, 2003; Bell and Lamb, 2006) and directly affect the distribution of surface water and in particular the partition between runoff and infiltration that controls the water cycle and the hydrological balance. The mesoscale associated with MCSs is therefore considered to be a key scale for describing hydro-climatic variability in the Sahel, at the interface between the scale of the regional features that govern the monsoon and the more local scale of hydrological or agricultural impacts (Peugeot *et al.*, 2003; Vischel and Lebel, 2007; Vischel *et al.*, 2009; Massuel *et al.*, 2011).

The impact of mesoscale rainfall on the notion of dry year and wet year

Particular effort has been made in the last 15 years to describe rainfall variability at the mesoscale. Most of the studies on the subject are based on data from the observation service AMMA-CATCH *(Analyse multidisciplinaire de la mousson africaine-Couplage de l'atmosphère tropicale et du cycle hydrologique)* (Lebel *et al.*, 2009), the only one in West Africa to provide rainfall data at infra-daily time steps and with dense distribution at three mesoscale sites (~ 10,000 km²) in Mali, Niger and Benin. The AMMA-CATCH rainfall networks have already made it possible to document the variability of distribution in terms of occurrence and intensity (Balme *et al.*, 2006 b), spatial structure (Guillot and Lebel, 1999; Ali *et al.*, 2003) and propagation (Depraetere *et al.*, 2009; Vischel *et al.*, 2011) of rainfall events associated with MCSs.

This chapter concerns a noteworthy finding concerning the contribution of MCSs to regional rainfall variability that is used fairly directly in the question of recovery and the associated spatial heterogeneity. In a recent study, Balme *et al.* (2006 a) called into question the notion of dry years and wet years by comparing annual isohyet maps plotted (1) at the regional scale using data from national pluviometric networks that are not very dense (1 or 2 rain gauges per 10,000 km²), and (2) using data from the AMMA-CATCH Niger observation network (1 to 2 rain gauges per 500 km²). It is shown in Figure 3a for 1992 that at the scale of the Sahel the spatial structure of rainfall is dominated by a latitudinal regional gradient (~ 1 mm per km). In contrast, at the scale of the observation service, local heterogeneous features are dominant in comparison with the north-south gradient as a result of several rainfall events whose positions on the ground determine the spatial distribution of rainfall, even at the annual scale. Balme *et al.* (2006 b) show that this type of very contrasted organisation is found at the observation service—whatever the year examined. The steep rainfall gradients can thus reach as much as 275 mm at gauging stations 9 km apart (in 1998) and their positions are random with regard to the network configuration and seen in both dry and wet years. The gradients can mark the spatial organisation of rainfall fields at aggregation scales of more than 10 years, as is shown in Figure 3b where, for example, a pluviometric anomaly can be seen centred on 2.2° E, 13.25° N, resulting from strong cumulation observed at the same point in 1992.

As a result, the classification as 'dry year' or 'wet year' and even 'dry period' and 'wet period' often used at the scale of the Sahel to describe the evolution of rainfall

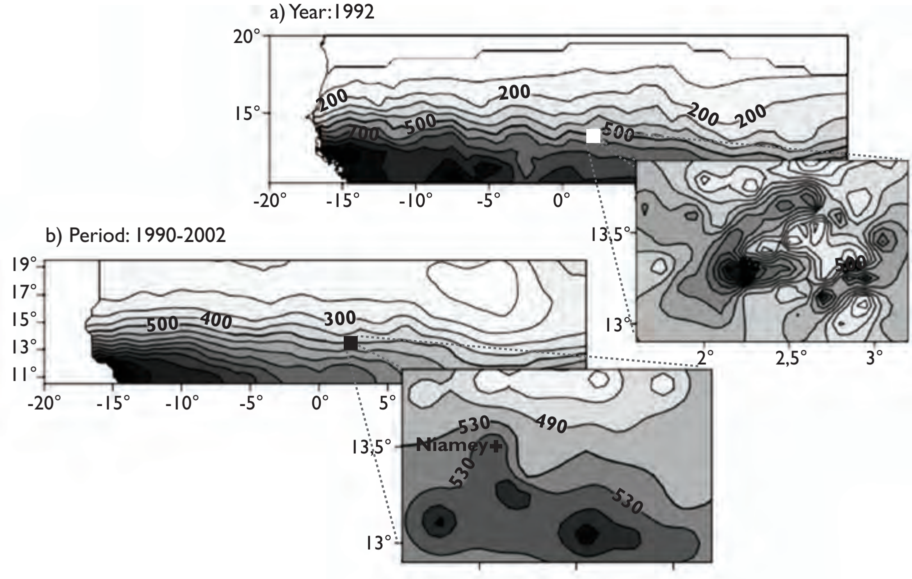

Figure 3.
Isohyets for the Sahel (isohyets at 100 mm intervals):
data from the Agrhymet centre of the Permanent Interstate Committee for Drought Control
in the Sahel (CILSS) and a zoom using the dense network
of the AMMA-CATCH Niger observation service.
(a) Cumulated figure for 1992 (from BALME et al., *2006 a).*
(b) Annual cumulated average for the period 1990-2002 (from BALME et al., *2006 b).*

is not very pertinent at the local rain gauge or village scale. This justifies a specific approach to the evolution of the rainfall regime at convective scales showing the questions of the impact of rainfall variability.

