Seasonal cycle and interannual variability of the Sahelian rainfall at hydrological scales

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Received 10 December 2001; revised 16 December 2002; accepted 11 March 2003; published 29 April 2003.

[1] Sahelian rainfall is characterized both by a strong interannual variability and by periods of long-lasting droughts, such as the years 1970–1997. The controlling factors of this variability have been the subject of a significant amount of research, but most of this research is carried out using low-resolution averages, typically, monthly to seasonal in time and over $5° \times 5°$ grid boxes (or larger) in space. This paper is an attempt at characterizing the Sahelian rainfall regime at finer scales, with the objective of establishing links between the seasonal cycle and the interannual variability. To that end, high space-time resolution data sets are analyzed. One is composed of around three hundred daily rain gauges covering a 1,700,000 km^2 area for the period 1951–1990. The second is a set of full resolution Meteosat images covering the years 1989–1999, allowing for a systematic tracking of the mesoscale convective systems (MCSs). The third data set was produced from an experimental network of recording rain gauges covering 16,000 km^2 in the region of Niamey, Niger, during the years 1990–2000. The analysis of the regional daily rainfall data set tends to revisit the common vision of the seasonal cycle of the Sahelian rainfall. It is shown that the average regime is in fact composed of two subregimes. One is an oceanic regime characterized by a progressive increase of the moist air flow from the ocean into the continent, associated with the seasonal migration of the ITCZ from its southern position in the boreal winter to its northern position in the boreal summer. The second regime is a continental regime in which rain is mostly produced by large convective systems embedded in the easterly circulation. This continental regime sets in abruptly during the second half of June, and 90% of the Sahelian rainfall is then produced by a small number (12% of the total number) of large and organized mesoscale convective systems. The mean event rainfall associated with these systems is larger than the mean event rainfall observed in the oceanic regime. The average proportion of the Sahelian rainfall occurring during the continental regime represents between 75% and 90% of the total annual rainfall. It is thus necessary to study this regime in order to understand the interannual rainfall variability of the region better. It is shown, for instance, that the main factor of interannual variability is the variability of the number of the large convective systems from year to year. It is also shown, using NCEP/NCAR reanalysis, that the easterly waves, which are a major synoptic feature of the region, are not systematically associated with rain-efficient convective systems and that further studies are needed to understand the differences between wet and dry waves. *INDEX TERMS:* 3309 Meteorology and Atmospheric Dynamics: Climatology (1620); 3354 Meteorology and Atmospheric Dynamics: Precipitation (1854); 3374 Meteorology and Atmospheric Dynamics: Tropical meteorology; 1812 Hydrology: Drought; *KEYWORDS:* West African Monsoon, Sahel, rainfall, seasonal cycle, convective systems

Citation: Lebel, T., A. Diedhiou, and H. Laurent, Seasonal cycle and interannual variability of the Sahelian rainfall at hydrological scales, *J. Geophys. Res.*, *108*(D8), 8389, doi:10.1029/2001JD001580, 2003.

1. Introduction

[2] The variability of rainfall in West Africa has been the subject of several studies in recent years making substantial contributions toward the identification of the numerous factors that may control this variability, whether considering ocean SSTs [*Palmer*, 1986; *Lamb and Peppler*, 1992; *Janicot et al.*, 1996; *Fontaine et al.*, 1998; *Ward*, 1998; *Rowell*, 2001], continental surface conditions [*Charney et al.*, 1977; *Semazzi and Sun*, 1997; *Zheng and Eltahir*, 1998; *Wang and Eltahir*, 2000], or atmospheric structures. [*Burpee*, 1972; *Reed et al.*, 1977; *Cook*, 1997; *Thorncroft and Blackburn*, 1999; *Diedhiou et al.*, 1998, 1999]. Obviously, all these factors interact in a complex way and it is possible to imagine that the importance of each controlling factor has

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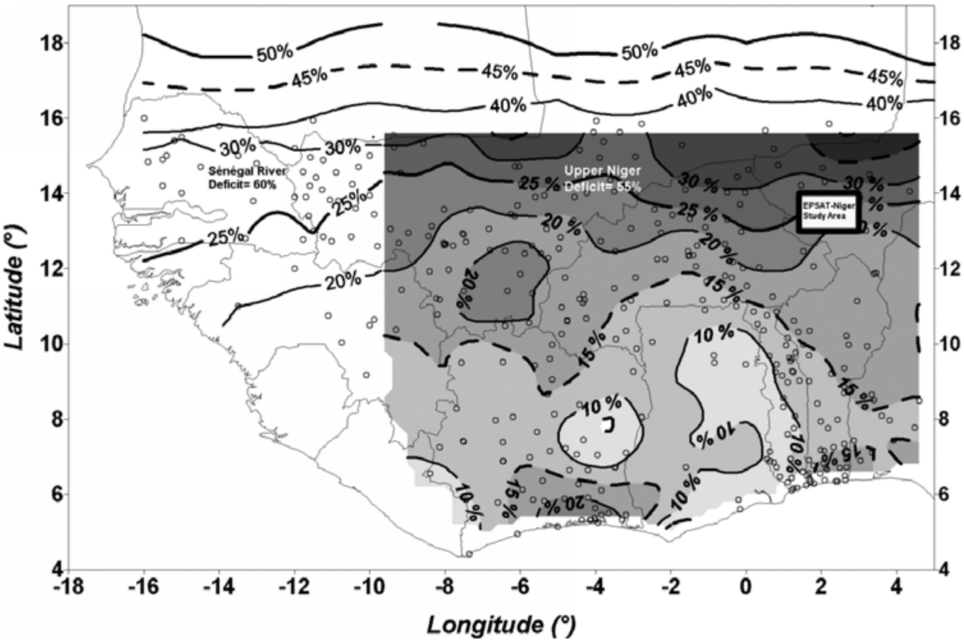

Figure 1. Map of the relative rainfall deficit of the years 1971–1990 compared to the wet years 1951–1970. Over the Sahel the deficit increases from 20% in the south to 50% in the north. The discharge deficit for the same period on the two largest Sahelian catchments (Sénégal and upper Niger) is indicated. The corresponding average rainfall deficit is about 30% over the Sénégal basin and 25% over the upper Niger basin. The area with filled contours is the region over which the average seasonal cycle was studied, using the daily reading rain gauges marked by open circles.

varied over the years, as pointed out by *Janicot et al.* [2001] showing significant differences in SST versus Sahelian rainfall correlation fields, depending on the period taken into account for the study. These authors show that the control from the oceans was probably not the same during the period 1954–1973, mostly composed of wet years (dominance of the Atlantic dipole), and during the period 1970–1989, almost exclusively composed of dry years (dominance of the ENSO signal, a warm ENSO event being associated with a lower than normal rainy season over the Sahel). Most surprising is the fact that when carried out over an intermediate period, still another region appears to dominate, that is the Indian Ocean. A number of reasons may be envisaged for explaining such an unstable behavior: modifications in the signal of the oceans themselves (the impact of the ENSO on the Sahelian rainfall becoming stronger, due to a decadal scale evolution of the global SST field); changes in the vegetation over the continent leading to a progressive shift in the meridional gradients of static energy, thus impacting on the signature of the oceans; modifications in the global atmospheric circulation, induced by changes in the global SST field and/or in the atmosphere itself.

