Theor Appl Climatol
DOI 10.1007/s00704-011-0414-z

ORIGINAL PAPER

Rain-based factors of high agricultural impacts over Senegal. Part I: integration of local to sub-regional trends and variability

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Received: 28 June 2010 / Accepted: 31 January 2011

Abstract The evolution of seasonal cycle and interannual rainfall, the number of rainy days and daily rainfall types, dry spells frequency of occurrence, onset/cessation/length of rainy season, sowing dates, and the duration of the cropping period, are investigated at local (individual sites) and sub-regional scales (four different rainfall zones) using daily records of station data (83 sites) over Senegal. In the limits of a case study, these analyses complement and update previous studies conducted in the extreme Western Sahel (11–16° N and 20° W–10° E). The results unveil noticeable evolution of some of these rain-based factors in the recent periods as compared to the previous dry years. In the regions recording less than 800 mm/year (Sudan and Sahel sub-regions), the positive and statistically significant trends of rainfall amount are associated with new features of increasing frequency of short dry spell category, increasing number of some classes of extreme daily rainfall amounts and shifts in the peak number of rainy days. At sub-regional scales, the starting years (or change points) the magnitude and the signs of the new trends are unevenly distributed in the period post-1990. Earlier and higher amplitude changes are found at local scales and not less than one third of the sites in each sub-regional network are significantly affected. The extreme Southern sub-region exhibits no significant changes. Statistically significant trends are not observed on daily rain records ≤ 10 mm, onset/cessation dates, successful sowing dates, rainy season length, cropping period, medium and extreme dry spell categories. Rather, some of these factors such as the successful sowing date and the cropping season length exhibit significant variability. The onset (cessation) dates of the rainy season are followed (preceded) by extreme dry spell episodes. In the perspectives of climate impact assessments on the local agriculture a sub-regional periodic synopsis of the major rain-based factors of interest to agricultural applications are provided at the end the paper. They document some important internal variability patterns to reckon with in a multi-decadal work over the 1950–2008 period for this region.

1 Introduction

In the West African Sahel, rainfed agriculture is closely linked to food security, and changes in rain regimes need to be monitored. Most of the previous reports based on station data emphasized the overturning of rainfall anomalies from positive in the 1950s to negative after the late 1960s up to the 1990s (L'Hôte et al. 2002; Sene and Ozer 2002; Dai et al. 2004; Bell and Lamb 2006). The persistent inter-decadal patterns of these anomalies were rated as changes rather

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than variability because their differences were proven statistically significant (Bell and Lamb 2006). In the recent time, both Central (11–16° N; 10° W–0° E) and Eastern Sahel (11°N–16° N; 0–10° E) are experiencing rainfall recovery. But the Western Sahel (11–16° N; 20–10° W) is still dry (the 1990–2007 average values are equal to the 1970–1989 average values) according to Lebel and Ali (2009). Senegal, as a case study, represents approximately 80% of the total land area of the Western Sahel. The recent characteristics of the rainy seasons led to the question: Are we still under dry conditions in this part of the Sahel? Some local features observed in the daily rainfall include the persistence of flood events (which was reported to have started since the early 1990s see Sene and Ozer 2002), and more often than not above normal total seasonal rainfall is recorded at some locations in the country. These relatively new and local developments prompted this study seeking to provide local detailed update of the rainfall features from agricultural perspectives. The important questions we address are: Which component of the rainfall regime has new pattern? What are the rates, signs and scales of the new patterns? Are they significant? How the locally observed changes (if any) are perceived at sub-regional scale and vice versa? Within the time limit of the available data, what is the most recent state of matters for documentation and application in agriculture?

All rainfall related factors have important agricultural implications. For instance, the development and yield of millet, sorghum, and maize are affected by rainfall amount, onset and early cessation and seasonal distribution of rainy days and dry spells (Catherinet et al. 1963; Misra and Misra 1991; Le Houerou 1992; Sivakumar 1992; Oladipo and Kyari 1993; Sultan et al. 2005). The space-time patterns of these factors are less documented in the recent time for this region. The lack of longer and updated time series (Ozer et al. 2003; Camberlin and Diop 2003; Fall et al. 2006), and insufficient spatial coverage of some previous studies in this topic (e.g., Sane et al. 2008) could not help answer the aforementioned questions. Camberlin and Diop (2003) found a single onset/cessation dates for the whole country and noticed a decreasing trend of the length of the rainy season due to shifts in the onset/cessation dates of the first efficient rainfall over the 1950–1992 period. However, the North–south intra-seasonal rainfall gradient over Senegal is so important (Fall et al. 2006; Salack 2007) that it would not be realistic to consider a single onset date for the whole territory. Sane et al. (2008) used only the southern Casamance region data (Kolda and Velingra sites) to analyze the quality of the rainy season. These two stations are not representative of the entire Senegal, much less the Western Sahel. Some other studies such as Le Barbé et al. (2002), Ali and Lebel (2009), Lebel and Ali (2009) only provided global average information (say 5×5° square box or more) on the rainfall regime of the West African window which undermine local details.

This study takes advantage of an updated and quality controlled data set of a dense observation network to share with the scientific community valuable information for applications in climate impact assessments on agriculture at local and sub-regional scales. This is also one of the objectives of the AMMA project (The African Monsoon Multidisciplinary Analyses) (Redelsperger et al. 2006; Lebel et al. 2009). Through statistical analysis of long-term daily rain records, we provide a local versus sub-regional perceptions of the observed changes found in some rain-based parameters important for agriculture. These factors include rainfall amount and number of rainy days and types (annual and intra-seasonal), the frequency of occurrence of four categories of dry spells, onset/cessation dates, and lengths of rainy season and cropping period (timing and length) using two different agro-meteorological criteria. The main objectives are to identify, statistically rate, update and document the magnitudes, signs and starting year of the major shifts (if any) found in the historical records of these rainfall components in order to update our state of knowledge of rainfall pattern in this region. This is also an agro-climatic approach that helps lay down a strong base for model validation and impact assessments on local rainfed agricultural systems in a multi-decadal time setting.