Rainfall evolution at the scale of hydrological and agronomic impacts

Evolution of the characteristics of mesoscale convective systems since 1950

The lack of long-term data at appropriate spatial and temporal resolutions makes it difficult to evaluate mesoscale changes over the last 60 years.

Using daily data available for Niger, LE BARBÉ and LEBEL (1997) gave a statistical breakdown on cumulated daily precipitation measured at rain gauge stations as a result of the occurrence and intensity of rainfall events. They thus show that the rainfall deficit of 1970-1990 was linked more with a decrease in the occurrence of rainfall—especially in the heart of the season—than with a change in the mean intensity of events, which remained fairly stable during the drought. These findings were generalised to cover the whole of West Africa (LE BARBÉ *et al*., 2002) and since confirmed for Senegal (MORON *et al*., 2006), Mali (FRAPPART *et al*., 2009) and Burkina Faso (IBRAHIM *et al*., 2012; LODOUN *et al*., 2013). Although these studies provide useful documentation of the rainfall events defined at the scale of a rain gauge station, they give no indication of the possible changes in spatial morphology (size or internal organisation of intensity) of the MCSs. Defining calibrated spatial criteria in networks of daily rainfall using infrared satellite data, BELL and LAMB (2006) worked on detecting the path of MCSs on the ground, using an integrated method in 5°x 5° windows distributed through the Sahel rather than on a one-off basis. BELL and LAMB (2006) thus found that MCSs during the drought period are characterised by much smaller spatial extension and intensity than during the wet period. Although the decrease of the spatial coverage of MCSs is compatible with the local decrease (at station level) of the events shown by LE BARBÉ *et al*. (2002), their lesser intensity would appear to be in contradiction with the other studies performed on the region.

This disagreement led ROSSI *et al*. (2012) to use methodology similar to that of BELL and LAMB (2006) by updating analysis of MCS characteristics in the most recent years. ROSSI *et al*. (2012) detected 'mesoscale rainy days' (MRD) that, as in the work of BELL and LAMB (2006), correspond to the pattern of MCSs measured on the ground using daily rain gauges. However, in contrast with the work of BELL and LAMB (2006), the detection criteria used by ROSSI *et al*. (2012) are calibrated directly using the high resolution rainfall data of the AMMA-CATCH Niger network that provide a reliable detection reference for the MCS pattern on the ground. ROSSI *et al*. (2012) showed in particular that the relative change in the features of MRDs during the period 1990-2010 was similar to that of MCSs and hence MRDs can indeed be used to describe the long-term evolution of mesoscale rainfall.

The criteria of ROSSI *et al*. (2012) are used here to analyse the movement of MRDs over the period 1950-2010 in the central Sahel 'window', as defined by LEBEL and ALI (2009). The evolution of anomalies (standardised variables) of four features of MRDs is shown in Figure 4: mean occurrence, mean spatial coverage, mean intensity of positive rainfall values within the MRDs and the mean intensity of the latter (incorporating positive and null rainfall values). It is to be noted that the null rainfall values correspond to internal intermittence of the MCSs (ALI *et al*., 2003), their frequency in rainfall systems being used to describe the spatial covers of MRDs. A synthesis of the values of the characteristics of MRDs is provided in Table 1 in the form of averages for 20-year sub-periods. Table 1 shows the well-known deficit in total annual rainfall during the 1970-1989 drought period (period P2), that is also visible in the annual cumulated MRD (forming a little more than 80% to total rainfall). The deficit results in the first order from a strong decrease in occurrence (- 19%) that started in the 1970s and became markedly accentuated at the beginning of the 1980s. The mean intensity of non-trace rainfall in the MRDs also seems to have contributed to the drought, but to a smaller degree as it fell by only 8%, in particular because of three years (1968, 1973 and 1984) with particularly marked shortfalls. Finally, as seen by Bell and Lamb (2006), a decrease in MRD spatial cover was observed (- 5%), especially during the 1980s. The major contribution of the decrease in the occurrence of MCSs during the drought is in agreement with the work of Le Barbé *et al*. (2002), especially as the decrease in occurrence combined with that of the spatial cover of MCSs automatically implies a decrease in the number of rainfall events measured at rain gauge stations. Furthermore, the decrease in MCS areas combined with a relative decrease in non-trace rainfall intensity caused an overall decrease in MCS rainfall (- 12%), but this is a secondary feature in comparison with the effects of occurrence, in contrast with what is suggested by Bell et Lamb (2006).