[3] A vast majority of the diagnostic studies cited above consider rainfall patterns at large space-timescales, using monthly rain accumulations as their basic input data. To further progress in the understanding of how the various control factors might influence the Sahelian rainfall and impact on the regional water cycle, time has come to consider smaller scales. There are two main reasons for this. First, the Sahelian rainfall is mostly of convective origin. In a preliminary study, *Laurent et al.* [1998] estimated that mesoscale convective systems (MCSs) produced 95% of the annual rainfall in the region of Niamey. They also showed that there was a strong co-fluctuation of the number of MCSs and of the total annual rainfall. It thus seems important to characterize these systems over the region and to study the synoptic structures capable of influencing their occurrence. Understanding how rainfall variability impacts on water resources variability is a second reason for studying the rainfall patterns at finer scales than monthly or seasonal. As shown in Figure 1, the discharge deficit computed in relative terms for the dry period 1970–1989 at the outlet of the large river basins of the region was twice the rainfall deficit. This amplification is linked to the intermittent nature of the rainfall signal forcing the hydrologic systems. The nonlinear response of these systems is strongly dependent on the timing of occurrence of the rain events. A dry spell will not have the same hydrological impact when it happens through a reduction of the average intensity of the rain events or as a reduction of the number of events over a given period, or as a mixture of both.

[4] As many rain events are associated with MCSs, there is a need to characterize the Sahelian rainfall regime at the scale of the convective event, in order to obtain a coherent vision from both the atmospheric and the hydrological points of view. This paper is therefore built around three converging investigations that are presented after a brief description of the data available to us (section 2). First, in section 3, the mean seasonal cycle of rainfall over West Africa is studied from daily rain observations. This tends to identify two regimes in the West African monsoon: an oceanic and a continental regime. This latter regime is associated with the Sahelian rainy season. Section 4 is

devoted to the study of the elements determining the seasonal cycle of this continental regime; these include rain events, convective systems and easterly waves. In section 5, it is shown that the interannual variability of Sahelian rainfall is strongly conditioned by the number of convective systems observed in the continental regime. A final discussion of future work concludes the paper.

2. Data Sets

[5] The study presented here makes use of four data sets. One consists of daily rainfall records obtained from a network of three hundred gauges covering an area of 1,700,000 km^2 (14° × 10°) and a period of 40 years (1951–1990). This data set is described by *Le Barbé et al.* [2002] and the area covered is boxed in Figure 1. The second data set is an ensemble of full resolution Meteosat IR images, covering the months of July through September for the years 1989–1999. This data set is described by *Mathon and Laurent* [2001], the area covered being the whole of West Africa. The third data set comes from the high space-time resolution EPSAT-Niger network, covering 16,000 km^2 in the surroundings of Niamey, Niger (see Figure 1 for the location of the study area and *Lebel et al.* [1995] for a description of the network and the sensors used). This network of tipping bucket rain gauges with digitized recording has now operated for 12 years (1990–2001). There is thus a period of 10 years (1990–1999) jointly covered by the METEOSAT data set and the EPSAT-Niger data set, allowing for a precise quantification of the rainfall produced by each convective system over the EPSAT-Niger study area during the core of the rainy season. Finally, use will be made of the long-term reanalysis datasets of the National Center for Environmental Prediction/the National Center for Atmospheric Research (NCEP/NCAR; period 1979–1995) in order to characterize the atmospheric environment of the Sahelian MCSs.

3. Seasonal Cycle of the West African Monsoon

3.1. Classical Vision

[6] The West African Monsoon (WAM) is characterized by a seasonal cycle controlled by the meridional migrations of the sun and the associated maximum of received solar energy. The maximum of precipitation occurs in the Intertropical Convergence Zone (ITCZ). At its southernmost position, the boreal winter solstice, the ITCZ is located over the Guinea Gulf. It then moves northward, reaching its northernmost position in the boreal summer. At that time of the year the northern edge of the ITCZ (the ITF) may be located as far north as 18°N, even reaching 20°N. Since the maximum of received solar energy in the atmosphere regularly moves from south to north, so does the ITCZ according to the common vision of its dynamics. This in turn implies a progressive and regular onset of rain on the continent. A zone of subsidence trails the southern edge of the ITCZ. There are consequently two periods of rainfall on the coast, separated by a short dry season, when the zone of subsidence is over the continent. This zone rarely moves further than 7°N or 8°N. North of these latitudes the seasonal cycle is a regime of a single rainy season. The length of this rainy season decreases from 8 months or so in the south to 3 months in the northern Sahel, since the ITCZ reaches this region only in June and retreats in September.

[7] Of course, this is an average climatology, and it has long been known that it is subject to a marked interannual variability. The ITCZ, for instance, may be confined south of 15°N on certain years or it can reach its normal position but retreat much earlier than normally. In both cases rainfall over the Sahel is in strong deficit. However, in this classical vision of monsoon dynamics, the main feature of the rainfall regime is a progressive transition from a regime of two rainy seasons on the coast to a single rainy season in the Sahel.

3.2. Revised Scheme Based on the Analysis of Daily Rainfall

[8] A few recent studies [*Eltahir and Gong*, 1996; *Fontaine et al.*, 1999] have suggested the importance of meridional gradients of moist static energy in controlling the dynamics of the WAM. A converging result of the theoretical study of *Eltahir and Gong* [1996] and of the data analysis presented by *Le Barbé et al.* [2002] is the nonlinear behavior of the rain onset on the West African continent. The two diagrams in Figure 2 are a clear illustration of this. They are derived from the regional daily rainfall data set. Regional daily rainfall maps were first obtained using a 2D kriging algorithm, for a period of 10 months (1 February to 30 November), the interpolation being performed on the 14° × 10° grid at a 0.5° × 0.5° resolution. Each map is a representation of the average over the years 1950–1990. These 300 maps considered together provide a 3D (latitude, longitude, day of year) representation of the rainfall regime. The two diagrams of Figure 2 are time-latitude sections in this 3D representation, each for a given longitude. This allows the examination of the time dynamics of the rain intrusion on the continent along two south to north transects. The two maps are similar on a few key points. First, the two well-known maxima of rain are clearly visible at the coast and, north of 10°N, there is a unique zone of rain. This conforms to the well-known basics of the rain climate in this region. There is, however, another common point between these two maps, which is a clear departure from the classical vision of the monsoon dynamics discussed above. Indeed, one can clearly see, looking for instance at the isohyet 5 mm/day, that the Sahelian rainy season is not totally connected to the first rainy season at the coast. Starting mid-June, a sudden reinforcement of the mean daily rainfall occurs between 9°N and 12°N. It then propagates rapidly to the north during the month of June. This jump is more abrupt on the 5°W map than on the 2°E map, but in both cases the idea of a rain front progressing regularly from the coast to the Sahel is challenged. Looking at these two maps, one could define the Sahel as the region where there is a sudden reinforcement of rain happening at the same time over a band covering several degrees in latitude. Before discussing further this issue, a few other important points deserve to be mentioned here, even though they concern the whole regime of West Africa, rather than the Sahel specifically.