The paper is organized as follows. The physical background of the study area, the available station data and its sampling are described in section 2. Then the estimation of the rain-based parameters and the Student's–Fisher's tests scheme (SFS) used to assess the statistical significance of the changes are exposed in section 3. The noticeable evolutions of the rain-based factors over 1970–2008 are analyzed and an updated synopsis is provided in section 4. Concluding remarks and perspectives are given in section 5.

2 Study area and data availability

2.1 Physical background of the study area

Senegal is located in the extreme West of West Africa between latitudes 12°30–16°30 N and longitudes 11°30–17°30 W. The territory covers approximately 197, 000 km^2. The topography of the country is free from steep terrain. Only a small portion of high elevation fields (altitude, >200 m above sea level) is found in the southeast border with Guinea. Shrub and tree steppes dominate the North, Savanna woodlands dominate the center and dense savanna and increasing forest are found toward the humid south (Moron et al. 2006). The atmosphere dynamic circulation over Senegal is influenced by the regional scale North/

North–East trade winds, the South/South-West humid flow called the monsoon and a minor maritime flux from the North Atlantic Ocean from the West. This flux keeps the coastal regions very humid and creates an East–West temperature gradient in the November–May dry season (Fall et al. 2006). The trade winds and the monsoon flux meet to form the continental inter-tropical convergence zone (ITCZ) which is the main evidence for the establishment of the rainy season in Senegal (Dieng et al. 2008). The large-scale dynamic factors modulating this zone of precipitation include the strength and position of the African Easterly Jet around 700–600 hPa, and Tropical Easterly Jet around the 250–100 hPa (Grist and Nicholson 2001; Nicholson 2009); African easterly waves with their associated low level deep convective vortices (Reed et al. 1977; Viltard and de Félice 1979; Diedhiou et al. 1999); and the less frequent equatorial Kelvin waves (Mounier et al. 2007; Janicot et al. 2008). The coexistence and interaction of these systems with others such as vegetation and soil types determine the dominating westward-moving convective meso-scale weather systems (Laurent et al. 1998; Gaye et al. 2005) recently addressed as disturbance lines (DLs) by Bell and Lamb (2006). Rainfall rate, associated to DLs imbedded in the large-scale atmospheric features, has an area average value around 5 mm h^{-1} (case of Dakar in 1993–1992 by Nzeukou and Sauvageot 2002). A Low spatial coherence is observed on daily mean intensity of rainfall which decreases northward from 19 to 10 mm day^{-1} according to Moron et al. (2006).

During summer period the monsoon availability influences temperature distribution which has an East–West rather than North–South gradient. The relative humidity decreases from south to north with a shallow drift towards the coastal regions. Clouds cover affects daily sunshine hours. However on the average sunshine hours are not below 6–7 h in the June–July–August (JAS) season from the North to the South (Fall et al. 2006). Considering its average rainy season length, mean temperature and land forms, Senegal falls within groups II, III, and AEZ5 classes of global Agro-Ecological zone according to the Food and Agriculture Organization (FAO 1978) and the TAC/CGIAR2 (1992)[1] criteria (see Sivakumar and Valentin (1997) for details on these classifications). These physical conditions are in favor of rainfed field crops such as millet, sorghum, maize, groundnut, cotton, and cowpea.

2.2 Data source and sampling

Observed daily rainfall data were collected from the Regional Centre for Improvement of Plants Adaptation to Drought (*Centre Régional pour l'Amélioration de l'Adaptation à la Sécheresse* (CERAAS)). The data set includes rainfall records from the network of the National Meteorological Agency (*Agence Nationale de la Météorologie du Sénégal* (ANAMS)) 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. ANAMS, ISRA/CERAAS and the Laboratory for Atmospheric and Ocean Physics (*Laboratoire de Physique de l'Atmosphère et de l'Océan-Siméon Fongang*) collaborate in multidisciplinary working teams through the AMMA project in order to improve the local/regional understanding of atmospheric processes and the application of the acquired knowledge in the adaptation of the local and regional population to drought, climate variability and long-term climate changes (this issue). The data from synoptic, climatic, agro-climatic, and pluviometric stations are assessed for quality and consistency. This was achieved through checking for erroneous values (e.g., negative precipitation); and outliers such as those above (below) a threshold of daily mean±3 standard deviations (thresholds/limits are set in terms of standard deviations from the 1950–2008 daily mean following Easterling et al. 2003; New et al. 2006). The generation of data plots enabled visual inspection. The local meteorological knowledge and experience was used in assessing outliers mostly caused by data entry typesetting errors. Considering the low density of raingauges (especially in the Central–East) and the spatial heterogeneity of daily rainfall, it is not recommended to interpolate the daily data when records are missing. Therefore, only the longest homogeneous time series, common to 83 sites (31 from 1950 to 2008 and 52 from 1987 to 2008) are retained for these analyses. The 1950–2008 station records are used in the combined Student's–Fisher's tests scheme (section 3). The 1987–2008 period of the 52 additional sites is used as back-up data to provide a space-time updates of estimated rain-based factors over Senegal (see section 4). Table 1 shows the number of sites per reference zone and the available daily rainfall records. The locations of the 83 selected sites are shown on Fig. 1. These rainfall recording stations/raingauges are unevenly distributed over the country, with the higher density found in Central–West part of Senegal, opposite to the Central–East agro-pastoral region (known as the "*Ferlo*" region).