The comparative increase in cumulated figures (+ 13% in comparison with P2) is confirmed for the last two decades (period P3) but, as is now well documented in the literature, the level reached remained well below that of the wet period P1 (- 16%). Here, the new feature was the evolution of the characteristics of mesoscale rain systems. MRD occurrence continued to decrease after the dry period, remaining at a low level, equivalent to that of the dry period until 2000, and then decreasing further during the last decade. The intensity of non-trace rainfall returned to a stable level close to the wet period P1. Finally, a singular increase in the mean spatial extension of MRDs was observed; this reached levels that had not been observed since 1950. The increase in the intensity and size of the rain systems combined to give mean MRD rainfall nearly 14% greater than it had been during the wet period. As a result, while decadal variability in rainfall during the period 1950-1990 was modulated mainly by the occurrence of rain systems (with the decrease in the number of events accounting for more than 70% of the rainfall deficit), changes in

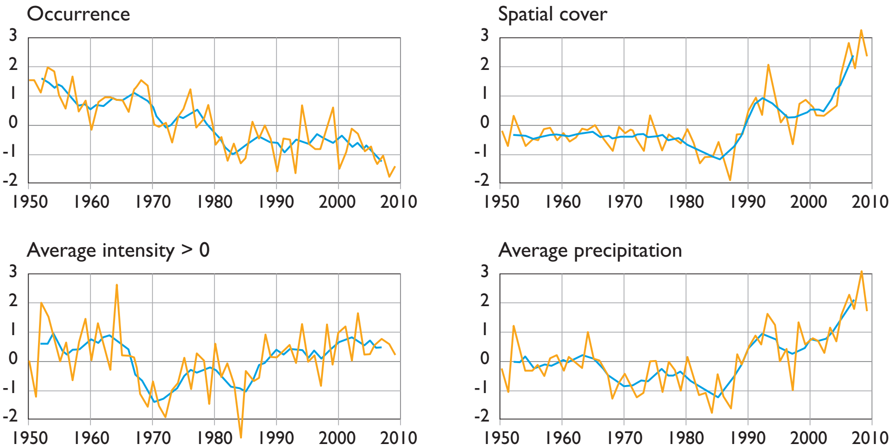

Figure 4.
Evolution of the characteristics of mesoscale convective systems using mesoscale precipitation days (MRDs) as defined by Rossi et al. *(2012).*
The blue lines represent a sliding mean for a 5-year period.

Table 1.
Mean characteristics of mesoscale rainy days (MRD).

			P1 1950-1696	**P2** 1970-1989	**P3** 1990-2009
	Tot. annual precip.	(mm)	664.2	490.0 (*- 21.6%*)	553.7 (*- 166%*, 13%)
JPM	Annual cumulation	(mm)	537.8	404.2 (*- 24.8%*)	451.2 (*- 16.1%*, 11.6%)
	Occurrence	(number/year)	88.7	71.95 (*- 18.9%*)	60.4 (*- 31.9%*, - 16.0%)
	Intensity > 0	(mm)	14.8	13.6 (*- 8.1%*)	15.2 (*2.7%*, 11.7%)
	Intensity ≥ 0	(mm)	6.5	5.7 (*- 12.3%*)	7.4 (*13.85%*, 29.8%)
	Spatial coverage	(% intensity > 0)	43.2	41.2 (*- 4.6%*)	48.9 (*13.2%*, 18.7%)

The percentages in brackets in columns P2 and P3 represent changes in relation to Period P1 (in italics) and P2 (italics and underlined).

the intensity and spatial coverage of the system during the last two decades are dominant in the decrease of occurrence and explain the increase in cumulated annual precipitation. This behaviour appears to be a turning point in the climatology of precipitations in the Sahel and raises the question of the possible intensification of rainfall. This cannot be answered without in-depth analysis of extreme events.

Evolution of the extreme precipitation regime

Several recent studies conducted mainly at the scale of the central Sahel countries support the results described above and suggest an increase in the heaviest rainfall, based on the pattern of mean rainfall intensity, which sometimes increases in a singular manner (LEBEL and ALI, 2009; FRAPPART *et al.*, 2009; LODOUN *et al.*, 2013), or on the evolution of maximum annual daily rainfall (IBRAHIM *et al.*, 2012). However, very few analyses have been focused specifically on the most intense rainfall in the region. The meagre documentation available on pluviometric extremes in the Sahel contrasts strongly with the number of studies on pluviometric variability related to the dry periods that affect the region (TSCHAKERT *et al.*, 2010). Until very recently, there were only two studies involving climatological analysis of extreme precipitation events in West Africa. NEW *et al.* (2006) analysed daily data for the period 1950-2006 from six rain gauge stations in West Africa (2 in the Gambia and 4 in Nigeria), showing significant (upward) trends in maximum annual daily rainfall at only one station. PAETH *et al.* (2010) made a detailed description of the precipitations in 2007 that caused widespread flooding in West Africa. Using TRMM satellite precipitation estimates, they considered that the 2007 events were exceptional (with a return period of several decades) in terms of cumulated precipitation for 5 to 15 days. The main reason for the small number of publications on the subject is once again linked to shortage of data and also to the methodological difficulties inherent in the study of extreme events. Indeed, extreme rainfall events are rare by definition and particularly sensitive to sampling effects, which, together with the strong interannual and decadal variability of rainfall in the Sahel make the solid detection of trends difficult.