[9] First, there is a transition zone, roughly located between 7.5°N and 9.5°N, where the rainfall regime is not characterized by one or two well identifiable rain peaks but rather by a succession of three maxima, each corresponding

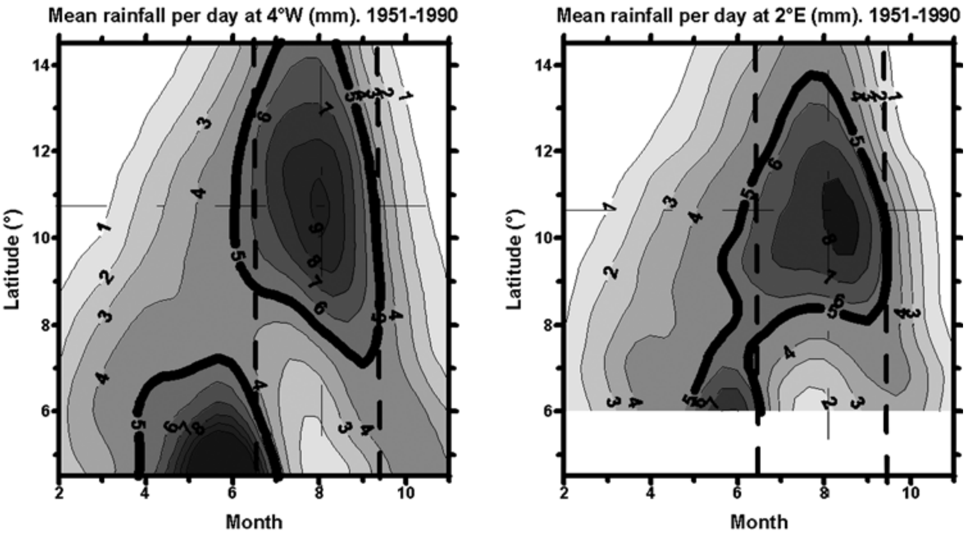

Figure 2. Space-time diagrams of the mean daily rainfall (1951–1990) for two cross sections: (left) 4°W and (right) 2°E. On the x axis, numbers indicate the start of the month (i.e., the representation starts 1 February and ends 31 October).

to one of the three steps in the WAM dynamics. The first maximum corresponds to the progressive intrusion of humidity from the ocean, peaking in May at 7.5°N (Bouaké in Figure 3), and in June at 9.5°N (Kafolo in Figure 3). Then there is a second maximum occurring at the beginning of July, corresponding to a change of regime, the "monsoon jump" (already mentioned by *Sultan and Janicot* [2000] and *Le Barbé et al.* [2002]). Finally, there is a third maximum, observed in September (the exact date depends on the latitude), corresponding to a retreat of the rain zone toward the coast. This is a second point worth noting: while the first rainy season at the coast is clearly disconnected from the sudden reinforcement of rain in the Sahel in June, the second rainy season occurs in continuity with the Sahelian rainy season, as is visible in Figure 2, indicating a regular and progressive retreat of the monsoon. Note however that this retreat is very rapid (less than one month) as compared to the preliminary onset which is spread over a 4-month period (February–June).

[10] Figure 3 provides a closer look at the Sahelian seasonal cycle. Obviously the main feature of this cycle is the single rainy season. However, the existence of a plateau is visible at Houndé (11.5°N) in June, corresponding to a secondary minimum in the hyetograms of the transition zone (Bouaké and Kafolo). This plateau is also visible, albeit less clearly, at Niafunké. During this first phase, the rain zone regularly progresses into the Sahel (note the linearity of the hyetograms and the regular time lag with increasing latitude) but it does not produce significant rain in the northern Sahel. It is only when the second phase abruptly sets in that significant rain is rapidly observed over the whole region. This second phase also has some influence on the transition zone, but in a reduced way. The coast is not affected. As may be seen from Figure 2, the timing of the monsoon jump depends slightly on the longitude considered, which might well be linked to the orientation of the monsoon flow (blowing from southwest) and to the presence of coastal chains like the Fouta-Djalon and the Atakora. Further studies are needed on the local atmospheric circulations interfering with the global monsoon dynamics.

[11] Synthesizing the above findings we propose to distinguish two regimes in the WAM. The first is an oceanic regime, characterized by a regular onset of rain on the continent, clearly reaching 11°N at the end of May but having effects as far north as 14°N to 15°N. The second regime may be qualified as continental, since it starts more or less independently of the oceanic regime and is characterized, as will be seen below, by the predominance of large and intense convective systems originating in the Sahel itself. These two regimes are superimposed together in the transition zone, thus defining the Soudanian climate as an intermediate between a coastal (Guinean) climate, one rainy

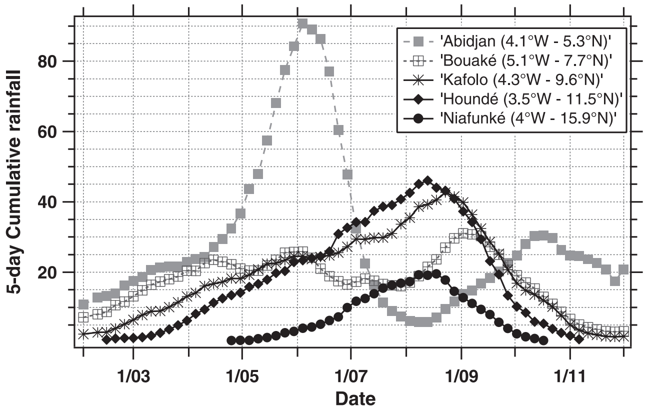

Figure 3. Seasonal cycle along a transect centered at 4°W. Values are 5-day cumulative rainfall averaged over the years 1951–1990. Abidjan has a coastal regime with two well marked rainy seasons. Bouaké has a Soudanian regime with three less pronounced maxima. Houndé and Niafunké are two Sahelian stations with a single rainy season. Kafolo is at the boundary between the Sahelian and the Soudanian regions.