Senegal has a relatively small land cover with stronger North–South (N–S) rainfall gradient (Fall et al. 2006; Dieng et al. 2008; Salack 2007) than the East–West (E–W) gradients seen on the Sahel at large (Lebel and Ali 2009). Sampling small sub-region with well distributed sites, for analysis of the average rainfall characteristics, can give a good image of what can be detected over the larger Western Sahel window. In the last 30 years (1979–2008), the mean

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[1] The Technical Advisory Committee of the Consultative Group on International Agricultural Research

Table 1 Daily rainfall times series and number of sites per reference zone as used in the study

Agro-climatic zone	1950–2008	1987–2008	Total
Northern zone	10	19	29
Central North zone	09	13	22
Central South zone	07	11	18
Southern zone	05	08	13
Grand total	31[a]	52[b]	83

[a] Used in the statistical significance check-up

[b] Used as back-up data to update the rainfall regime

annual rainfall ranges from ~1,200 mm in the South to 200 mm in the North (Fig. 1). According to Moron et al. (2006), spatial coherence of interannual anomalies across stations is much stronger for seasonal rainfall amount and daily occurrence frequency. But each station conveys almost independent information on the daily mean intensity. This suggests a multi-site approach to the analysis of rainfall and rainfall related agro-climatic factors, in order to reduce the uncertainties due to high spatial gradient. For this study, the country was divided into four reference zones following an annual rainfall latitudes and agricultural features criterion rather than geo-references (Longitude x Latitude coordinates). On Fig. 1, the white, light grey, grey, and black color bands stand for the Northern Zone (NZ), Central North Zone (CN), Central South zone (CS), and Southern zone (SZ), respectively. The NZ is the area above the 400 mm isohyet extending up to 200 mm isohyets. In this zone rainfed agriculture is technically not possible every year due to rainfall deficits. The CN and the CS are confined between the 400–600 mm and 600–800 mm isohyets, respectively. They globally cover the well-known "*Groundnut Basin*", an area of high groundnut, millet, sorghum, and cowpea productivity. The SZ is south of the 800 mm isohyet. It has a more secured rainfed agriculture that uses cotton, maize and long lived cultivars including rice and Sanyo. This is the only zone in which E–W rainfall variability is also important. For example at Oussoye (Ous), Ziguinchor (Zig) further South-West, annual average rainfall is above 1,100 mm over the 1979–2008 period as compared with Kold, Velingara Casamance (Vel Cas) where annual records are below 1,000 mm.

These rainfall latitudes are relatively thin bands having a ~200–300 mm/annum intra-zonal gradient. Therefore, a well-spread site sampling along the longitude (as seen on Fig. 1) can help capture the spatial rainfall variability within each reference zone (sub-region, henceforth). The present agro-climatic zonation is very close to the natural zones of the country (Moron et al. 2006). Although this method of zonation is not sufficient for assign crop potentials as a general approach according to Sivakumar and Valentin (1997). But in the specific case of Senegal an ensemble of background factors is in favor of this approach. Most of these background factors are physical, as already stated (section 2.1) and others are related to the rain regime itself: (a) spatial coherence of rainfall at the seasonal time scale shown by previous studies (e.g., Moron et al. 2006); (b) the seasonal average potential evapotranspiration rate is approximately 5–7 mm day^{-1} in JAS (Salack et al. personal communication, 2009a, 2009b). As a result, the average

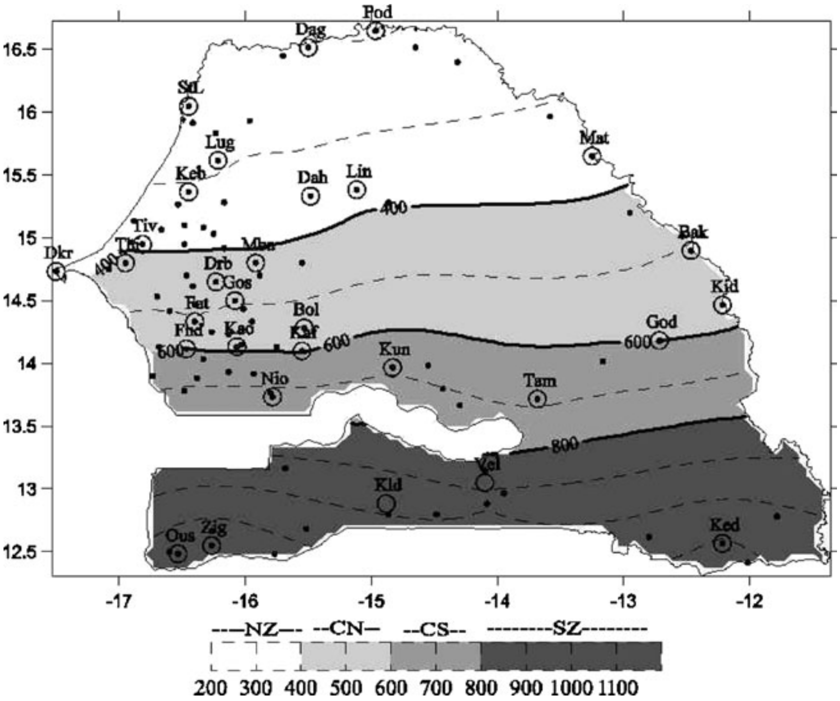


Fig. 1 Stations location, rainfall climatology, and reference rainfall zones. The *circles* identify the sites with longer daily records (1950–2008) and full dots are the set of sites with 1987–2008 daily records. The Isohyets are based on the 1979–2008 period (*dashed lines*) and the main rain bands represent the reference agro-climatic zones. The *white*, *light grey*, *grey*, and *black* color bands stand for the Northern zone (*NZ*), Central North zone (*CN*), Central South zone (*CS*), and Southern zone (*SZ*) respectively

ratio of 10-day rainfall to the potential evapotranspiration is hardly less than the threshold for crop water satisfaction, i.e., 0.33 (Cochemé and Franquin 1967); (c) All short term isohyets mapped for the country (set of maps issued before this analyses are done) have shown no major spatial shifts on the main period of interest (1970–2008). For example, maps of mean annual rainfall were issued for 1970–2008, 1970–1989, 1979–2008, 1961–1990, 1991–2008, and 2000–2008. Their inter-comparison did not show major spatial drift of isohyets. However there is a clear southward drift of the 1950–1969 isohyets compared with the recent years within the 1970–2008 time interval.