Given these constraints, PANTHOU (2013) succeeded in assembling a set of 43 daily pluviometric series available continuously for the period 1950-2010 in a window in the central Sahel (10°N-15°N, 5°W-7°E). Statistical analysis based on the theory of extreme values provided an integrated regional view of the spatial organisation of extremes (PANTHOU *et al*., 2012) and made it possible to develop innovative methods for the robust detection of trends in series of extremes (PANTHOU *et al*., 2013). This enabled PANTHOU *et al*. (2014) to study the evolution of the extreme precipitation regime in relation to the decadal variability of cumulated annual pluviometry data. Figure 5 shows a distinct difference in the multi-decadal evolution of annual totals and daily maxima in the central Sahel since 1950. Whereas the annual totals remained markedly short in comparison with the mean for the 1950-1970 wet period, the sliding mean of annual maxima displays higher values than those of 1950-1970. The two curves are distinctly differentiated from the end of the 1990s. This confirms that an important change in the pluviometric regime occurred at the change of century, with pluviometric extremes becoming more marked.

The curves in Figure 5 were plotted using data from 43 stations, thus making a total sample of 43 annual totals and 43 annual maxima. In order to increase the size of the heavy rainfall sample, PANTHOU *et al*. (2014) used a statistical model of regional extremes to select the rainfall threshold exceeded on average *n* times per year during the period 1950-2010 at each of the 43 stations (with *n* varying from 2 to 15, corresponding to rainfall threshold figures varying with the north-south gradient). Distributions (generalised Pareto distribution - GPD) were then adjusted for each year to this bulkier sample (for $n = 10$, the annual sample is 430 figures for rainfall events of between 12 mm in the north and 32 mm in the south of the study zone).

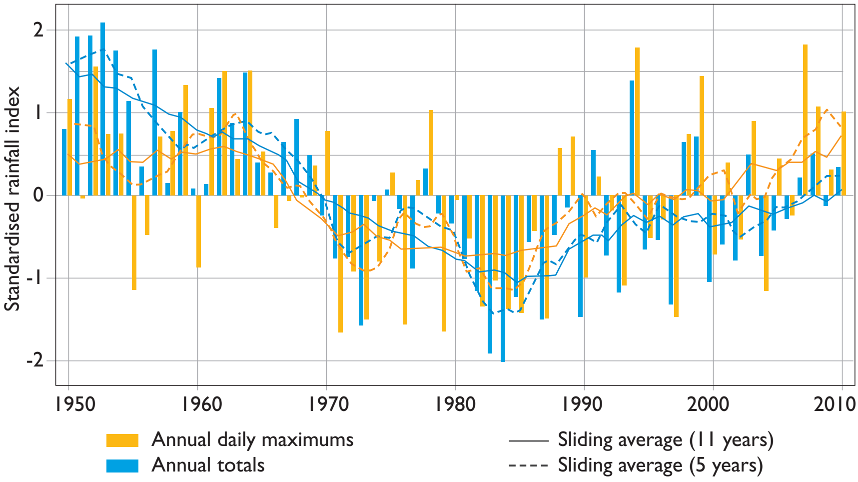

Figure 5.
Comparative evolution of annual rainfall totals and maximums in the central Sahel (window 9.5°N-15.5°N 5°W-7°E) from 1950 to 2010.
After PANTHOU et al. *(2014).*

This allows examination of the quantiles of the distributions for different values of *n*. Two major results emerge and are illustrated in Figure 6. First, the annual number of events exceeding the rainfall threshold is smaller than it was in the 1950s and 1960s except for *n* = 2 (Fig. 6a), where the level of the 1950s has been attained in recent years. However, the contribution of these rainfall events as a percentage of the annual total has increased significantly, especially when high thresholds are involved (Fig. 6b). While there has still been a deficit in the number of rainfall events, the last decade features several extreme rainfall events that were more extreme than in the past.

It is noted that for the western Sahel a recent study (SARR *et al.*, 2013) also seems to indicate an increase in the most intense rainfall events since the 1990s. However, these results should be confirmed by a regional approach that is suited to the specific study of extreme rainfall events.