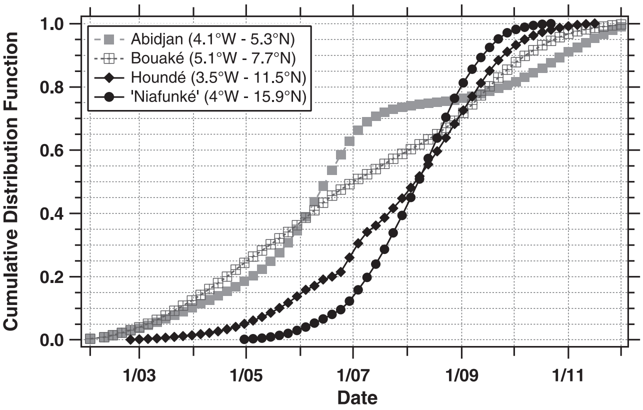

Figure 4. Cumulative distribution function of the total annual rainfall at four stations of Figure 3. For the two Sahelian stations it is seen that the continental regime which starts at the end of June, accounts for 75% (Houndé) and 90% (Niafunké) of the total annual rainfall, respectively.

season associated with the oceanic regime and a second rainy season associated with the continental regime, and the Sahelian climate, mostly dominated by the continental regime.

[12] It has already been stressed by *Le Barbé and Lebel* [1997] that most of the rain deficit of the dry years in the Niamey region, was produced by a deficit of rain during the core of the rainy season rather than by a shorter rainy season. In the light of the above discussion it is implied that it is the continental regime that was mostly affected. Figure 4 shows that the continental regime accounts for between 75% and 90% of the total annual rainfall over the Sahel, depending on the latitude considered. In order to progress in our understanding of the strong interannual variability of the Sahelian rainfall it is therefore necessary to link the seasonal cycle and the interannual variability, focusing on the continental regime. This will be done by characterizing the rain events that shape this regime and by looking simultaneously at the convective systems that produce these rain events.

4. Rain Events, Convective Systems and Synoptic Weather Systems in the Continental Regime of the WAM

4.1. Rain Events

[13] Time intermittency is a critical aspect of rain. In the tropics, where rain is mostly of convective origin, this intermittency is controlled to the first order by a succession of convective systems. While convective systems lasting for more than 24 hours account for more than 60% of the total cloud cover over the Sahel, as shown by *Mathon and Laurent* [2001], they generally produce rain for only a few hours at a given location, due to their relatively high speed of displacement. These periods of rain are separated by several hours or days of no rainfall. *Le Barbé and Lebel* [1997] have proposed a model that is able to retrieve the statistics of rain event occurrences and of cumulated event rainfall from the statistics of the daily rainfall. The model was validated on several Sahelian data sets and has proven to be an efficient tool for the analysis of the overall climatology of rain events over West Africa [*Le Barbé et al.*, 2001]. An example of this is given in Figure 5, where the time-latitude diagram of the daily rainfall R at 5°W of Figure 2 is decomposed into a map of the mean daily number of events, n, and a map of the mean event rainfall, h.

[14] The space-time dynamics of these two signals may be studied in much the same way as the space-time dynamics of the daily rainfall R, remembering that, at each node of the grid, we have $R = nh$. Note that the h map is blanked for values of n below 0.1, since the deconvolution algorithm does not provide reliable values of h when n is too low.

[15] The two maps display extremely meaningful and coherent patterns. The h map is characterized by a regular

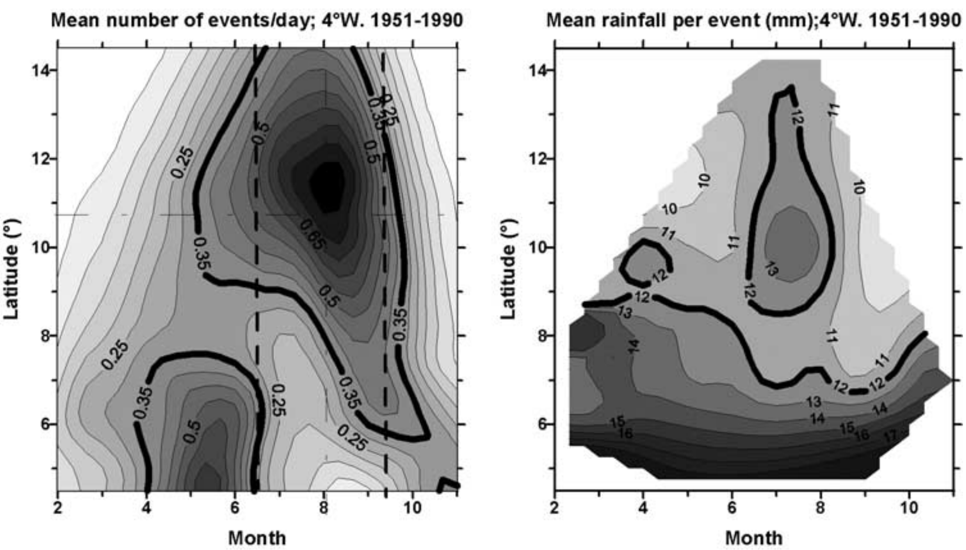

Figure 5. Space-time diagrams of the mean number of rain events per day and of the mean event rainfall (1951–1990) at 4°W. On the x axis, numbers indicate the start of the month (i.e., the representation starts 1 February and ends 31 October).

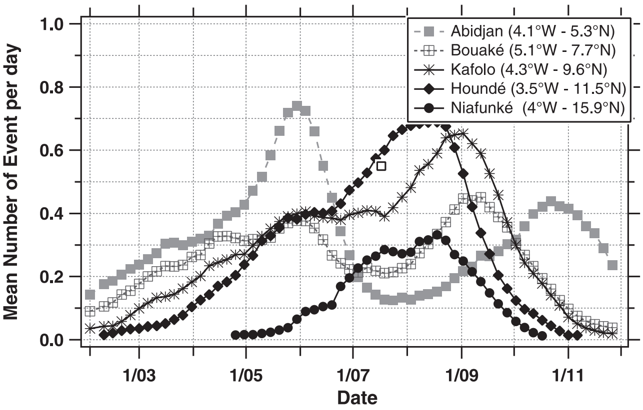

Figure 6. Rain event regime along a transect centered at 4°W.

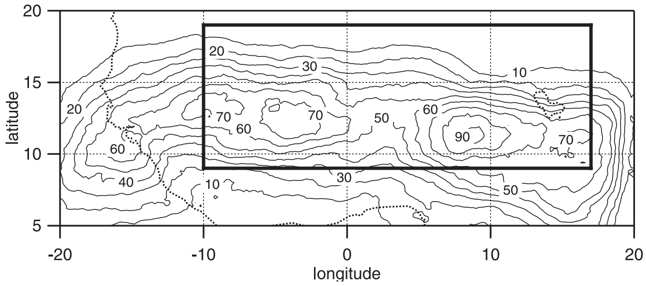

Figure 7. Spatial distribution of mesoscale convective complex (MCC) occurrences over West Africa for the period 1 July to 15 September. Values refer to the total number of MCCs recorded over the years 1989–1999 [after *Mathon*, 2001].

