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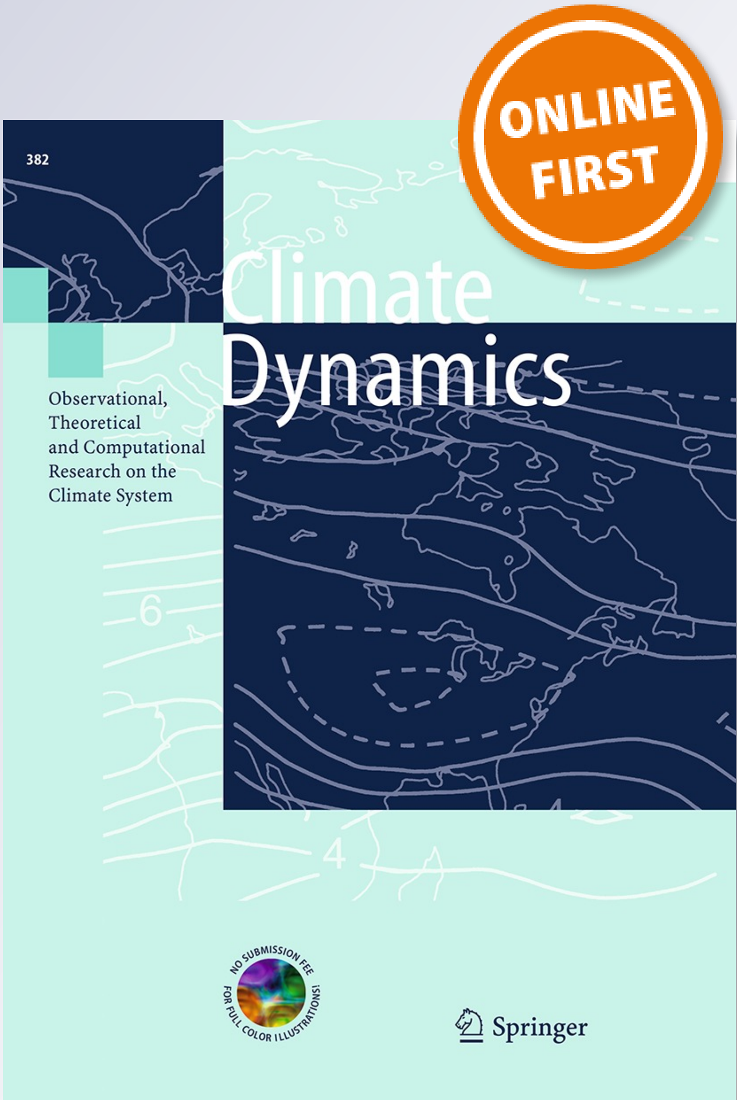

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Abstract Intra-seasonal drought episodes (extreme dry spells) are strongly linked to crop yield loss in the West African Sahel, especially when they occur at crop critical stages such as juvenile or flowering stage. This paper seeks to expose potentially predictable features in the sub-seasonal to inter-annual occurrence of "extreme dry spells" (extDS) through their links to sea surface temperature anomalies (SSTAs). We consider two kinds of extreme dry spells: more than 2 weeks of consecutive dry days following a rain event (often found at the beginning of the rainy season, after the first rain events) and more than a week (observed towards the end of the rainy season, before the last rain events). We extract dry spells from daily rainfall data at 43 stations (31 stations in Senegal over 1950–2010 and 12 stations in Niger over 1960–2000) to identify the intra-seasonal distribution of extDS and their significant correlation with local rainfall deficits. Seasonality of distribution and high spatial coherence are found in the timing and the frequency of occurrence of extDS in different rainfall regions over Niger and Senegal. The correlation between the regional occurrence index (ROI), necessary to capture the spatial extent of extDS, and observed global sea surface temperature anomalies (SSTAs) sheds light on the influence of the external factors on the decadal, interannual and sub-seasonal variability of extDS over the West African Sahel. When the global tropics and the Atlantic are warmer than normal, more coherent and delayed June–July extDS are observed after onset of rainy season, as well as early cessation type in August–September. When the Indo-Pacific is cooler and the equatorial south Atlantic is warmer than normal little to no extDS are found in the onset sub-period of the monsoon season. Mostly late types of extDS occur in October as a result of late cessation. These results show potential predictability of extreme dry spells after onset and before cessation of monsoonal rain based on global patterns of sea surface temperature anomalies.

Keywords Extreme dry spells · Seasonality · Spatial coherence · Regional Occurrence Index · SST anomaly · Niger and Senegal · West African Sahel

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1 Introduction

Seasonal forecast and other climate outlooks over West Africa are mostly issued in terms of the expected seasonal total—above, below or normal rainfall amounts. For example, every year in May–June, the meeting of the PRESAO (*Prévisions saisonnières pour l'Afrique de l'Ouest,* or West African climate outlook forum) publishes the results of a consensus forecast on the probability that the upcoming seasonal amount of rainfall will be above, below or normal (PRESAO_SG 2011). This forecast does not say how this total amount of rainfall will be distributed within the upcoming season. Conversely, farmers want information on the intraseasonal distribution of rainfall events. The main reason is that the intra-seasonal episodes of "rainless days" or dry spells (DS) affect crop development and productivity, especially when they occur at crop critical stages (Sivakumar 1992). Current knowledge of seasonal forecasting as exemplified by the PRESAO process does not provide this information.

A dry spell (DS) is a function of starting date (STDATE), duration (L) and seasonal frequency of occurrence (F). An empirical assessment of DSs by Salack et al. (2012) reveals that at the beginning of the rainy season, in May–June–July (MJJ), DS greater than 2 weeks (DS4 category) may be associated with important rain events. These "false start" rain events cause seed abortion as a result of water stress at the juvenile stage of field crops such as millet and sorghum in the West African Sahel (Ati et al. 2002; Sultan et al. 2005). Other DS types, of 1–2 weeks duration (DS3 category), may be found in the August–September–October period (ASO). They usually have a negative impact on the vegetative and reproductive phases of millet (Winkel and Do 1992). Both DS4 and DS3 categories are highly correlated to severe annual rainfall deficits (or drought) (Sivakumar 1992; Salack et al. 2011), especially if they occur in the same season (Salack et al. 2012). Therefore, we define two categories of extreme dry spell episodes (extDS, henceforth): those characterized by two or more weeks of consecutive dry days following a rain event, which are often found at the beginning of the rainy season (DS $\geq$ 15 days, or DS4), and those lasting more than a week mostly found towards the end of the rainy season (DS = 8–14 days or DS3). The seasonal frequency of occurrence of these extDS is low compared to the short and medium categories (Sivakumar 1992; Salack et al. 2011). Henceforth these two categories of extreme dry spells are qualified as "extreme events".

The proper knowledge of the distribution and forecasting potential of extDS's is important for seasonal food security and drought crisis alleviation in the Sudan and Sahel regions of West Africa. To present, the seminal empirical dry spell analyses by Sivakumar (1992) have not been updated. However, the recovery tendencies in the Sahel rainfall regimes associated with high variability in the seasonal and interannual time scales (Bell and Lamb 2006; Lebel and Ali 2009; Salack et al. 2011) and the perspectives of increasing extreme events in the nearest future (IPCC 2012) suggest the need for new approaches to analyze extDS over this region. Several schemes were suggested for forecasting dry spells, which do not focus specifically on extDS. They include: (1) the schemes based on the adjustment of a probability density function to the empirical distribution of average dry spell length (Martin-Vide and Garcia 1993; Denise et al. 2009); and (2) the schemes based on estimating the return period to forecast extDS occurrence (Lanà et al. 2008). However, these statistical methods are known for their stationary characteristics and the lack of sufficient observed data can also be a limiting factor to their use in this region. Recent attempts by Sane et al. (2008), Frappart et al. (2009) and Salack et al. (2011, 2012) to characterize dry spells over Senegal, Niger and the Gourma region (central Sahel) do not address the predictability of extDS nor do they relate their occurrence to the large scale influence of the Oceans.