2.3 Determination of rain-based parameters

2.3.1 Rain days and amount

The rainfall total needed for a day to be classified as a rainy day (RR) is fundamental to determine the dates of onset of rainy season, cessation, and dry spells (Stern et al. 2006; Segele and Lamb 2005). The amount used has been in the range greater or equal to 1.0 mm/day, in agricultural applications (Sivakumar 1992). This threshold is also used here to define a RR. The seasonal total number of rainy days (RD), the number of RR records ≤10 mm day^{-1} (RD10), the number of RR records ≥50 mm day^{-1} (RD50) and other thresholds are extracted on yearly basis from the first to the last record in the time series (they include $10<\text{RR}\leq 20$, $20<\text{RR}\leq 30$, $30<\text{RR}\leq 40$, and $40<\text{RR}<50$). Our interest in knowing their spatial distribution and historical patterns is indeed agronomic, but also resides in the fact that the frequency of extreme events has increased in some parts of West Africa (News et al. 2006) and may become severe in the nearest future climate according to the IPCC (2007) report. Likewise, the recurring flood events from the late 1990s (Sene and Ozer 2002) until nowadays draw our attention towards soil erosion and crop devastation. The seasonal cycle of rainfall is studied using a 5-day cumulated rainfall following Dieng et al. (2008). The annual total rainfall (AR) and 10-day (5-day) seasonal cumulated rainfall (DR) are computed by simple arithmetic summing of daily RR irrespective of threshold value. The values of AR, DR, 5-day, RD, RD10, RD50, and other classes of rainfall amounts from individual sites are area averaged to define the areal values (AAV) for each reference sub-region (cf. NZ, CN, CS, and SZ). The analyses are carried out with more emphasis on the rainy season period discussed below.

2.3.2 Onsets/cessation and seasons' lengths

The onset of the monsoon system over West Africa and precipitation regime in Senegal are linked to the northward migration of the ITCZ and the associated westward-moving disturbance lines (DL) during summer time (Sultan et al. 2005; Bell and Lamb 2006; Nicholson 2009; Fall et al. 2006; Dieng et al. 2008). On the average, the rainy season lasts from May to October. It begins in the South/South–East and spreads north in conjunction with the latitudinal migration of the ITCZ, bringing monsoonal moisture from the Gulf of Guinea; 99% of the seasonal rainfall total is found in this 6-month intra-seasonal period with 30–42% of the rainfall amount are recorded in the only month of August. Potential onset/cessation dates are bound to this period of the year (Gueye and Sivakumar 1992; Camberlin and Diop 2003).

Two agro-meteorological criteria are used to determine onset and cessation dates. The first method was established from empirical study on millet at the International Crop Research Institute for Semi-Arid Tropics for some Sudanian and Sahelian stations. It was applied to a large part of the Senegal, Niger, Mali, Burkina Faso rainfall networks (Sivakumar 1988, 1992; Gueye and Sivakumar 1992; Ozer et al. 2005; Balme et al. 2004 among others). With this method, the sowing date (CS_a) is that date after 01 May when rainfall cumulated over 3 consecutive days is at least 20 mm and when dry spell, within the following 30 days, does not exceed 7 days. The cessation date (CE) is the day after the 01 of September when no rainfall is recorded for 20 consecutive days. It is a site-by-site approach that associates water availability and stress factors such as dry spell, classically known as the "*Sivakumar method*". In this study, this method is referred to as the "Successful Sowing Date". The cropping season (CL_a) is computed by subtracting CS_a from CE. The second is also a classical rainfall-based criterion used by the Famine and Early Warning System (FEWS) given in AGRHYMET (1996) and also used by Hachigonta et al. (2008) for maize applications in Zambia. The first dekad (10-day period) should have a total rainfall of 25 mm and this should be followed by two dekads with a total of at least 20 mm of rain. The onset date is then taken as the first day of the first dekad. The CE of this method is taken as the same as in the *Sivakumar method*. This method (*Agrhymet-FEWS* method) exhibits a strong spatial coherence of rainfall occurrence per zone (Salack et al. personal communication, 2009a). Henceforth, it is taken as the method of "Onset of Rainy Season" (CS_b). The length of rainy season (CL_b) is obtained by subtracting CE from CS_b. The quality of CL_b is more or less dependent on the intra-seasonal distribution of dry spells as discussed in the next subsection.

2.3.3 Dry spells

Dry spells (DSs) are the dominating adverse factors affecting crops development and production in the intra-seasonal time scale. They may occur at the vegetative or reproductive phase of crops leading to a tremendous loss in the seasonal yield of millet, sorghum, maize and groundnut the basic food and cash crops.

A preliminary task, when looking at DS, is to define a "*dry day*". In this analysis a day is considered DD at site level, when the daily rainfall amount is less than 1 mm. The sum of consecutive *dry days* between two rainy days is referred to as a DS or dry episode (Sivakumar 1992; Lanà et al. 2008; Salack et al. personal communication, 2009b). The number of DSs, at individual sites is estimated from the onset of the CS_b to the CE. All DS types found are classified in ascending order, according to their frequency of occurrence and potential threats they cause to rainfed millet, sorghum and maize. The 1–7 days (DS1) class is the short category. It has the highest average seasonal frequency of occurrence and contains about 60% of 1–3 days sub-class (Sane et al. 2008; Salack et al. 2009b). The distribution of DS1 is a proxy to rainfall occurrence especially in the northern regions, because it is correlated to high frequency of rainfall events. The class of DS1 is followed by the 8–14 days category (DS2). This is the medium type of DS in this region. 15–21 days (DS3) and more than 21 days (DS4), make the third and fourth categories respectively. They are the main sources of water stress to rainfed crops. The seasonal mean frequency of each category of DS, at individual sites, is area averaged to obtain the sub-regional values for each zone (cf. NZ, CN, CS, and SZ zones).