zonal decrease of h from the coast up to 8.5°N, and by a nucleus of stronger h values in the Sahel between mid-June and August, when the continental regime sets in. The n map looks very similar to the R map of Figure 2. Indeed, the space-time pattern of the R map is almost totally derived from the space-time pattern of the n map. The influence of h is mostly visible in shaping the area of larger R-values over the Sahel. Here again, a more detailed analysis is possible by looking at the curves obtained at a few stations along a south to north transect (Figure 6). Comparing Figures 3 and 6 shows how the transition between the oceanic regime and the continental regime at the end of June affects the rainfall regime in the north of the zone of Soudanian climate (Kafolo) and in the south of the Sahel (Houndé). In Kafolo, there is a decrease in the occurrence of rain events due to a weakening of the oceanic regime. At the same time, the mean rainfall per event increases, due to a larger proportion of more intense rain events corresponding to the beginning of the continental regime. At Houndé there is a similar behavior. At both stations, the result is an increase in rainfall at the beginning of July. Then, a clear difference appears between the two stations. Both the number of events and the 5-day rainfall increase continuously at Houndé, during July until mid-August when it peaks at 0.7 events/day, corresponding to a strong influence of the continental regime. Kafolo, on the other hand, is located at the southern edge of the region of maximum occurrence of large convective systems associated with intense rain events (Figure 7). The number of rain events remains stable around 0.7 events/day for the whole of July.

4.2. Convective Systems

[16] In an earlier work combining ground data from the EPSAT-Niger network and Meteosat data, *Laurent et al.* [1998] found that, over the region of Niamey, most of the intense rain events producing 80% of the annual rainfall were associated with large cloud clusters well identified from IR imagery. A more comprehensive study carried out by *Mathon and Laurent* [2001] on a 1989–1998 Meteosat data set has later shown that, for the period extending from July to mid-September (corresponding to the continental regime defined above), there is a region of maximum occurrences of mesoscale convective complexes (MCCs), defined following the criteria of *Maddox* [1980]. This region is precisely centered on 11–13°N, spreading in longitude between 10°W and 15°E (Figure 7). According to *Laing et al.* [1999], these MCCs produce 22% of Sahelian rainfall. This proportion is not sufficiently large to account for the year-to-year variability of Sahelian rainfall. *Mathon and Laurent* [2001], on the other hand, have shown that long-lived Mesoscale Convective Systems (MCSs) defined at 233 K account for 60% of the Sahelian deep convective coverage at 213 K. In their study, MCSs are defined as cloud clusters larger than 5000 km^2 at the 233 K temperature threshold and long-lived MCS are those lasting for more than 24 hours. During the period of the continental regime, the total number of MCSs recorded over the box shown in Figure 7 is a little less than 20000 for the years 1990–1999. As may be seen from Figure 8, a very small number of this total population accounts for most of the cloud coverage. In fact, 80% of the total cloud coverage at 233 K is produced by the 240 largest systems, that is little more than 12% of the MCSs. The minimum size of these 240 largest MCSs is greater than 50,000 km^2. They include 23 MCCs. In order to quantify the rainfall produced by these large systems, only those which covered at least 80% of the 16,000 km^2 EPSAT-Niger study area were retained. Since the rain gauges of the EPSAT-Niger network record 5-minute rainfalls, it is possible to compute precisely the rain produced by each system during its

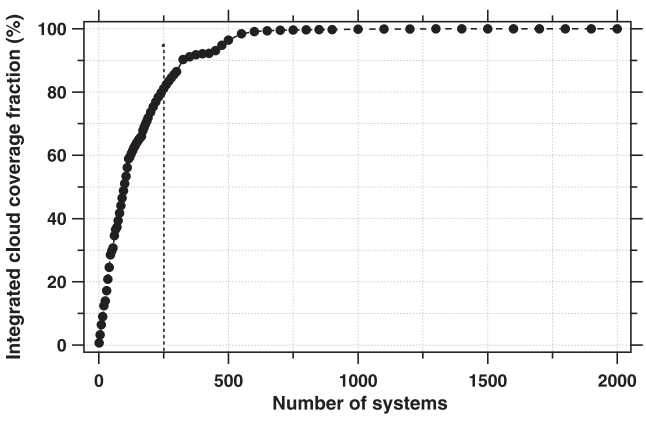

Figure 8. Cumulative distribution function of the cloud cover at 233K computed over JAS for the period 1990–1999.

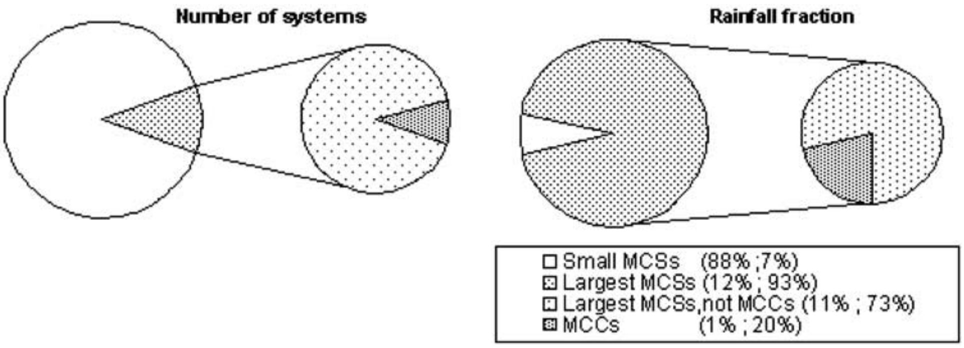

Figure 9. Proportion of the rainfall associated with the continental regime that is produced by the largest convective systems. These systems are producing 93% of the rainfall recorded over the EPSAT-Niger study area (16, 000 km^2), while they represent only 12% of the total number of MCSs observed over the region (statistics computed over the years 1989–1999 for the period 1 July to 15 September).

passage over the study area. The calculation synthesized in Figure 9 gave the following results: (1) the largest 12% of the systems produce 93% of the July–September (JAS) rainfall in this part of the Sahel with an average event rainfall of 14.7 mm and (2) the MCCs (that are all included in the largest 12% of the systems) represent only 1% of the total number of systems, producing 20% of the JAS rainfall. Figure 9 is very close to the statistic of *Laing et al.* [1999], given that the period and area considered for their calculation is significantly different from those of *Mathon and Laurent* [2001]. This also confirms that, even though MCCs are by far the most rain efficient systems, producing on average 19 mm per event, they account for a relatively small share of the JAS rainfall because they are few in number.

[17] Since the subpopulation of MCCs is too small for climatological analysis, it is necessary to select a larger population of MCSs, objectively defined, that account for a more significant share of the JAS rainfall. A detailed analysis of the most efficient systems in our sample revealed that they all include at least one 213 K cluster, imbedded in a larger 233 K cluster and lasting for more than 3 hours. It was further found that by selecting among these systems those moving at a speed greater than 10 ms^{-1} when passing over the ground validation area, we obtained a subpopulation of rain efficient systems very similar to the subpopulation of the largest 12% of the systems selected in Figure 7. It similarly accounts for more than 90% of the JAS rainfall in the region of Niamey. Based on these two criteria, 213 K clusters lasting for more than 3 hours and ground speeds larger than 10 ms^{-1}, it is possible to objectively count the number of rain efficient systems passing over the ground validation area each year. This opens the way for relating this number to the JAS rainfall for a given year, as will be seen in section 5.