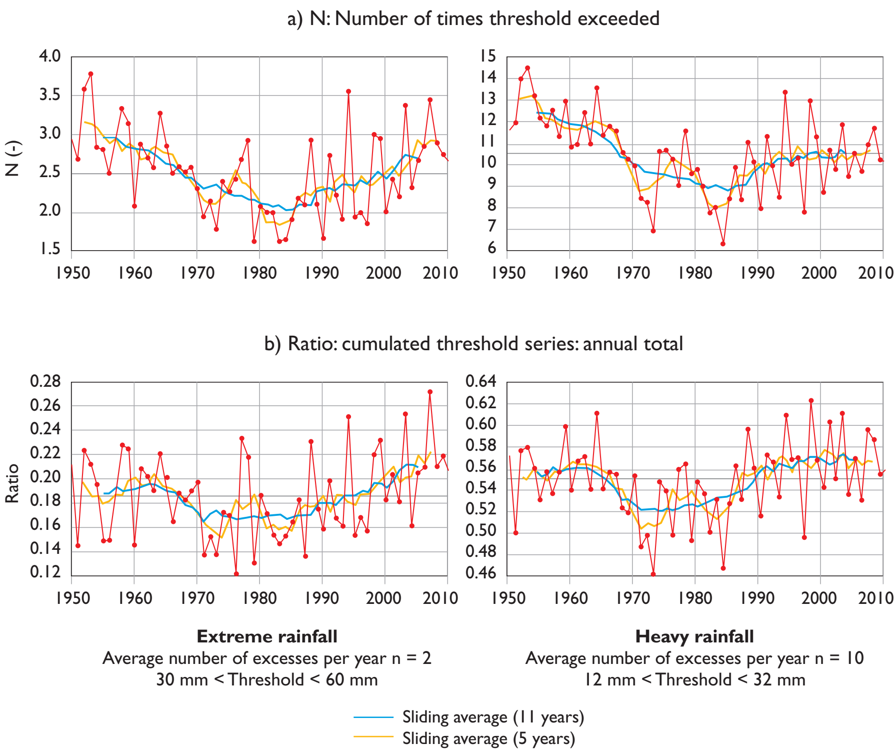

Figure 6.
(a) Evolution of the number of daily rainfall events greater than the mean n *times per year,*
(b) Evolution of cumulated rainfall exceeded on average n *times per year*
expressed as a percentage of total rainfall.
On the left, n *= 2 defines extreme precipitations*
and on the right n *= 10 defines the heaviest rainfall.*
After PANTHOU et al. *(2014).*

Summary, discussion and questions still unanswered

After the major drought that hit the Sahel at the end of the 1960s, rainfall recovered in the last decade of the 20th century, especially in the central part of the region but without a return to the conditions of 1950-1969, while the drought continued in the western Sahel. Beyond regional disparities, analysis of the evolution of rainfall in the Sahel is also a question of scale. When the rainfall regime is examined at the mesoscale level, the key scale for understanding the impact of pluviometric variability on the hydrological and agronomic systems in the Sahel, it is seen that the evolution of cumulated annual rainfall results from changes in the characteristics of rainfall systems that differ strongly from one decade to another.

The last 20 years of evolution of the pluviometric regime—comparatively well-documented until the 1990s—has been updated in this chapter by focus on the evolution of mesoscale characteristics and on extreme rainfall events that have been very little documented in the region. It is noted above all that the deficit in the number of days of rain has continued in the last decade but has been compensated by the more frequent occurrence of heavy rainfall linked with the most widespread rain systems. This change in the rainfall regime has had two effects: 1) a return to 'better' annual pluviometry, with the more common occurrence of heavy rain more than making up for the continued deficit in the number of days of rainfall and, 2) new modulation of the decadal pluviometric signal by the intensity of the heaviest rains.

The evolution of the regime, as shown here, leads to considering with caution the terms 'recovery' or 'a return to wet conditions' often used to qualify the rainfall of the last two decades. Although average annual rainfall is indeed greater than it has been since the 1990s, it is smaller than that of the 1950-1969 wet period. In addition, there has still been a rainfall event deficit in recent years, implying a continued risk of dry years that may potentially affect crop yields and water resources. In addition, the increase in the heaviest rainfall may cause direct damage to certain crops and infrastructure and increase risks of flooding. By combining an increase in extremes and dry periods, the Sahel displays all the signs that GIORGI *et al*. (2011) define as an 'increase in hydro-climatic intensity'. This term or that of the 'intensification of the daily rainfall regime' are therefore preferred to describe the trend taken by pluviometry in the Sahel over the past 20 years.

The results described in this chapter suggest that certain lines of research should be strengthened, including:

– analysis of the recent evolution of rainfall at intra-season scales and the mesoscale: the evolution of the rainfall regime remains at the heart of understanding changes in the climatic environment in the region. The approaches described above for characterising the evolution of the seasonal cycle and the features of rainfall events must be consolidated, first by updating the datasets for the most recent years and for the region as a whole (with strong emphasis on the western Sahel for which there is a serious shortage of information), and secondly by developing appropriate methodologies for detecting non-stationary features in rainfall series and their seasonal contrasts;

– study of the link between the evolution of rainfall and the functioning of the monsoon: the signs of the intensification of the rainfall regime are fully in line with those expected in the context of climate change; this should be accompanied by an intensification of the hydrological cycle at the global scale. Have the last two decades displayed the early signs of a more lasting change caused by global warming or do we still see the natural conditions of variability of the climate in the region? The projections drawn from climate models are still too uncertain for a clear cut answer (See Chap. 3). The reply to the question is more likely to lie in the understanding of the mechanisms (atmospheric, land surface and ocean) that have modulated the functioning of the West African monsoon and that have generated stronger hydro-climatic intensity. Much has already been published on this question (MONERIE *et al*., 2012; GIANNINI *et al*., 2013; BIASUTTI, 2013), but the work often suffers from the lack of a link with ground observations, the only objective references that enable the documentation of changes in rainfall in the Sahel;

– attribution of the increase in flood risk in the Sahel: this risk combines uncertainty and vulnerability factors. Up to now, its increase in the Sahel has been attributed mainly to (1) the growing vulnerability of populations exposed increasingly to flood risk (DI BALDASSARRE *et al*., 2010) and (2) the recent increase in hydrologic uncertainty observed in the Sahel region and resulting directly from the increase in runoff coefficients caused by changes in the state of ground surfaces (DESCROIX *et al*., 2009). These two points cannot be contested and have obviously contributed to the increase in the flood risk in the region. However, the intensification of the rainfall regime may also have played a role (see chapter 7). It would thus be important to be able to quantify the share of each of the three factors in the increase in the flood risk.