3 Statistical algorithm for magnitude, sign and start of observed changes

What is the most pertinent scale to consider for an agro-climatic investigation of changes: individual station data (local) or AAV? Figure 2 illustrates the seamless discrepancy that usually appears in issues related to rainfall analyses. A standardized precipitation anomaly index (SPI) is computed with respect to the 1950–2008 period (upper panels) and 1979–2008 (lower panels) for Central Senegal (including both central north and central south reference zones) and Bambey (a site in the local network). Looking at the 9-year moving average centered on the 5th (grey thick line), there are different perceptions of the recovery at local and sub-regional scales. This is imputable to the sensitivity of the SPI to both the number of stations used to compute it, their locations and the reference period considered (Ali and Lebel 2009). Although, many versions of the SPI were given and extensively used to describe rainfall (Nicholson 1983; Katz and Glantz 1986; Dai et al. 2004; Ali and Lebel 2009), none of them can alone describe the rainfall pattern of the Sahel (Moron et al. 2006). Nevertheless, Fig. 2 helps show that the characteristics of the rainfall anomalies depend on both time and space scales. Are there abrupt and significant changes in the rainfall regime? What are their magnitudes and time of start? What are the scale issues related to these changes? Do they concern other features of the rainy season that influence agriculture? To answer these questions, the SPI can only be an indicator and more often climate impact assessment studies use raw station data (rainfall, temperature, etc.) rather than the SPI. It is, therefore, necessary to assess the internal structure of the true values of both local (individual sites) and AAV of smaller areas that could be considered climatologically homogenous using statistical tests (Sene and Ozer 2002). The following statistical assessments are based on the site sampling and zonation discussed in section 2.2.

We use a scheme that combines the Fisher Snedecor (*F* test) for variability, the Student's (*t* test) for trend detection and a simple relative percent difference estimate for magnitude and sign (Student's–Fisher's tests scheme or SFS, henceforth) on station/raingauge data (Local) and zonal AAV. The scheme was applied on the annual and 10-day cumulated rainfall (AR and DR), the total number of rainy days (RD), the number of daily rain records ≤10 and ≥50 mm (RD10 and RD50), dates of onsets of seasons (CS_a and CS_b), CE, the cropping period durations (CL_a and CL_b), and the annual frequency of the four categories of dry spell (DS1, DS2, DS3, and DS4) as defined earlier. Previous studies of this type used the Pettit test and focused only on rainfall amount (Ozer et al. 2003; Ozer et al. 2005). However it has been demonstrated by Yue and Pilon (2004) that the Student's *t* test has the highest power in trend detection as compared with other tests. This same parametric test was used by Bell and Lamb (2006) to investigate the significance of the inter-decadal differences of rainfall amount over the 1950–1987. Lebel and Ali (2009) also used it to investigate the level of significance of the difference between the Western and Eastern Sahel rainfall index. Details on these tests and their application in meteorology and hydrology can be taken from Der Megreditchian (1992) and Hirsch et al. (1993). We use the word "change" in this study for any 11–38 years trend that is statistically rated as significant by the SFS.

The pre-requisites in the use of the SFS are described in the following ways. The 1950–2008 period is subjected to the Lilliefors test for normality, which is a modification of the Kolomogorov–Smirnov test of goodness of fit (Lilliefors 1967; Abdi and Molin 2007). Where the normality test is not accepted, the Box–Cox (1964) method of normalization is used. An example of the results of this test is given in Table 2. Then the sample is fragmented into three sub-periods (P1, P2, and P3, respectively). The 1950–1969 period (P1), which appears uniformly humid (i.e., positive anomalies, see Fig. 2) all over the 31 sites, is separated from the 1970–2008 period. It is also defined as