4.3. Synoptic Weather Systems

[18] Since the work of *Carlson* [1969], *Burpee* [1972, 1974], and *Reed et al.* [1977], easterly waves have been identified as key synoptic features modulating convection and rainfall over the Sahel. They have a wavelength between 1500 km and 4000 km and a speed of about 8 m/s, giving rise to periods between 2.5 and 5.5 days. These 3–5 day easterly waves occur in the low- and middle-troposphere and are linked to the African Easterly Jet (AEJ) located in the vicinity of 15°N and 600 hPa, which satisfies the *Charney and Stern* [1962] barotropic and baroclinic instability criterion.

[19] *Duvel* [1990] was the first to investigate the relationship between easterly waves and cloudiness using ECMWF analyses and METEOSAT images. Although carried out on a sample limited to the summer of 1985, this study led to results similar to those obtained by *Burpee* [1974] and *Reed et al.* [1977] using the GATE radio sounding data. Maximum low-level convergence and upward vertical motion, as well as the greatest convective cloud cover and the largest precipitation amounts, are located in the region ahead and slightly south of the wave trough. However at 20°N, the positive rainfall anomalies are located behind the trough between the southerly wind and ridge sectors, indicating the primary influence of the northward horizontal transport of moisture. No vertical tilt is evident south of the AEJ because of the influence of convective heating whereas at 15°N and further north a vertical tilt opposed to the vertical wind shear shows the significant role of dry baroclinic processes in cloud free areas. At these latitudes, deep convection has a primary maximum in the southerly wind sector, fuelled by the horizontal transport of moisture. At and ahead of the trough axis, there is highly suppressed cloud condition consistent with strong shallow dry convection. According to the work of *Thompson et al.* [1979], it seems that latent heat release plays a major role in energizing the waves over land whereas diabatic effects appear to extract wave energy over the ocean.

[20] Recently, *Diedhiou et al.* [1998, 1999] have identified two main periodicities, one lying between 3 and 5 days and the other between 6 and 9 days. The 3–5-day easterly waves are more active in August–September. They have a mean wavelength and a mean phase speed varying from 3000 km and 8 m/s north of the AEJ to 5000 km and 12 m/s south of the jet. Rainfall, convection and the monsoon flux are significantly modulated by these waves, with convection in the ITCZ being enhanced in and ahead of the trough. The 6–9-day waves are mostly observed along one main track, located north of the AEJ along 17.5°N. The mean wavelength is about 5000 km, and the mean phase speed is about 7 m/s. The perturbation of the wind field is then mostly evident at and north of the AEJ latitude. It is similar to the

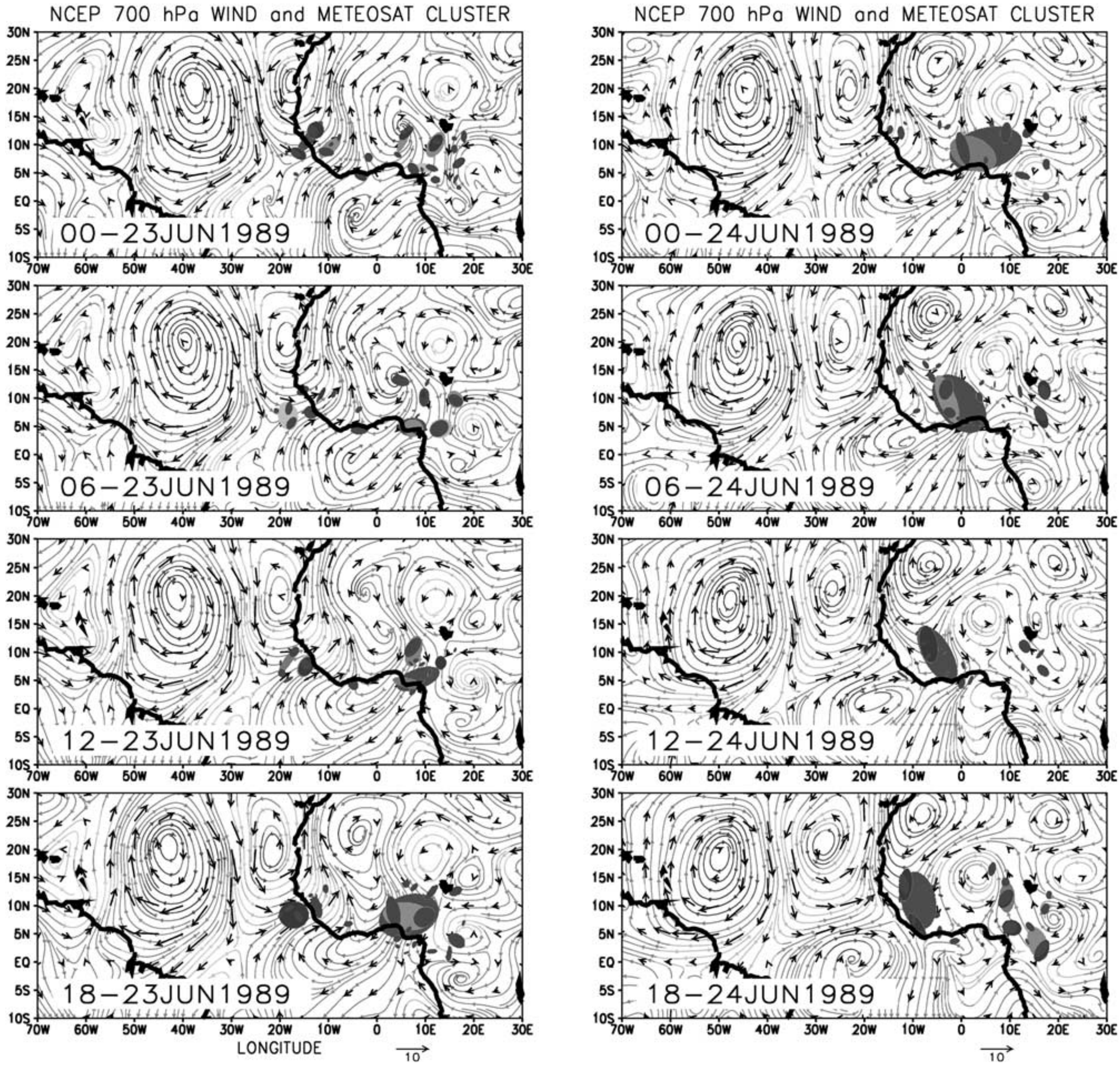

Figure 10. Illustration of an interaction between wave and convection during a time sequence from 0000 UT, 23 June 1989, to 1800 UT, 24 June 1989. The streamlines represent the disturbances in the NCEP/NCAR reanalyses wind field at 700 hPa filtered between 3 and 10 days. The shaded ellipsoids are cloud clusters obtained at 3 METEOSAT temperature threshold: 253°K (light gray/red), 233°K (dark gray/blue) and 213°K (black and violet). See color version of this figure in the HTML.