This paper addresses two main questions: (1) are there potentially predictable features in the seasonal and interannual occurrence of extreme dry spells, e.g. as evidenced by spatial coherence in their recurrence? (2) given such spatial coherence, how does variability in the characteristics of dry spells relate to the sea surface temperature anomalies (SSTAs)? The potential predictability of extDS's can be derived from the analysis of a network of daily rainfall observations over a relatively small, homogenous region, as demonstrated by Moron et al. (2006) and Marteau (2011) for seasonal frequency of rainy days, rainfall amount and medium category of dry spells. The spatial coherence can be estimated by testing the statistical significance of the inter-station correlations. Hence, a study of the inter-station correlations with respect to the distance across pairs of raingauges shows how far spatial coherence can be observed in the spectrum of extDS's. Seasonality in the intra-seasonal dry spell oscillations and high spatial coherence between stations are both indicators of potential predictability (Moron et al. 2006). This approach is used, in this paper, to show that the sub-seasonal variability of extDS's can be due to two sources: (1) the daily fluctuation of some internal factors of the West African summer monsoon such as the Intertropical Convergence Zone (ITCZ), African Easterly Jet (AEJ), Tropical Easterly Jet (TEJ) etc. and (2) the influence of external factors such as SSTAs.

Our analyses of extreme dry spells use observed and quality controlled station data and the Hadley Centre Improved SST data set (Sect. 2). The definition and typology of dry spells are derived from a single and multiple raingauge extraction algorithm and classification developed by Salack et al. (2012), (and the establishment of a regional occurrence index (ROI) necessary to capture extreme dry spells (Sect. 3). The seasonality in extDS timing and frequency, their spatial coherence, the relationships between extDS variability and the quality of the rainy season, and their links to Oceans' surface temperature anomalies are provided in Sect. 3. The concluding remarks of this study are given in Sect. 4.

2 Data

2.1 Station data and rainfall climatology

For Senegal, a 31-raingauge data set was made available by the Regional Centre for the Improvement of Plant Adaptation to Drought (*Centre Régional pour l'Amélioration de l'Adaptation à la Sécheresse* (CERAAS)). The data set includes daily rainfall records from the network of the former National Meteorological Agency (actual *Agence Nationale de l'aviation Civile et de la Météorologie du Sénégal* (ANACIM)) and other raingauges managed by the Senegalese Institute for agricultural research (*Institut Sénégalais de la Recherche Agricole* (ISRA)), and by CERAAS for crop monitoring and forecasting (additional information can be taken from Salack et al. 2011).

Senegal is located at the extreme western edge of West Africa, with a marked coastal influence on its atmospheric dynamics. The rainfall climatology reveals four different rainfall zones in Senegal (Fig. 1a). The northern zone (NZ) has an average annual rainfall below 400 mm. The North Central zone (CN) is between 400 and 600 mm. The South Central zone (CS) is located between 600 and 800 mm annual average. The southern zone (SZ) is the entire region where average rainfall exceeds 800 mm/year (Fig. 1a). Rainfall intensity is high and rainy days are more frequent in the central (CN, CS) and southern (SZ) zones than in the northern regions (Dieng et al. 2008). This zonation is consistent and correlated with on-farm agronomic conditions and the natural agro-ecological zones found in these regions (Moron et al. 2006, Salack et al. 2011). Starting in the early 1970s, a 10–20 % rainfall deficit lasted almost three consecutive decades. Since the late 1990s, this deficit was significantly reduced; hence rainfall has been recovering from the mid-1980s drought situation. According to Salack et al. (2011), there is a statistically significant return of intense daily rainfall amounts and an increase in the occurrence of short dry spells in accordance with the increase in the number of rainy days. As compared to decades of drought such as the early 1970s and late 1980s, the past 15-year rainfall trend exhibits significant differences in the range of +10 to +17 % at sub-regional scale and +23 to +32 % at raingauge scale. These inter-decadal trends are more pronounced in the Sudan and Sahel regions of Senegal (i.e. CN, CS and NZ) where the average annual rain records are below 800 mm. The recovery pattern over Senegal is consistent with what was reported by Lebel and Ali (2009) for the central and eastern Sahel, and by Frappart et al. (2009) for the Gourma region.

For Niger, the daily data set comes from the National Meteorological office in Niamey. Daily rainfall records are available for 12 stations over 1960–2000. Niger is continental, with 90 % of its land covered by desert. Here, too, frequency and intensity of rainfall decrease from south to north, with average values oscillating between 800 mm and 100 mm per year. In fact, only Gaya station has average rainfall totals around 800 mm. Two thin rainfall regions are observed from the spatial distribution of rainfall, north of Gaya (Fig. 1b). The southwest and west, including stations of Magaria, Maradi, Konni, Dosso, Niamey and Tillabery, fall within the 600–400 mm rainfall zone. Anywhere north of this rainfall zone, average rainfall is less than 400 mm/year. Despite its arid and semi-arid climate characteristics, Niger is part of the central Sahel, whose rainfall has also increased over the past two decades (Lebel and Ali 2009; Ali and Lebel 2009). The space–time variability of rainfall in this region of the West African Sahel was extensively analyzed at local and regional scales in recent years, with many contributions stemming from the *African Monsoon Multidisciplinary Analyses* program (AMMA program, Redelsperger et al. 2006; Lebel et al. 2010).

2.2 Sea surface temperature anomalies

In the Sahel, it is well known that sea surface temperatures (SSTs) account for most seasonal, interannual and decadal rainfall variability (Folland et al. 1986; Fontaine et al. 1998; Giannini et al. 2003; Hoerling et al. 2006 amongst others). Correlation analysis with observed SSTs and simulation experiments based on atmospheric global circulation models support the idea that Atlantic Ocean, equatorial Indian Ocean and tropical Pacific Ocean (through the El Niño-Southern Oscillation phenomenon, or ENSO) temperature anomalies modulate summer Sahel rainfall (Folland et al. 1986; Janicot et al. 2001; Mohino et al. 2011), including the spatial extent of drought during El Niño events (Lyon 2004). Is extreme dry spell occurrence also related to SST anomalies? To answer this question, we use the observed Hadley Centre Improved SST data set (Rayner et al. 2003). HadISST is a monthly SST archive from 1870 to present. We extracted SST during the period 1950–2010. Then we constructed sub-seasonal SST anomaly indices (SSTAs) by subtracting the climatology. These global SSTAs are regressed against the regional occurrence index (ROI) of both Niger and Senegal to assessment the links between the sub-seasonal occurrence of extDS and the Ocean temperature anomalies (Sect. 3).