However that may be, finding answers to the major scientific and societal questions raised in the Sahel today requires access to the long-term meteorological data for the region. The contribution of national meteorological services must be strengthened for this by a clear, constructive policy of collaboration set in the ongoing international data sharing procedure in order to achieve better surveillance of the global climate change that is a threat to the world. To complement data from national networks, initiatives for denser observations in the region must also be supported on a long-term basis. The AMMA-CATCH observation service forms part of such an approach. It provides the scientific community with sets of data consisting of high-resolution documentation of the hydrological cycle, forming an excellent base for analysis of hydro-climatic variability. It operates as a laboratory for the development of key methodology for better understanding of the major environmental changes affecting West Africa.

References

Ali A., Lebel T., 2009
The Sahelian standardized rainfall index revisited. *Int. J. Climatol.*, 29 : 1705-1714, doi:10.1002/joc.1832.

Ali A., Lebel T., Amani A., 2003
Invariance in the Spatial Structure of Sahelian Rain Fields at Climatological Scales. *J. Hydrometeorol.*, 4 : 996-1011.

Balme M., Galle S., Lebel T., 2005
Analysis of the variability of the onset of the rainy season in the Sahel at hydrological and agronomical scales, based on EPSAT-Niger data. *Sécheresse*, 16 : 15-22.

Balme M., Lebel T., Amani A., 2006a
Années sèches et années humides au Sahel : quo vadimus ? *J. Sci. Hydrol.*, 51 (2) : 254-271.

Balme M., Vischel T., Lebel T., Peugeot C., Galle S., 2006b
Assessing the water balance in the Sahel: Impact of small-scale rainfall variability on runoff:
Part 1: Rainfall variability analysis. *J. Hydrol.*, 331 : 336-348.

Bell M. A., Lamb P. J., 2006
Integration of weather system variability to multidecadal regional climate change: The West African Sudan-Sahel zone, 1951-1998. *J. Clim.*, 19 : 5343-5365.

Biasutti M., 2013
Forced Sahel rainfall trends in the CMIP5 archive. *J. Geophys. Res. Atmospheres*, 118 : 1613-1623, doi:10.1002/jgrd.50206.

Bunting A. H., Dennett M. D., Elston J., Milford J. R., 1976
Rainfall trends in the West African Sahel. *Q. J. R. Meteorol. Soc.*, 102 : 59-64, doi:10.1002/qj.49710243105.

Dai A., Lamb P. J., Trenberth K. E., Hulme M., Jones P. D., Xie P., 2004
The recent Sahel drought is real. *Int. J. Climatol.*, 24, 1323-1331, doi:10.1002/joc.1083.

Dardel C., Kergoat L., Hiernaux P., Grippa M., Mougin E., 2015
« Entre désertification et reverdissement du Sahel : que se passe-t-il vraiment ? » *In* : *Agricultures familiales et changements climatiques en Afrique de l'Ouest : entre opportunités, vulnérabilités et adaptations*, IRD.

Demarée G. R., 1990
An indication of climatic change as seen from the rainfall data of a Mauritanian station. *Theor. Appl. Climatol.*, 42 : 139-147, doi:10.1007/BF00866869.

Deme A., Gaye A., Hourdin F., 2015
« Les projections du climat en Afrique de l'Ouest : évidences et incertitudes ». *In : Agricultures familiales et changements climatiques en Afrique de l'Ouest : entre opportunités, vulnérabilités et adaptations*, IRD.

Depraetere C., Gosset M., Ploix S., Laurent H., 2009
The organization and kinematics of tropical rainfall systems ground-tracked at mesoscale with gages: First results from the campaigns 1999-2006 on the Upper Ouémé Valley (Benin). *J. Hydrol.*, 375 : 143-160, doi:10.1016/j.jhydrol.2009.01.011.

Descroix L. *et al.*, 2009
Spatio-temporal variability of hydrological regimes around the boundaries between Sahelian and Sudanian areas of West Africa: A synthesis. *J. Hydrol.*, 375 : 90-102.

Descroix L. *et al.*, 2015
« Facteurs anthropiques et environnementaux de la recrudescence des inondations au Sahel ». *In* : *Agricultures familiales et changements climatiques en Afrique de l'Ouest : entre opportunités, vulnérabilités et adaptations*, IRD.

Di Baldassarre G., Montanari A., Lins H., Koutsoyiannis D., Brandimarte L., Blöschl G., 2010
Flood fatalities in Africa: From diagnosis to mitigation. *Geophys. Res. Lett.*, 37, doi:10.1029/2010GL045467.

Fontaine B., Janicot S., 1996
Sea Surface Temperature Fields Associated with West African Rainfall Anomaly Types.
J. Clim., 9 : 2935-2940,
doi:10.1175/1520-0442(1996)009.

Frappart F. *et al.*, 2009
Rainfall regime across the Sahel band in the Gourma region, Mali.
J. Hydrol., 375 : 128-142.