northern part of the 3–5-day wave, except that the more developed circulation centers, traveling a little further northward, lead to a large modulation of the zonal wind component of the jet. These 6–9-day easterly waves also significantly modulate rainfall and convection but in a different way from 3–5-day waves, resulting in zonal convective bands in the ITCZ, extending mostly in and behind the trough. Over the continent, the 6–9-day waves are more active at the beginning and at the end of the rainy season. Figure 10 is an illustration of how a large MCS evolves in a synoptic atmospheric disturbance from 0000 UT, 23 June 1989, to 1800 UT, 24 June 1989. Over the Atlantic, a strong anticyclonic cell crosses the ocean reaching the Brazilian coast at the end of the period considered. It is followed by a 6–9-day wave, associated with clusters of small size (small dark-gray ellipsoids), located behind the trough in a southern flux. The 6–9-day wave is itself followed by a 3–5-day wave located over Central Africa at 0000 UT, 23 June. In the initial phase, one can observe an ensemble of small clusters located in and ahead of the trough. They get organized into a large cluster by the end of the day. This cluster starts moving westward with the 3–5-day wave, extending from 8°N to 15°N and approaching the ocean at the end of the next day.

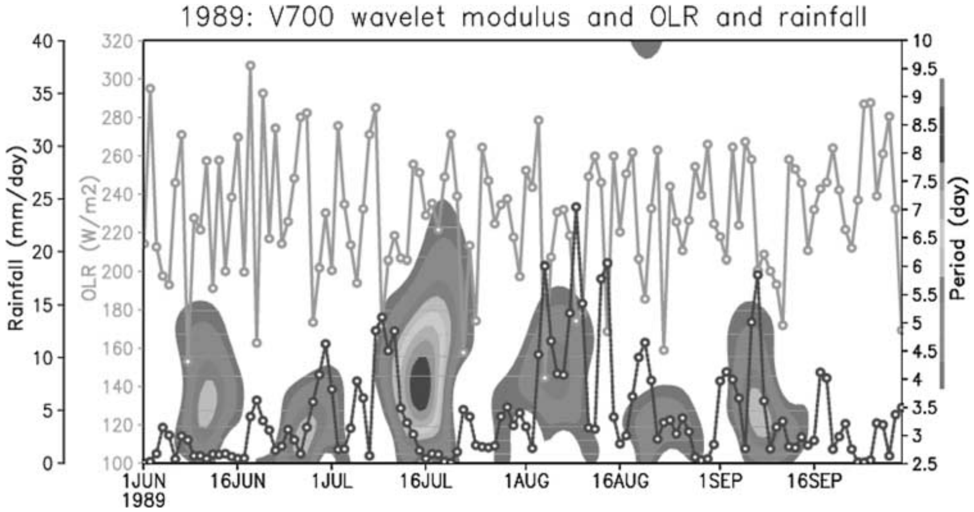

Figure 11. Evolution from June to September 1989 of the different wave regimes (wavelet modulus on the meridional wind at 700 hPa, shaded), the OLR (gray/orange line) and the observed daily rainfall (black dashed line). See color version of this figure in the HTML.

[21] Combining the NCEP/NCAR reanalyses, satellite measurement of the Output Longwave Radiation (OLR) and the observed daily rainfall, it is possible to analyze the seasonal cycle of rainfall and convection in interaction with easterly waves. Figure 11 shows the evolution of the OLR and of the observed rainfall for the Niamey grid point from June to September 1989 superimposed on the wave regime characterized by a Morlet-wavelet analysis of the meridional wind at 700 hPa. Wavelet analysis (shaded) confirms that most of the disturbances over the Sahel have a period lying between 3 and 5 days, the maximum in the 6–9-day band period occurring mainly in the beginning and at the end of the rainy season.

[22] Analyzing the association between waves and rain reveals a rather complete pattern. From 1 to 10 August and around 7 September, waves are associated with cold clouds and high rainfall heights (wet waves). The waves observed during the second week of June and around 21 August are associated with dry events and cold clouds (OLR between 180 and 200 W/m^2 for the first case and less than 160 W/m^2 for the second) and almost no observed rainfall at the surface (dry waves). There is also a "warm" wave observed around 16 July, which is not associated with either convection or rain at the surface. Finally, on 14 August, a strong convection (OLR less than 170 W/m^2) and a high rainfall (up to 15 mm) are recorded without any wave. As the modulus of the wavelet is positively correlated to the variance of the wave, all this indicates that the variance of the wave, considered only from the fluctuations of the meridional wind, is not a good indicator of the rainfall variability. Convection and rainfall can occur without any easterly waves present and not all easterly waves are associated with rainfall.

5. Interannual Variability

[23] As shown by Figure 12, the interannual variability of Sahelian rainfall is strongly linked to its seasonal cycle. In Figure 12 the difference of the average rainfall between the 20 driest years and the 20 wettest years is represented in the following way. First, the mean annual relative deficit of the 20 driest years for grid mesh ***j***, (the resolution of the grid being 0.5° × 0.5°) is computed as:

$$D_j = \left(R_{wet}(j) - R_{dry}(j)\right)/R_{wet}(j),$$

where $R_{wet}(j)$ is the average annual rainfall of the 20 wettest years and $R_{dry}(j)$ is the average annual rainfall of the 20 driest years.

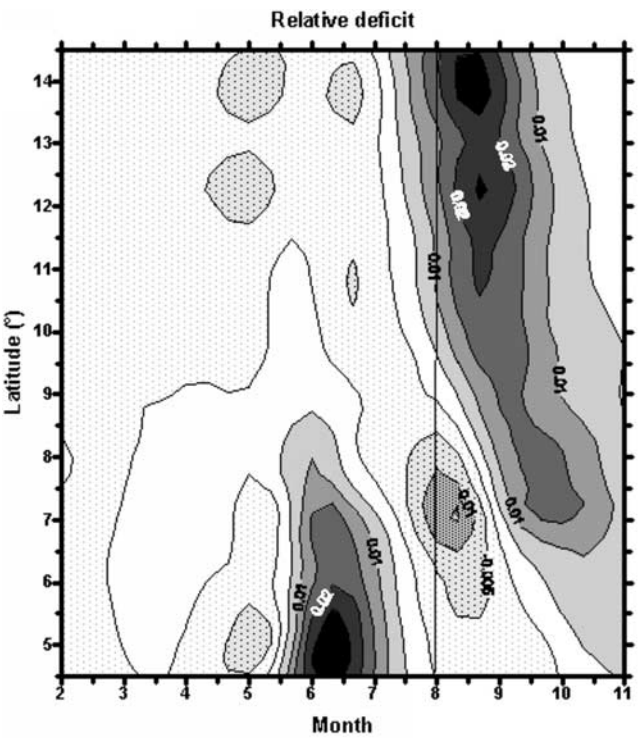

Figure 12. Hovmoeller diagram of the relative rainfall deficit between a composite of the 20 wettest years and a composite of the 20 driest years at 4°W. Shaded areas correspond to lower rainfall in dry years, while dotted areas correspond to higher rainfall in dry years.