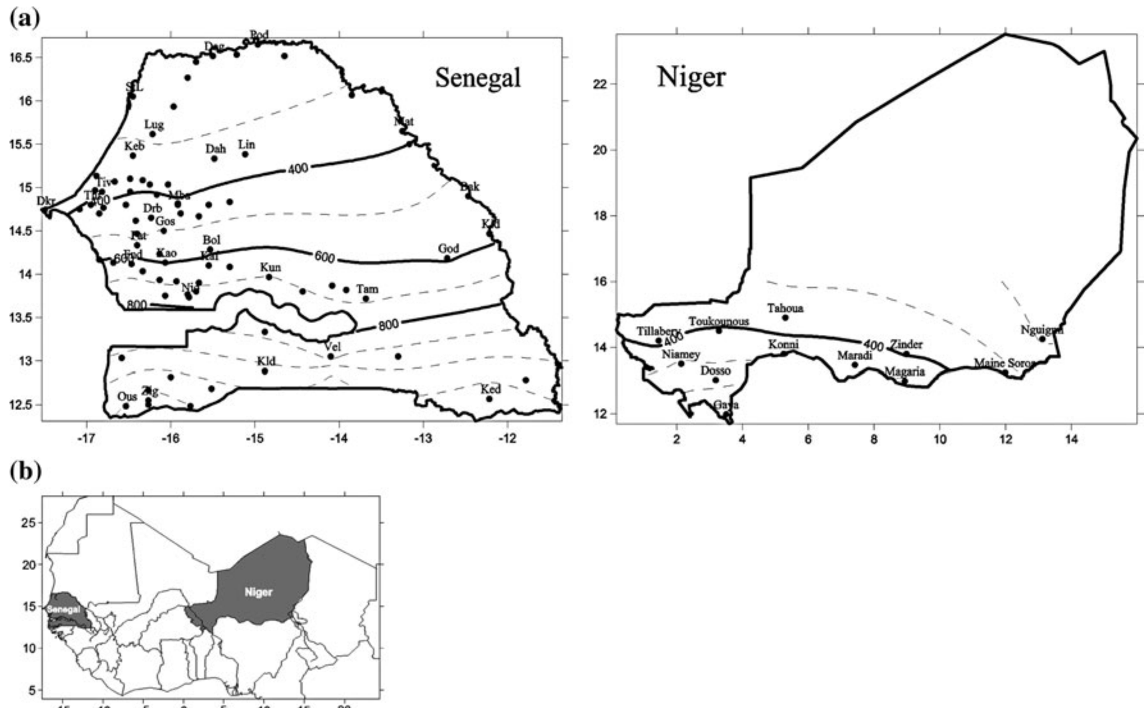


Fig. 1 Orientation maps and rainfall climatology of the study areas. **a** Location and overlay isohyets of 1981–2010 average rainfall for Senegal. The labelled dots are encoded names of the 31 stations with long term daily rainfall (1950–2010). **b** Location of stations and overlay isohyets of 1971–2000 average rainfall for Niger, and full name of the station with long term daily rainfall (1960–2000)

3 Analysis of extreme dry spells and their links to SST aenomalies

The analyses of extreme dry spells are based on a single and multiple raingauge extraction algorithm and classification developed by Salack et al. (2012), and the establishment of a regional occurrence index (ROI) to capture the spatial coherence of extreme dry spell types.

3.1 Dry spells extraction and typology

At the level of the raingauge (local scale), we adopted the threshold of 0.1 mm/day to define a rainy day in order to capture all daily rainfall events (RR) recorded on the observer's note book. All daily records are coded into alternating 1 and 0 (for rainy and dry days respectively). After each rainy day, we count the following consecutive dry days (i.e. sequence of days in which RR = 0) to define a dry spell (DS). The total numbers of consecutive dry days before the next rainy day is the duration or length (L) of the DS. The Julian day of first count corresponds to the onset date (STDATE). The total number of DS with length L found in a season is the frequency of occurrence (F). Extractions are made on the basis of "the first rainfall event recorded by the raingauge after May 1st". This principle helps extract all types of dry spells irrespective of a predefined onset date of the rainy season at a station as stated by Sivakumar (1992). This approach is a way to account for the high spatial variability of onset dates of rainy seasons over the Sahel. As we know, these onset dates of rainy seasons are not observed, rather they are computed based on a rainfall threshold (e.g. the classical Sivakumar method (Sivakumar 1988), Agrhymet-FEWS method (Agrhymet 1996)). They exhibit high internal variability in the recent years as reported by Marteau (2011) and Salack et al. (2011). Therefore our methods of extraction and classification of dry spells can help identify optimum cropping periods. The extraction algorithm is applied to each station, for all the available time series, such that every year's record of DS_L is identified. This procedure defines the local dry spell (DS) database for both Senegal and Niger.

Dry spells are analyzed using their starting date (STDATE), duration i.e. the number of days to the next rains (L) and frequency of occurrence per season (F). These are key indicators of the daily rainfall events' distribution during the cropping season. The STDATEs, the indicators of DS calendar, are extracted at irregular time intervals. To obtain uniform sampling in time, these dates in the Julian calendar are rounded to the pentad or the month in which they fall. Figure 2 depicts the average seasonal frequency-duration curves of DS in the reference rainfall regions

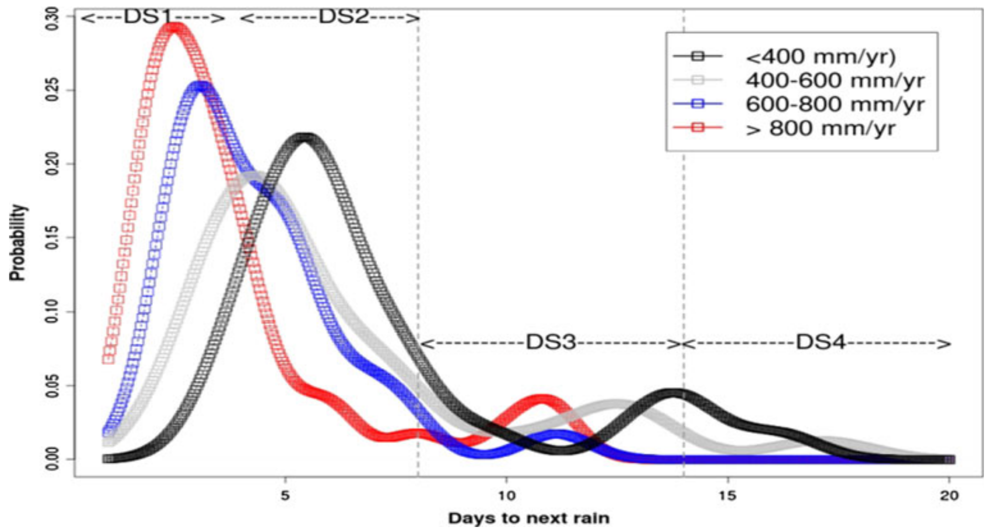


Fig. 2 Average seasonal probability distributions of all categories of dry spells depicted at all reference rainfall regions

identified in each country (see Fig. 1). The categories of dry spells are identified with the vertical dotted lines and horizontal arrows showing the nominal extent of L of each on the probability distribution function (PDF). From the space–time characteristics of these three components (STDATE, L and F) in Niger and Senegal, short and medium duration DS are classified as "ordinary dry spells" because they are often observed in any rainy season (Salack et al. 2011, 2012). The short categories of DS are 1–4 days (DS1) and 5–7 days (DS2). The medium category of observed DS is the class of 8–14 days (DS3). The long dry spells category is the set of DS greater than 2 weeks (DS4). Categories DS1 and DS2 are more frequent in the regions of the two countries where average annual rainfall is above 600 mm. These regions correspond to the Sudan zone in Niger, Sudan and North Guinea zones in Senegal. DS1 and DS2 are also classified as short in other arid and semi-arid areas of Africa (Sivakumar 1992; Barron et al. 2003; Segele and Lamb 2005). In agricultural practice, the DS1 and DS2 categories are not detrimental to crop development, but show high frequency of rainfall events in those regions. However, DS3 and DS4 are irregular and have a low number of occurrences per season. They are mostly responsible for the skewed portion of the PDF, which is very hard to adjust using a probability model according to Denise et al. (2009).