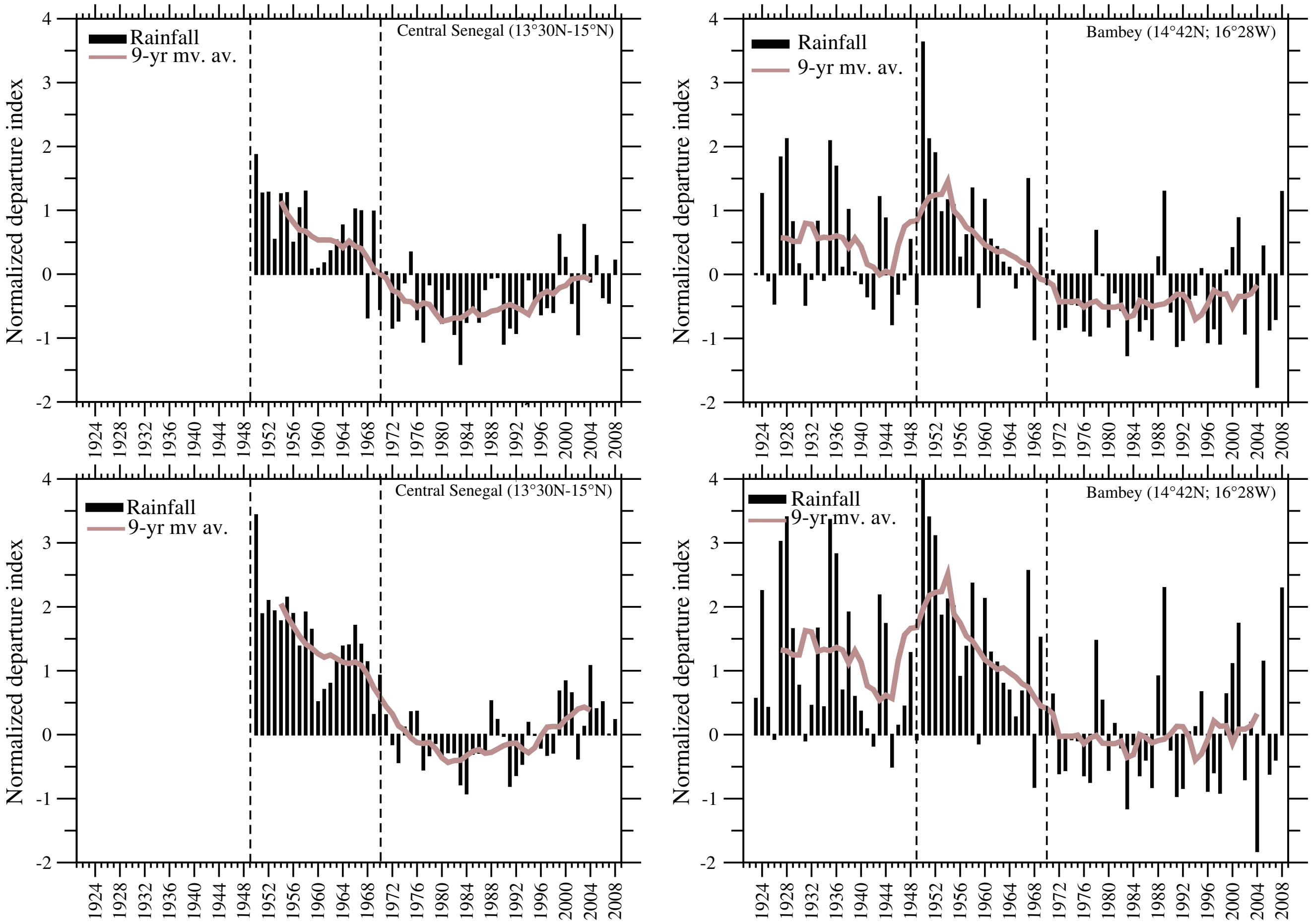


Fig. 2 Area average (Central Senegal) and local (Bambey) standardized precipitation anomalies index (SPI according to Katz and Glantz 1986; Moron et al. 2006) relative to 50–2008 mean (*top panels*) and 1979–2008 mean (*bottom panels*). The vertical dash lines define the humid period of reference 1950–1969

humid in other parts of the Sahel according to Lebel and Ali (2009). P1 stands for the *standard* period. The two other sub-periods P2 and P3 are found by means of a systematic checkup for statistical significance over 1970–2008.

From the assumption that the limits of P2 and P3 are not known over 1970–2008. We therefore consider two independent intervals P_{sty} and $P_{\mathrm{sty}-1}$. The interval P_{sty}=[starting year (STY), 2008] (with a mean$\overline{P}_{\mathrm{sty}}$a variance σ^2_{sty} and length n_1) is compared with $P_{\mathrm{sty}-1}$=[1970, (STY−1)] (with a mean $\overline{P}_{\mathrm{sty}-1}$variance $\sigma^2_{\mathrm{sty}-1}$ and length n_2). The value STY (STY−1) is the upper (lower) bound of the interval, denoting the starting (ending) year of P_{sty} ($P_{\mathrm{sty}-1}$). We continue the

Table 2 Some results of the Lilliefors test for normality (α=5%) of the 1950–2008 time series

Parameter	Northern zone		Central North zone		Central South zone		Southern zone	
	D	*p* value	D	*p* value	D	*p* value	D	*p* value
Rain	0.11	0.73	0.17	0.22	0.16	0.29	0.16	0.26
Rainy days	0.09	0.89	0.10	0.87	0.09	0.90	0.06	0.99
Onset/rainy seas	0.09	0.91	0.08	0.95	0.11	0.76	0.12	0.64
Sowing date	0.07	0.98	0.10	0.88	0.10	0.86	0.11	0.68
Length of seas	0.14	0.45	0.13	0.53	0.11	0.76	0.11	0.72
Cropping seas	0.10	0.87	0.14	0.44	0.11	0.72	0.14	0.39
Cessation date	0.15	0.36	0.21	0.07	0.18	0.17	0.25	0.02[a]
Short dry spells (1–7 days)	0.08	0.95	0.12	0.65	0.09	0.90	0.08	0.95

[a] normalized parameter using Box-Cox (1964) method

comparison by increasing (decreasing) STY by 1 over 1988–1999. But, is the interannual variability between P_{sty} and $P_{\mathrm{sty}-1}$ homogeneous? The reason for this question is that statistical analyses on raw climate data can overwhelm substantial variability within mean term scale (Ward 1998). In order to answer this question, we use a bilateral *F* test under the hypothesis that it is an alternative and strong complementary condition to a bilateral *t* test. The aim of this approach is to explicitly rate the internal homogeneity of variances of the two independent sub-periods (cf. P_{sty} and $P_{\mathrm{sty}-1}$) prior to trend detection in each comparison. The null hypothesis of the *F* test is input to the null hypothesis of the homoscedastic Student's *t* test on local and AAV. This condition is only relaxed for local values where the null hypothesis of the *F* test is not *accepted* (i.e., sample variances not equal). In such case, an unequal variances *t* test is applied.

The SFS works in the following steps. On the first, it tests the equality of variances σ^2_{sty} and $\sigma^2_{\mathrm{sty}-1}$ using the *F* test (ratio of σ^2_{sty} to $\sigma^2_{\mathrm{sty}-1}$) as stated earlier. The success of this test implies, hypothetically, that the interannual variability between periods P_{sty} and $P_{\mathrm{sty}-1}$ can be assumed homogeneous. On the second step, if the hypothesis of equal variances is accepted at a 95% confidence level, the scheme compares the mean value $\overline{P}_{\mathrm{sty}}$ to $\overline{P}_{\mathrm{sty}-1}$using a bilateral t_{sty} (Equation 1).

$$t_{\mathrm{sty}} = \frac{\overline{P}_{\mathrm{sty}} - \overline{P}_{\mathrm{sty}-1}}{\sqrt{\frac{\sum_{j=0}^{n_1-1}\left(P_{\mathrm{sty}}-\overline{P}_{\mathrm{sty}}\right)^2+\sum_{j=0}^{n_2-1}\left(P_{\mathrm{sty}-1}-\overline{P}_{\mathrm{sty}-1}\right)^2}{n_1+n_2-2}\cdot\left(\frac{1}{n_1}+\frac{1}{n_2}\right)}} \tag{1}$$

The SFS compares systematically the samples P_{sty} and $P_{\mathrm{sty}-1}$ through their variances and mean values by sequentially varying STY from 1988 to 1999. Each time the two sample periods remain independent. The degrees of freedom (d1 and d2) of the *F* test vary in opposite sense and the degree of freedom of the bilateral *t* test is always constant (df=37). An output of the scheme is a probability value p_{sty} ($T \le t$) associated to the t_{sty} statistics. The difference of the sub-periods P_{sty} and $P_{\mathrm{sty}-1}$ is significant, if $p_{\mathrm{sty}} \le 0.05$ (α=5%). When a significant probability is achieved, the scheme computes the corresponding relative percent difference ($\mathrm{RPD}_{\mathrm{sty}}$) (Eq. 2).