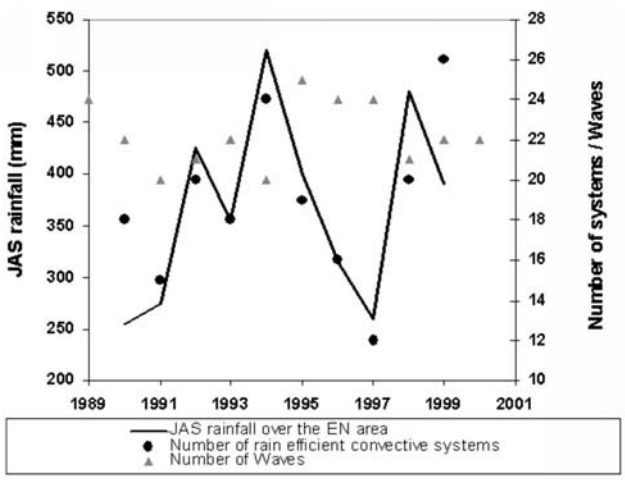

Figure 13. Rainfall recorded over the EPSAT-Niger study area, versus the number of large convective systems and the number of easterly waves.

[24] Then, for each day of the year, i, the relative deficit for grid mesh j, is computed as:

$$D_{i,j} = (R_{wet}(i,j) - R_{dry}(i,j))/R_{wet}(i,j).$$

The variable plotted in Figure 12 is

$$\delta_{i,j} = D_{i,j}/D_j$$

The integral of $\delta_{i,j}$ over the whole year for a given mesh j is equal to 1. If the entire deficit were evenly distributed over a hundred days, the value of $\delta_{i,j}$ would be equal to 0.01. Focusing on the Sahelian latitudes, it appears in this Figure 12 that all the rainfall deficit of the dry years is due to a rainfall deficit concentrated between mid-July and the end of September, that is during the period of the continental regime identified in section 3. Dry years are also characterized by the months of the oceanic regime (April–June) having a slightly larger than normal rainfall in the south (dotted area in Figure 12), although this might not be a statistically significant trend. This is a confirmation of the results of *D'Amato and Lebel* [1998], stating that dry years in the Sahel are not so much determined by a late start of the rainy season, but rather by a marked deficit during the core of the rainy season. *Robock et al.* [1993], in their work on the creation of regional climate scenarios, also found that the time between rainstorms is greater in dry years during the core of the rainy seasons.

[25] This rainfall deficit during July–September is associated with a lower number of the large rain-efficient convective systems identified in section 4.2, as is clear from Figure 13. By comparison, the mean event rainfall produced by these large systems does not vary significantly from year to year (not shown). Figure 13 also shows that the number of easterly waves recorded for a given year is not significantly correlated to the rainfall of that year. This has two consequences. First, monitoring the convective systems from IR images of geostationary satellites provides a simple tool for drought monitoring over an entire region such as the Sahel. It should be kept in mind however, that strong local gradients may exist and that ground data are a necessary complement to these satellite data. Secondly, it remains elusive to explain the year to year variation in the number of rain-efficient convective systems by simply looking at the synoptic weather patterns. It is therefore important to better understand at the intraseasonal scale the links between the life cycle of Sahelian convective systems and synoptic weather patterns, in order to improve our comprehension of the interannual variability.

6. Conclusion

[26] Rainfall in the Sahel, and more generally in all semi-arid regions of the world, displays a large degree of variability over a range of timescales. This variability is rarely characterized at relevant scales from an hydrological point of view despite the often dramatic consequences of intraseasonal dry spells and pluri-annual droughts on the water cycle of these regions. Rain events are a key element of the rainfall regime of semi-arid regions. They are associated with convective systems. To understand the hydrological impact of dry spells and droughts, it is therefore necessary to describe the rainfall regime at the scale of these rain events. This study provides such a description for the seasonal cycle and the interannual variability of Sahelian rainfall. Three complementary data sets were used to this end, covering 40 years for the regional daily rain gauge network, and 10 years for a full resolution meteosat data set and a high-resolution recording rain gauge network.

[27] It was initially shown that the seasonal cycle comprises two phases. The first phase corresponds to a progressive onset of rain on the West African continent from the tropical Atlantic. For that reason, this phase is considered to be as an oceanic regime. The second phase involves a sudden jump in the mean daily rainfall and mean daily number of rain events that occur concurrently over the whole Sahelian band. An overwhelming proportion of large convective systems embedded in the easterly circulation characterizes this second phase. Given the contrast between these two phases, the first has been referred to as an "oceanic regime" and the second as a "continental regime". The continental regime starts at the end of June and represents from 75% (in the south) to 90% (in the north) of the total annual rainfall in the Sahel. A small number of large and rain efficient convective systems account for more than 90% of the rainfall in the continental regime, each of theses systems producing in average a little less than 15 mm per event in their mature stage. This value is relatively homogeneous over the whole Sahelian band, whereas the mean event rainfall in the oceanic regime displays a strong meridional gradient ranging from 18 mm on the coast to 10 mm in the northern Sahel.

[28] The interannual variability of the Sahelian rainfall is largely controlled by the annual fluctuations in the number of these rain efficient convective systems. A composite analysis comparing dry and wet years revealed that the deficit of dry years was essentially concentrated around the core of the continental regime (August). During the dry years, the rainfall during the months of the oceanic regime (April to June) is equal to or even slightly larger than normal. Thus the length of the rainy season is not particularly reduced in dry years, contrary to a common belief.

Also, the mean event rainfall of the large convective systems characterizing the continental regime does not display significant differences between wet and dry years. These results are important in an hydrological perspective because runoff is affected differently by a decrease in the number of large rain events or by a decrease in the overall mean event rainfall.

[29] It was also shown that the raw number of 3–5-day wave is not a good indicator of the number of rain efficient convective systems recorded over the Sahel for a given year. This suggests the distinction between "wet" waves and "dry" waves. This tends to assume the existence of an intraseasonal signal modulating the rainfall during the continental regime. This modulation is currently analyzed using the NCEP/NCAR reanalyses. Phases of stronger AEJ/weaker TEJ, which have been identified in previous studies, might be connected to the existence of dry waves. The question is then to determine the nature of this intraseasonal signal and how it is linked to the interannual variability. Is it dominantly a modulation of the cyclonic activity of the waves or is it related to two different regimes of convection? Improving our understanding of the links between the interannual variability of Sahelian rainfall and its seasonal cycle is thus an important issue for future work on the WAM and its hydrological impact.

[30] **Acknowledgments.** We are grateful to the various national meteorological services which helped IRD (Institut de Recherche pour le Développement, formerly ORSTOM) to build the daily rainfall data base used in this study. This research was funded by IRD.

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