3.2 Seasonality of extreme dry spells

Long-term PDFs issued from the starting dates (STDATE) of DS4 and DS3 are illustrated by Fig. 3 for Senegal and Niger respectively. These are PDFs for all stations that lie within a reference rainfall region. The PDFs are then converted into cumulative PDFs and the most common STDATEs (between the 2.5th and 97.5th percentiles) are extracted. This gives the range of STDATEs summarized in Table 1. The results in this table correspond to the highest mode of variability of STDATEs in the intra-seasonal time scale and depict the seasonality in the occurrence of extDS at different rainfall regions of the study area. An analysis of Table 1 reveals a clear similarity of the risk periods over Niger and southern Senegal (regions of 600–800 and >800 mm/year) in the MJJ sub-period. The occurrence of extDS's in May–June is related to the onset of the rainy season. As stated earlier by Sultan and Janicot (2003), Janicot et al. (2008) and Nicholson (2009), the onset of the African summer monsoon is linked to an abrupt latitudinal shift of the Intertropical Convergence Zone (ITCZ) from a quasi-stationary location at 5°N in May–June to a second quasi-stationary location at 10°N in July–August. The atmospheric circulation is characterised by successive northward excursions of the monsoon flux mostly driven by the Saharan heat-low at a 3–5-day time scale (Couvreux et al. 2010). This monsoon flux is responsible for the intermittent rainfall events associated with the 2–3-week duration dry spells. Therefore the similarity between May and June average STDATEs over Niger and southern Senegal confirms the spatial coherence in the onset of the rainy season. However, a time lag of 20 days to a month is found between southern Senegal (Niger), and northern Senegal, where rainfall is less than 600 mm/year. In these northern regions, the periods of high risk of extDS's occurrence extend beyond mid-July (Table 1). At the end of the rainy season, the occurrence of extDS denotes early cessation of the rainy season (Sivakumar 1992). In Niger and Senegal, the cessation dates are uniformly observed in the interval between the 1st dekad of September and the 1st dekad of October, except for the dryer regions of Senegal (where average annual rainfall is <400 mm). This result is in line with those found by previous studies using rainfall amount rather than dry spells (Le Barbé et al. 2002; Lebel and Ali 2009 and Salack et al. 2011).

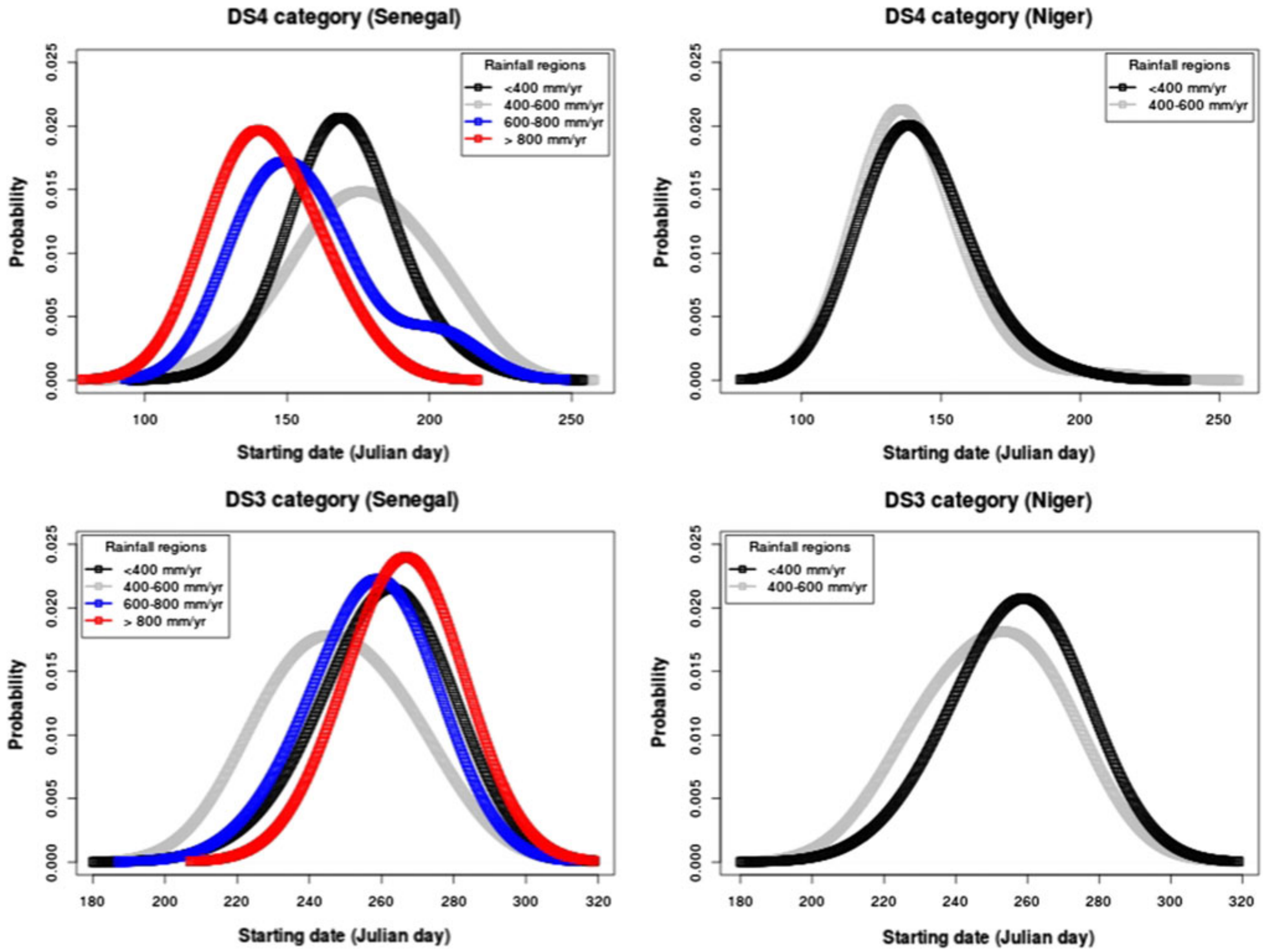


Fig. 3 Empirical probability distribution extreme dry spells occurrence dates as depicted from each rainfall region from the 1950–2010 daily rainfall time series

The average distribution of starting dates shows that the DS4 category (DS $\geq$ 15 days) occurs often in May–June–July (MJJ) and the DS3 category (8–14 days) is mostly observed in August–September–October (ASO) (Salack et al. 2012). Crop simulation experiments over Niamey (in Niger) show that these rain events can cause 35–50 % millet yield loss as a result of the subsequent water stress due to long dry spell occurrence (Sultan et al. 2005). As a result, in the remainder of this paper we will focus on these events: DS4 dry spells in MJJ and DS3 dry spells in ASO, which we refer to collectively as extreme dry spells.