$$\mathrm{RPD}_{\mathrm{sty}} = \left(\frac{\overline{P}_{\mathrm{sty}} - \overline{P}_{\mathrm{sty}-1}}{\overline{P}_{\mathrm{sty}-1}}\right) \times 100 \tag{2}$$

This is a quantitative indicator of the difference between the two means resulting from the tendency. Dividing the difference by $\overline{P}_{\mathrm{sty}-1}$ insures that the rate of change in the recent period is weighted with respect to the previous period. The magnitude and the sign of the changes are given by the $\mathrm{RPD}_{\mathrm{sty}}$. The absolute value of the $\mathrm{RPD}_{\mathrm{sty}}$ is the magnitude and its negative or positive sign denotes the increase or decrease of the observed changes at each significant probability. If no significant probability is found at the end of the diagnostic period (1988–1999) then $\mathrm{RPD}_{\mathrm{sty}}$ is not available (NA). Alternatively, RPD is computed instead by comparing 1970–2008 to 1950–1969 period using the same Eq. 2. A STY is considered as a change point i.e. the starting year of significant change, if and only if the *p* value of the period starting from that year is significantly different from the previous period and the significance persists till the end of the statistical check-up. At each STY, the scheme also computes the proportion of significant *p* values at local scale. This is given as the fraction of the number of *p* values ≤0.05 at individual sites to the total number of the sites in the zone. This ratio (p_{local}) is seen here as the empirical relationship between the large (sub-regional) and small (local) scales.

Some sensitivity assessments are also included in the SFS to account for the effect of local variability on the AAV. For example, if the *F* test *is rejected* at a site (i.e., null hypothesis is not accepted), the values of the rain-based factor of that site are removed from the AAV. Another AAV is computed and tested. Afterward, if the second results of the SFS on the AAV are still unaffected (especially if the statistical significance is unchanged) then this case is considered as a trivial internal variability inherent to that particular site. At such site, the unequal variance *t* test is used to rate the local trend. This situation is only encountered at particular sites such as Dakar (for its land-ocean interface), Kaffrine, and Boulel (transition sites between the CN and the CS). The total statistical parameters resulting from the whole process of the Student's–Fisher's tests scheme include: the STY, the fraction or ratio of p_{sty} at local and the *p* values of zonal scales ($\mathrm{p}_{\mathrm{local}}$ and $\mathrm{p}_{\mathrm{AAV}}$ respectively), the relative differences ($\mathrm{RPD}_{\mathrm{sty}}$ or RPD). The results of this statistical assessments are discussed in the section below.

4 Is there any noticeable evolution of the rain-based agro-climatic factors from 1970 to 2008?

4.1 Rainfall amounts

The evolution of the interannual rainfall total (AR) has been debated over time. Especially the issue of recovery or no recovery has been a subject of controversy between groups of authors (L'Hôte et al. 2002 and Ozer et al. 2003). Later, supporting arguments of *modest* recovery were given by Nicholson (2005) and Bell and Lamb (2006). Following the recent findings over the larger domain of the Western Sahel on this issue (Ali and Lebel 2009; Lebel and Ali 2009), details about Senegal are hereby provided. This is a contribution to complement the previous studies and update our state of knowledge about the pattern of rainfall amounts in this part of the Sahel.

Figure 3 is an example of the results from the aforementioned Student's–Fisher's tests scheme, applied for significance check-up between the years 1988 to 1999 on AR. The evolution patterns of AR are unevenly distributed over Senegal. In the northern zone (NZ), the AAV results show that the test is significant starting from 1995. In the central north zone (CN) significant test is found from 1992 and in the Central South zone (CS) from 1998 (ensemble Fig. 3a). This statistical characteristic persisted over the following years till the end of the diagnostics. At local scale, about 2:5 (40%) sites reported significant probability (p_{local}) in the NZ, but the STYs are different. Hence at Kebemer the STY is 1988, at Matam it is 1992, at Podor and Saint-Louis it is 1993 (Table 4). From 1992 in the CN, only a ratio of 1:3 (33%) sites reported significant tests. The persistent significance of $\mathrm{p_{AAV}}$, up to 1999, is followed by an increasing proportion of significant p_{local} from 40% to 60%. This means that more than half of the observation network in the zone is affected (Fig. 3b). Exceptionally, stations such as Bakel and Boulel showed significant probabilities as early as 1988 persistently. From 1998, the CS shows significant $\mathrm{p_{AAV}}$. This is followed by a ratio of 2:3 (65%) significant local probabilities ($\mathrm{p_{local}}$) (Fig. 3c). The sites at which the change points (the starting years) were found earlier than 1998 include Foundougne (1995), Kaffrine and Nioro Du Rip (1997). In the SZ, no significant $\mathrm{p_{AAV}}$ was reported by the Student's–Fisher's tests scheme. However, at local scale Kolda reported significant probabilities since 1988 and Zig from 1997. This corresponds to 22% of the local network (Fig. 3d).

From the above analysis, we can say that the forenamed STYs mark the beginning of noticeable recovery of the annual total rainfall amount (AR) at local and sub-regional scales. The recovery is persistent throughout the years after 1990. This is particularly observed in the regions which annual records are less than 800 mm/year (CS, CN, and