Giannini A., Salack S., Lodoun T., Ali A., Gaye A. T., Ndiaye O., 2013
A unifying view of climate change in the Sahel linking intra-seasonal, interannual and longer time scales.
Environ. Res. Lett., 8 : 024010,
doi:10.1088/1748-9326/8/2/024010.

Giorgi F., Im E.-S., Coppola E., Diffenbaugh N. S., Gao X. J., Mariotti L., Shi Y., 2011
Higher Hydroclimatic Intensity with Global Warming.
J. Clim., 24 : 5309-5324,
doi:10.1175/2011JCLI3979.1.

Grist J. P., Nicholson S. E., 2001
A Study of the Dynamic Factors Influencing the Rainfall Variability in the West African Sahel.
J. Clim., 14 : 1337-1359.

Guillot G., Lebel T., 1999
Disaggregation of Sahelian mesoscale convective system rain fields further developments and validation.
J. Geophys. Res., 104 : 31533-31551.

Hubert P., Carbonnel J. P., 1987
Approche statistique de l'aridification de l'Afrique de l'Ouest.
J. Hydrol., 95 : 165-183.

Hulme M., 1992 –
Rainfall changes in Africa: 1931-1960 to 1961-1990.
Int. J. Climatol., 12 : 685-699,
doi:10.1002/joc.3370120703.

Hulme M., 2001
Climatic perspectives on Sahelian desiccation: 1973-1998.
Glob. Environ. Change, 11 : 19-29,
doi:10.1016/S0959-3780(00)00042-X.

Ibrahim B., Polcher J., Karambiri H., Rockel B., 2012
Characterization of the rainy season in Burkina Faso and it's representation by regional climate models.
Clim. Dyn., 39 : 1287-1302,
doi:10.1007/s00382-011-1276-x.

Lamb P. J., 1982
Persistence of Subsaharan drought.
Nature, 299 : 46-48,
doi:10.1038/299046a0.

Le Barbé L., Lebel T., 1997
Rainfall climatology of the HAPEX-Sahel region during the years 1950-1990.
J. Hydrol., 188-189 : 43-73.

Le Barbé L., Lebel T., Tapsoba D., 2002
Rainfall Variability in West Africa during the years 1950-1990.
J. Clim., 15 : 187-202.

Lebel T., Diedhiou A., Laurent H., 2003
Seasonal cycle and interannual variability of the Sahelian rainfall at hydrological scales.
J. Geophys. Res., 108.

Lebel T., Ali A., 2009
Recent trends in the Central and Western Sahel rainfall regime (1990-2007).
J. Hydrol., 375 : 52-64.

Lebel T. *et al.*, 2009
Amma-Catch studies in the Sahelian region of West-Africa: An overview.
J. Hydrol., 375 : 3-13.

L'Hote Y., Mahé G., Some B., Triboulet J. P., 2002
Analysis of a Sahelian annual rainfall index from 1896 to 2000; the drought continues.
Hydrol. Sci., 47 (4) : 563-572.

Lodoun T., Giannini A., Traoré P. S., Somé L., Sanon M., Vaksmann M., Rasolodimby J. M., 2013
Changes in seasonal descriptors of precipitation in Burkina Faso associated with late 20th century drought and recovery in West Africa. *Environ. Dev.*, 5 : 96-108,
doi:10.1016/j.envdev.2012.11.010.

Mahé G., Paturel J.-E., 2009
1896-2006 Sahelian annual rainfall variability and runoff increase of Sahelian Rivers.
Surf. Geosci. Hydrol.-Hydrogeol., 341 : 538-546.

Massuel S., Cappelaere B., Favreau G., Leduc C., Lebel T., Vischel T., 2011
Integrated surface water-groundwater modelling in the context of increasing water reserves of a regional Sahelian aquifer. *Hydrol. Sci. J.*, 56 : 1242-1264, doi:10.1080/02626667.2011.609171.

Matho V., Laurent H., Lebel T., 2002
Mesoscale Convective System Rainfall in the Sahel.
J. Appl. Meteorol., 41 1081-1092.

Monerie P.-A., Fontaine B., Roucou P., 2012
Expected future changes in the African monsoon between 2030 and 2070 using some CMIP3 and CMIP5 models under a medium-low RCP scenario.
J. Geophys. Res. Atmospheres, 117, n/a – n/a, doi:10.1029/2012JD017510.

Moro V., Robertson A. W., Ward M. N., 2006
Seasonal Predictability and Spatial Coherence of Rainfall Characteristics in the Tropical Setting of Senegal.
Mon. Weather Rev., 134 : 3248-3262, doi:10.1175/MWR3252.1.

New M. *et al.*, 2006
Evidence of trends in daily climate extremes over southern and west Africa.
J. Geophys. Res., 111, D14102, doi:10.1029/2005JD006289

Nicholson S., 2005
On the question of the "recovery" of the rains in the West African Sahel.
J. Arid Environ., 63 : 615-641.

Nicholson S. E., 2001
Climatic and environmental change in Africa during the last two centuries.
Clim. Res., 17 : 123-144.