3.3 Regional occurrence index of extreme dry spells

In order to capture the climatic signal of the DS3 and DS4 categories of extreme dry spells whose STDATEs fall between May and October, we define a regional occurrence index (ROI). We write the individual raingauge time series of monthly number of extDS as F_{mM}, F_{mN}, F_{mP}, F_{mQ}, the elements of m x M, m x N, m x P, m x Q dimension matrices for each rainfall region (e.g. <400, 400–600, 600–800 and >800 mm/year respectively). The country-wide, yearly *ROI* is a column vector whose elements are calculated in the form of Eq. 1.

$$ROI_m = \begin{pmatrix} f_1 \\ f_2 \\ f_3 \\ \cdots \\ \cdots \\ \cdots \end{pmatrix}$$

with

$$f_m = \frac{1}{M}\sum_{i=1}^{M} F_{mi} + \frac{1}{N}\sum_{j=1}^{N} F_{mj} + \frac{1}{P}\sum_{k=1}^{P} F_{mk} + \frac{1}{Q}\sum_{l=1}^{Q} F_{ml} \tag{1}$$

The elements f_1, f_2, f_3 … are the monthly totals of the average number of cases (F) of extDS of category DS4 in May, June, July (category DS3 in August, September,

Table 1 Main seasons of extreme DS occurrence after onset of rainy season for different rainfall regions over Niger and Senegal

Country	Sub-season	Rainfall regions			
		<400 mm/year	400–600 mm/year	600–800 mm/year	>800 mm/year
Niger	May–June–July	19-May to 8-June	19-May to 8-June	–	–
	Aug–Sept–Oct	6-sept to 6-Oct	6-sept to 6-Oct	–	–
Senegal	May–June–July	29-May to 18-July	29-May to 18-July	19-may to 8-June	19-may to 8-June
	Aug–Sept–Oct	17-Aug to 26-Sept	6-sept to 6-Oct	6-sept to 6-Oct	6-sept to 6-Oct

These dates are depicted from the assessments of starting dates (STDATE) extracted in 1960–2000 (Niger) and 1950–2010 (Senegal)

October). m are the treated months in a year (m = M, J, J (A, S, O)) and i, j, k, l ($i = j = k = l = 1, 2, 3, 4, \ldots$) are the raingauge counts with M, N, P, Q being the total number per rainfall region. The terms used to compute f_1, $f_2, f_3, \ldots$ change according to the number of rainfall regions found in a country. In the case of Niger, they reduce to the first two terms of Eq. 1. The areal values of the ROI corresponds to the total area average number of extDS observed in a rainfall region. The sub-seasonal cumulative ROI's (i.e. MJJ, ASO sub-seasons) are regressed against the standardized annual rainfall anomaly index (RAI) of each country and the global SSTAs. The objective is to look for the statistically significant correlations between the quality of the rainy season, remote ocean surface temperature anomalies and the seasonal occurrence of extDS in the MJJ (DS4 category) and ASO (DS3 category) periods (see Sects. 3.4, 3.6).

3.4 Implications for the quality of the rainy season

Is there a relationship between the occurrences of extDS's and the final state of the rainy season (i.e. below, near or above normal precipitation)? In order to determine the state of each season, we use the standardized precipitation index averaged over each country (henceforth called rainfall anomaly index, RAI). To the RAI we apply the Ali and Lebel (2009) criterion: we consider a year to be wet when its RAI value is higher than 0.5; normal when the RAI value is in the range [−0.5, 0.5]; and dry when RAI value is below −0.5 (Ali and Lebel 2009). Figure 4a, b presents the scatter plot and a regression line graph of the RAI against the anomalies of the average regional occurrence index (ROI) of each country. The correlation coefficients are all negative ($r = -0.50$ ($r = -0.15$) in the upper panel and $r = -0.4$ ($r = -0.46$) in the bottom panel for Senegal (Niger)) and significant at 95 % confidence level, using a two-tailed t test (von Storch and Zwiers 2003). Only the case of Niger in the MJJ sub-seasonal where $r = -0.15$ in not statistically significant. The low correlation observed over Niger is explained by the fact that the occurrence of DS4 events only is frequent in normal rainy seasons. Beside the statistical significance, the negative signs of these correlation coefficients are very important result. In other words, the occurrence of extreme dry spells over these two countries is related to annual rainfall deficits. Sivakumar (1992) had shown that this relationship can be fitted by a negative power exponential function and the correlation coefficients can reach 0.89 at most stations in the Sahel and Sahel-Sudan

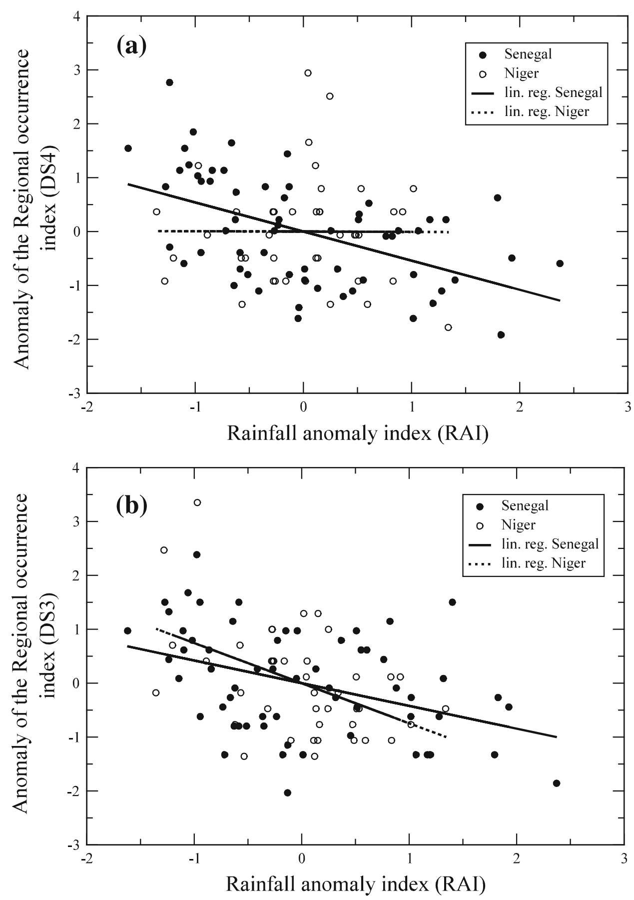


Fig. 4 Relationship between annual rainy season's quality (expressed as a rainfall anomaly index, RAI) and the occurrence of extreme dry spells. A year is wet when its RAI value is higher than 0.5; a near normal year has a RAI value in the range [−0.5, 0.5]; and a dry year is one whose RAI value is below −0.5 (Ali and Lebel 2009). **a** May–July DS4 category's occurrence anomalies versus rainfall anomalies. **b** Aug–Sept DS3 category's occurrence anomalies versus rainfall anomalies. Negative anomaly of the regional occurrence index (ROI) is equivalent to absence of extreme dry spell

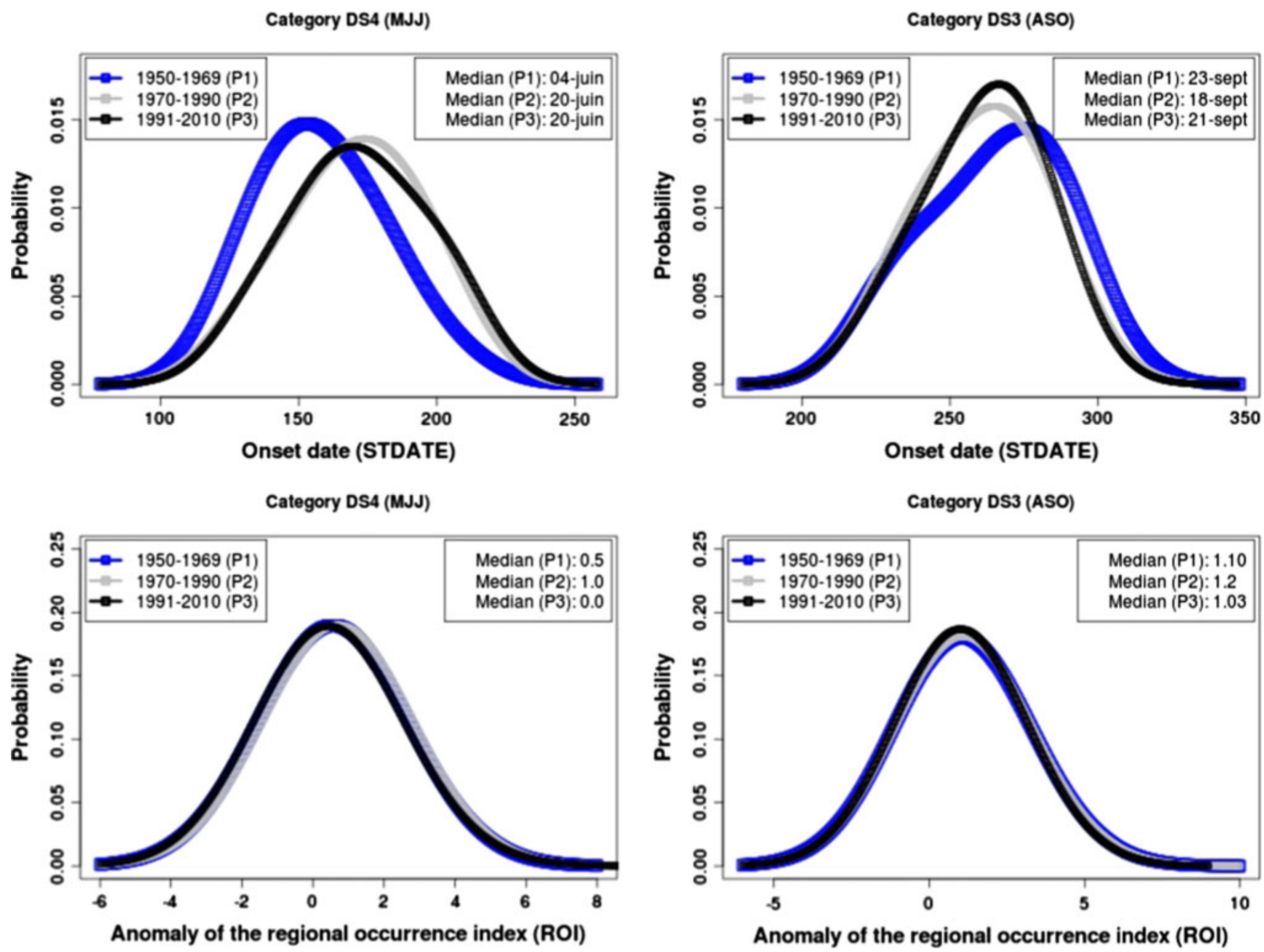


Fig. 5 Sub-seasonal distribution of extreme dry spells (extDS), DS4 category (DS $\geq$ 15 days) in May–June–July (MJJ), and DS3 category (8–14 days) in August–September–October (ASO). In the upper panel (**a**, **b**) are the onset dates (STDATE), in the lower panel (**c**, **d**), the monthly number of occurrence. The reference periods are P1 (humid), P2 (drought) and P3 (recovery)

regions of West Africa. Salack et al. (2012) show that when both DS4 and DS3 events are observed during the same year (in MJJ and ASO respectively) then the rainy season of that year is extremely dry. However, if only DS4 or DS3 is observed over one-third of the raingauge network the rainy season of that year is normal to dry.

It is unanimously accepted that rainfall regimes in the Sahel have had different spatio-temporal patterns from the 1950s to present (Lebel and Ali 2009). A majority of recent reports distinguish three reference periods: humid 1950–1969 (P1), dry 1970–1990 (P2) and "recovery" starting from the end of the 1990s (P3) (Ozer et al. 2003; Nicholson 2005; Bell and Lamb 2006; Agrhymet (2010)). For example, an assessment of daily rainfall over Senegal (Salack et al. 2011) reveals that in recent years (P3), the onset date of the rainy season has not undergone a statistically significant change, compared to the previous dry period (P2). Rather, onset dates are embedded within long dry spells. This situation can explain the high interannual variability of rainfall in recent years. The monthly distribution and number of cases of extDS are depicted in the Fig. 5 (upper panel). According to the onset dates (STDATE), the shift of the PDF towards the 1st half of June shows that in 1950–1969 (P1) extDS were more frequent earlier, in May–June. In contrast, since 1970 (P2 and P3), this mode of variability is centred on June–July. The extDS of category DS3 is later, in P1 as compared to P2 and P3. In other words, humid years tend to exhibit early extDS occurrence of category DS4 and longer cropping season with later DS3 events. On the contrary, in recent years, whose annual total rainfall regime seems closer to normal, early cessation events are more likely in September (with a higher probability of occurrence of DS3 events). The monthly average number of extreme dry spells has not shown a significant change in the study area as revealed by Fig. 5 (bottom panels). Nevertheless, a strong variability is

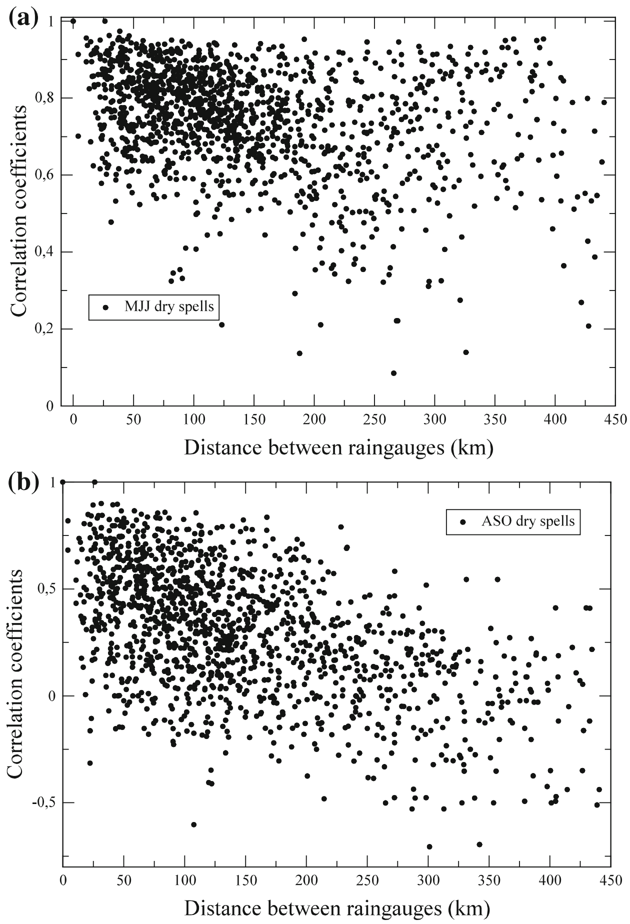


Fig. 6 Inter-raingauge correlation coefficients w.r.t. inter-raingauge distance. **a** In the MJJ sub-period, the spatial coherence is shown by the dense significant correlation coefficients (0.6–1) from 0 km up to ~150 km. **b** In ASO sub-period the spatial coherence is limited to 0 up to ~70 to 100 km

observed on the decadal signal of these events. These results are in agreement with the conclusions of the IPCC Special Report on Extremes (SREX), which noticed an increase in length of drought episodes and interannual variability over West Africa (IPCC 2012).