Nicholson S. E., 2013
The West African Sahel – A Review of Recent Studies on the Rainfall Regime and Its Interannual Variability.
ISRN Meteorol., 2013 : 1-32, doi:10.1155/2013/453521.

Ozer P., Erpicum M., Demarée G., Vandiepenbeeck M., 2003
The Sahelian drought may have ended during the 1990s. *Hydrol. Sci. J.*, 48 : 489-492, doi:10.1623/hysj.48.3.489.45285.

Paeth H., Fink A. H., Pohle S., Keis F., Mächel H., Samimi C., 2010
Meteorological characteristics and potential causes of the 2007 flood in sub-Saharan Africa. *Int. J. Climatol.*, 31 : 1908-1926, doi:10.1002/joc.2199

Panthou G., 2013
Analyse des extrêmes pluviométriques en Afrique de l'Ouest et de leur évolution au cours des 60 dernières années.
Université de Grenoble, 270 p.

Panthou G., Vischel T., Lebel T., Blanchet J., Quantin G., Ali A., 2012
Extreme rainfall in West Africa: A regional modeling.
Water Resour. Res., 48, W08501, doi:10.1029/2012WR012052.

Panthou G., Vischel T., Lebel T., Quantin G., Pugin A.-C. F., Blanchet J., Ali A., 2013
From pointwise testing to a regional vision: An integrated statistical approach to detect nonstationarity in extreme daily rainfall. Application to the Sahelian region.
J. Geophys. Res. Atmospheres, 118 : 8222-8237, doi:10.1002/jgrd.50340.

Panthou G., Vischel T., Lebel T., 2014
Recent trends in the regime of extreme rainfall in the Central Sahel.
Int. J. Climatol., n/a – n/a, doi:10.1002/joc.3984.

Peugeot C., Cappelaere B., Vieux B. E., Séguis L., Maia A., 2003
Hydrologic process simulation of a semiarid, endoreic catchment in Sahelian West Niger. 1. Model-aided data analysis and screening.
J. Hydrol., 279 : 224-243.

Rasmusson E. M., Arkin P. A., 1993
A Global View of Large-Scale Precipitation Variability. *J. Clim.*, 6 : 1495-1522, doi:10.1175/1520-0442(1993)006<1495:AGVOLS>2.0.CO;2.

Redelsperger J. L. *et al.*, 2006
Amma, une étude multidisciplinaire de la mousson ouest-africaine.
Météorologie Trop., 54 : 22-32.

Rossi A., Vischel T., Lebel T., 2012
Analyse spatiale et temporelle de la variabilité à méso-échelle du régime pluviométrique sahélien depuis les années 1950.
25e colloque de l'Association internationale de climatologie, Grenoble (France).

Sarr M. A., Zoromé M., Seidou O., Bryant C. R., Gachon P., 2013
Recent trends in selected extreme precipitation indices in Senegal – A changepoint approach. *J. Hydrol.*, 505 : 326-334, doi:10.1016/j.jhydrol.2013.09.032.

Sultan B., Janicot S., Diedhiou A., 2003
The West African Monsoon Dynamics. Part I: Documentation of Intraseasonal Variability. *J. Clim.*, 16 : 3389-3406.

Tarhule A., Woo M.-K., 1998
Changes in rainfall characteristics in northern Nigeria. *Int. J. Climatol.*, 18 : 1261-1271, doi:10.1002/(SICI)1097-0088(199809)18:11.

Tarhule A. *et al.*, 2014
Exploring temporal hydroclimatic variability in the Niger Basin (1901-2006) using observed and gridded data. *Int. J. Climatol.*, n/a – n/a, doi:10.1002/joc.3999.

Tschakert P., Sagoe R., Ofori-Darko G., Codjoe S. N., 2010
Floods in the Sahel: an analysis of anomalies, memory, and anticipatory learning. *Clim. Change*, 103 : 471-502, doi:10.1007/s10584-009-9776-y.

Vischel T., Lebel T., 2007
Assessing the water balance in the Sahel: Impact of small-scale rainfall variability on runoff. Part 2: Idealized modeling of runoff sensitivity. *J. Hydrol.*, 333 : 340-355.

Vischel T., Lebel T., Massuel S., Cappelaere B., 2009
Conditional simulation schemes of rain fields and their application to rainfall-runoff modeling studies in the Sahel. *J. Hydrol.*, 375 : 273-286, doi:10.1016/j.jhydrol.2009.02.028.

Vischel T., Quantin G., Lebel T., Viarre J., Gosset M., Cazenave F., Panthou G., 2011
Generation of high resolution rainfields in West Africa: evaluation of dynamical interpolation methods. *J. Hydrometeorol.*, 110426113802000, doi:10.1175/JHM-D-10-05015.1.

Vischel T., Lebel Thierry, Panthou G., Quantin Guillaume, Rossi A., Martinet M.

The return of a wet period in the Sahel ? : observations and prospects.

In : Sultan Benjamin (ed.), Lalou Richard (ed.), Amadou Sanni M. (ed.), Oumarou A. (ed.), Soumaré M.A. (ed.).

Rural societies in the face of climatic and environmental changes in West Africa.

Marseille : IRD, 2017, p. 43-60. (Synthèses). ISBN 978-2-7099-2424-5