3.5 Measures of spatial coherence

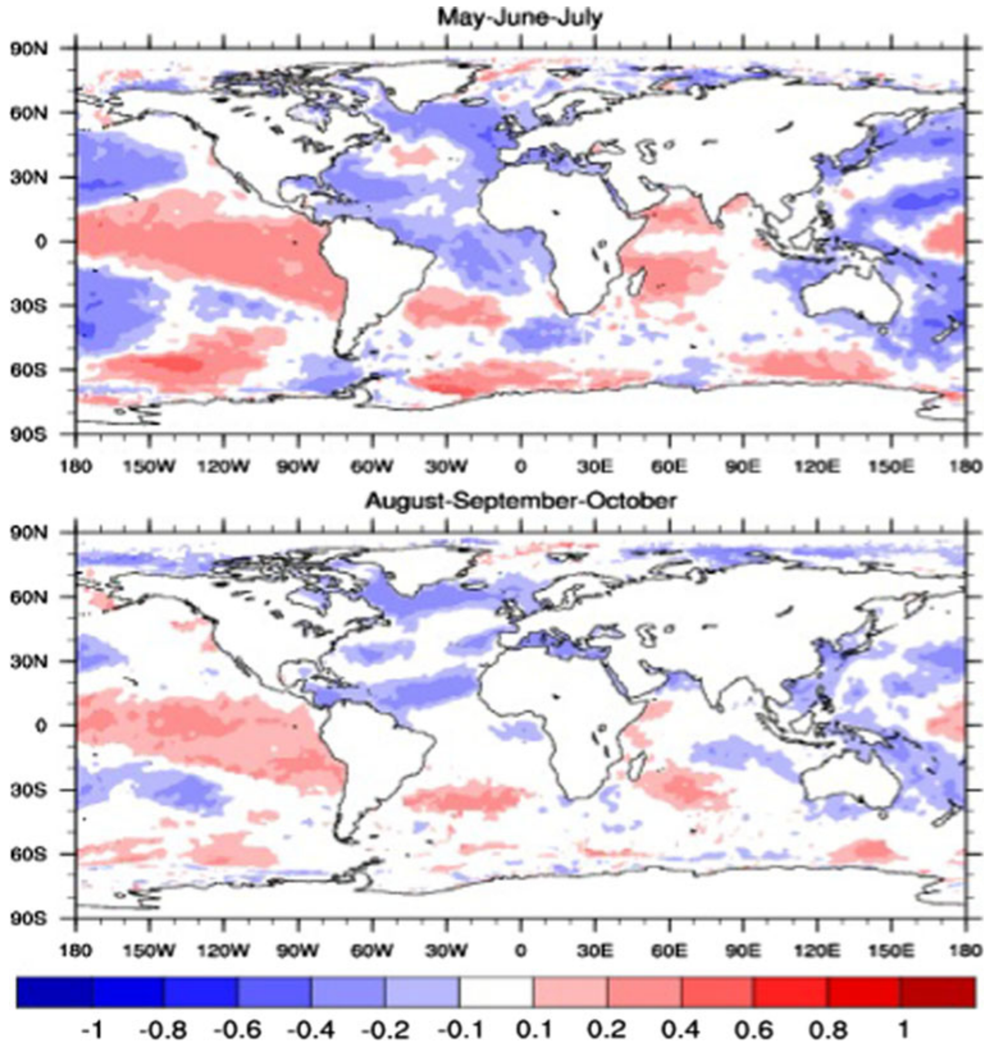
Is there a predictable, large-scale pattern in the occurrence of dry spells? To answer this question, STDATEs are associated to the durations (L). To obtain uniform sampling in time, the dates in the Julian calendar are rounded to the pentad in which they fall. When there is no extDS, the pentad takes the value zero (i.e. L = 0). This provides a regular time series of L in MJJ, ASO of each year at each raingauge. The average seasonal cycle of L, at pairs of raingauges, are then correlated. Examples of seasonal cycles of L at individual raingauges (local dry spells) are given by Salack et al. (2012). A correlation matrix is computed using the actual durations (L) at pairs of raingauges. Likewise, raingauges' coordinates (longitude and latitudes) are used to compute the matrix of distances across pairs of raingauges.

Spatial coherence is found by testing the statistical significance of the correlations between pairs of raingauges (inter-raingauges correlation, hereafter). In each country, the similarity of the inter-raingauges correlation coefficients is assessed with respect to the distance between pairs of raingauges (Fig. 6). The scatter plot of correlation coefficients is presented with respect to the distance between pairs of raingauges (km) for both MJJ (Fig. 6a, ASO Fig. 6b). In MJJ, a high density of correlation coefficients significant at 95 % level (r = 1 to r = 0.5) are depicted between 0 and 150 km inter-raingauge distance. This shows that DS occurring in MJJ can be spatially coherent from a given raingauge up to other surrounding raingauges over a radius of 150 km. Beyond this spatial extent, the high correlation coefficients seen on Fig. 6a are due to long-term climatological analogues between raingauges. In ASO the spatial correlation of DS occurrence exhibits lower spatial coherence, limited to approximately 70–100 km: significant inter-raingauges correlations (r = 1 to r = 0.5) decrease more rapidly with inter-raingauges distance (Fig. 6b). This sub-seasonal period includes peak and retreat phases of the rainy season in both Niger and Senegal. Therefore, a situation of mesoscale extDS (DS3 category) can possibly be followed by isolated convective rainy days at some stations, especially in the regions above 800 mm/year.

3.6 Relationship between extreme dry spell occurrence and SST anomalies

It is well established that rainfall variability in the Sahel is closely linked to SST anomalies (Vizy and Cook 2002) with the Atlantic, Pacific and Indian Oceans all playing a role (Folland et al. 1986; Janicot et al. 2001; Giannini et al. 2003; Mohino et al. 2011). Figure 7 shows the regression between global SSTs and the regional occurrence index (ROI) of extreme dry spells (DS4 and DS3) in each sub-season. Strong anti-correlations are found between the occurrence of the DS4 category of extreme dry spells in MJJ and SST anomalies in the entire tropical Atlantic. Conversely, the occurrence of the DS3 category in ASO is anti-correlated with SST anomalies in the subtropical north Atlantic only. A strong, widespread correlation is found between the occurrence of extreme dry spells (DS4, DS3 categories) and the equatorial Pacific and Indian Oceans (global tropics, henceforth). We hypothesize as follows. Global tropical mean sea surface temperature sets the vertical stability globally from the top down through deep convection (Neelin et al. 2003; Chiang and Sobel 2002), while the tropical Atlantic modulates it locally from the surface up through

Fig. 7 Inter-seasonal correlation between global SST anomalies and the inter-annual regional occurrence index of extreme dry spells at sub-seasonal periods over Niger and Senegal



atmospheric moisture supply (Giannini et al. 2008). Warmer global tropical SSTs set a higher threshold for convection, which is met less frequently, hence the positive correlation in the greater frequency of dry spells. A higher threshold for convection is met less frequently, that is, unless the tropical Atlantic also warms. In this case, increased moisture flow in the monsoon can meet the higher threshold, and result in reduced frequency of occurrence of extreme dry spells. The difference in the tropical Atlantic regions of correlation involved during MJJ and ASO points to variations in the regions of moisture origin that will be investigated in further diagnostic work.

The scatter plot in Fig. 8 aligns along a steep slope the Atlantic, Indo-Pacific temperature anomalies and timing and occurrence of extDS. The full circles represent the total number of cases of extDS observed in MJJ (DS4 category) and ASO (DS3 category). The open circles depict the number of cases occurring only in JJ and AS (DS4, DS3 respectively). When the global tropics and the tropical Atlantic are warmer than normal, more coherent and delayed June–July extDS are observed after the onset of rainy season, as well as early cessation types (DS3, 8–14 days) in August–September (upper right quadrants of FIG. 8). This relationship is statistically significant at the 95 % confidence interval according to a "pooled variance" Student *t* test (von Storch and Zwiers 2003) ($R^2 = 64$ and 27 for MJJ and ASO respectively). However, when the global tropics are cooler but the equatorial south Atlantic is warmer than normal, a lower threshold for convection is met. No extDS are found in the onset sub-period of the monsoon rainfall. Mostly late DS3 types of extDS are observed in October as a result of late cessation (lower right quadrants of FIG. 8). This is consistent with the occurrence of wet years (Giannini et al. 2012). From a global perspective and on interannual timescales, the global tropics remain the largest known source of rainfall predictability in the Sahel.

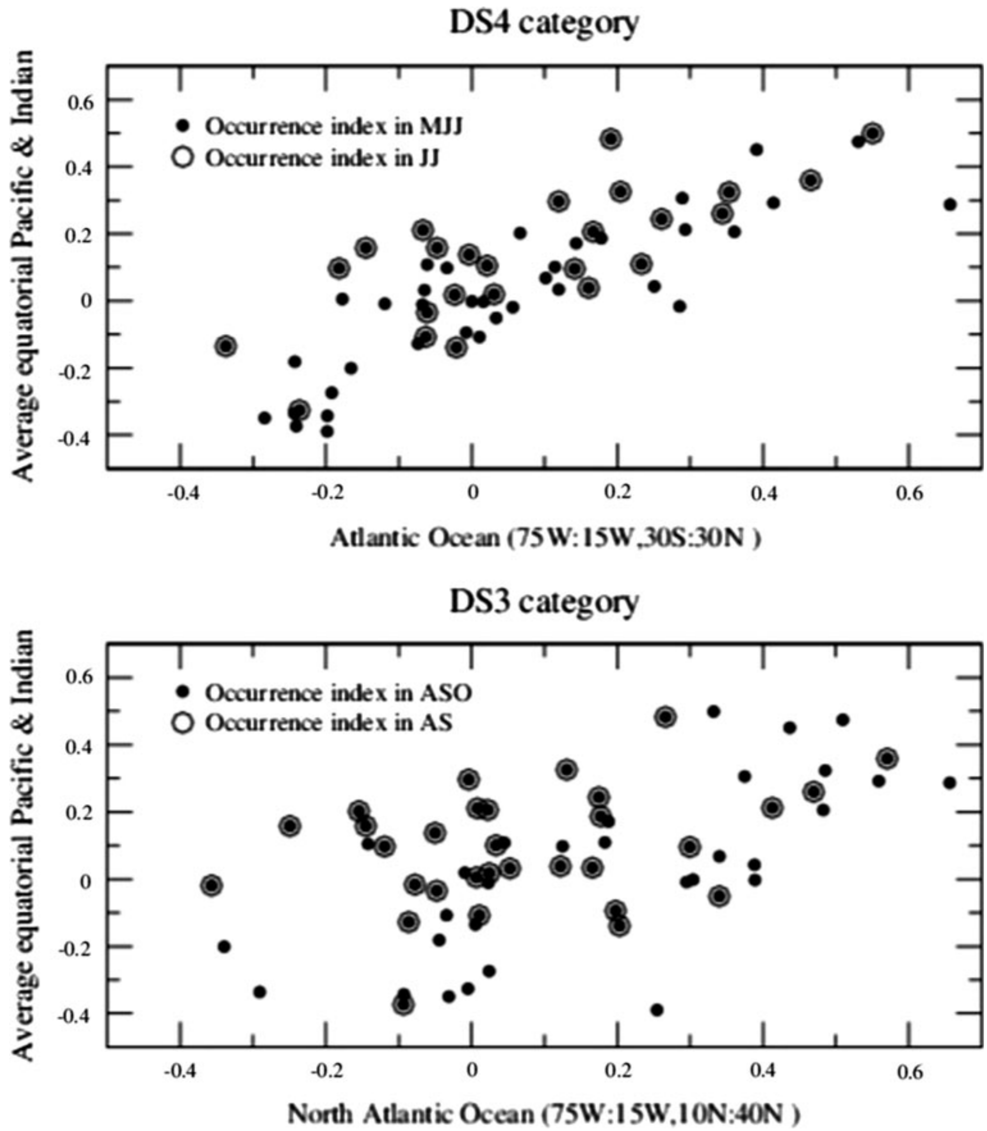


Fig. 8 Sub-seasonal relationship between the occurrence of extreme dry spells and the state of the Indo-Pacific and Atlantic Oceans. The upper window depicts the extreme dry spells occurring in May–June–July. The bottom plot depicts the extreme dry spells occurring in August–September–October. The *full circles* indicate the average number of cases of extDS found in MJJ (ASO) and the open circles depicts the special cases of June–July and August–September

4 Conclusion

The analysis of extreme dry spells (extDS) from station records of daily rainfall provides insight into their timing and seasonal frequency of occurrence. Their typology reveals two categories: (1) the irregular, longer than 2 weeks types which are associated with intermittent rain events at the beginning of the rainy season (DS4 category) and (2) the less frequent, 8–14 day-long dry spells (DS3 category), which are lethal to crops when they occur at the core of the rainy season. The average distribution of starting dates shows that the DS4 category occurs most often in May–June–July (MJJ) and the DS3 category is mostly observed in August–September–October (ASO). Their occurrence is related to false start and early cessation of rainy season, and correlates with rainfall deficits in the region.

The historical assessment of both the monthly timing (STDATEs) and frequency of cases observed (F) shows that humid years tend to exhibit early extDS occurrence of DS4 category events, and longer cropping season with fewer DS3 category events. On the contrary, in recent years, with a return to a near-normal situation in terms of total seasonal rainfall, early cessation events have become more likely in September (with a higher probability of occurrence of DS3 category events). The monthly average number of extreme dry spells has not significantly changed. Nevertheless, a strong variability is observed on the decadal signature of these events. At the intra-seasonal time-scale they also exhibit a high spatial coherence which is consistent with the remote influence of ocean surface temperature anomalies.

We associate more coherent and delayed June–July extDS after the onset of the rainy season, and early cessation types of extDS in August–September to a situation when the global tropics and the entire tropical Atlantic are warmer than normal. In contrast, when the Indo-Pacific is cooler and the equatorial south Atlantic warmer than normal we find little to no extDS in the onset sub-period. Mostly late DS3 types of extDS occur in October as a result of late cessation. These relationships are statistically significant and prove once more the key role played by the oceans in the timing and frequency of occurrence of extreme dry spells in the Sahel.

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