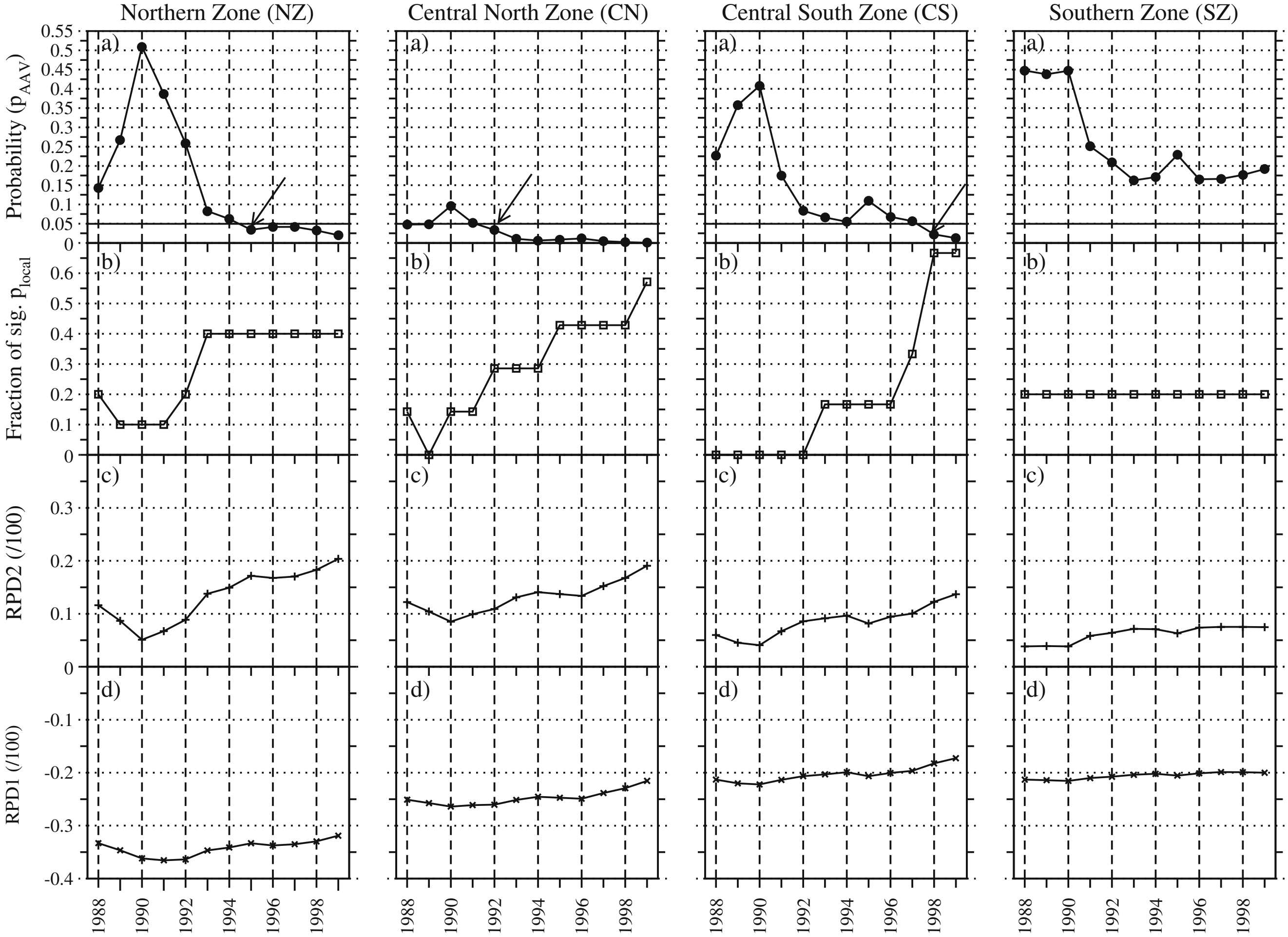


Fig. 3 Results of the Student's–Fisher's tests scheme for annual rainfall amount. **a** Probability of area average values (p_{AAV}); **b** fraction of significant probability at local scale (p_{local}); **c** relative difference between the recovery period and the previous dry period (*RPD2*); **d** relative difference between the recovery period and the humid 1950–1969 period (*RPD1*) at each sub-region in Senegal. Error of the first type, α, is indicated by the *bottom line* on the **a** line figures (*top panel*). Periods of significant probability are indicated by the *arrow*. They mark the starting year of the recovery period

NZ). These sub-regions are under the classical umbrella of Sudan–Sahel and Sahel regions of the country. Although, the zonal AAV did not markedly show abrupt shift for the SZ sub-region. This can be justified by the small number of stations used in the check-up (five sites). It is a potential source of uncertainty in the results for the sub-region. Although these sites are well spread to capture the spatial variability in the zone, the computation of the AAV for SZ may be influenced by individual site differences. For instance exceptional local cases are found for Kolda and Ziguinchor (Table 3).

The percent differences between the recovery period and the humid 1950–1969 period (RPD1), and the dry period (RPD2) also vary per zone (see the ensemble Fig. 3b). From the starting years, the signs of the changes are all negative for RPD1 (P1 vs P3) and positive for RPD2 (P2 vs P3, Fig. 3d). In the NZ zone the rate of the significant changes over the last period (1995–2008) is +17%. In the CN zone the rate of the significant changes observed over 1992–2008 is +10%. In the CS the rate of the significant changes observed over the 1998–2008 period is +12%. The magnitudes are still increasing towards the beginning of the 2000 s. These positive changes are found with respect to the dry periods, on the area average values (sub-regional scales), and they are statistically significant. They are rated as significant recovery. At local scale, the rates are higher in magnitude (+16 to +32%). This is detailed on Table 3. Sometime, the relatively small perceptions of the changes on the areal values hide greater cases at some individual sites. Therefore aggregated or area average values tend to hide important local patterns (Baron et al. 2005). On the other hand, we can say that short term changes, which absolute value is less than 10%, are not significant. This was the case of all other local and AAV which RDP_{sty} are not associated with significant probabilities in the SFS. Countrywide updated details of this type may not be found in the literature for Senegal. But the general argument of local recovery of rainfall amount (AR) is, hereby, supported and evidence is established. Similar results were also given by Ozer et al. (2003). Even though actual AR values are below the 1950–1969 period's as already pointed out by Lebel and Ali (2009), the magnitude of some local changes exceeds both the humid and dry years. Other results of this type were found by New et al. (2006) at other locations in West Africa and Frappart et al. (2009) for the Gourma region in the Central Sahel. In the recovery time interval, the intra-seasonal 10-day (dekad) cumulated rainfall (DR) shows higher peaks. From the 1st dekad of August (DR21) to the 2nd of September (DR26) DR outweighs the previous dry period in the NZ, CN, and CS zones. The difference between their means is statistically significant according to a classical *t test*. However, average DR is lower than that of humid period, P1 (1950–1969) in the NZ and approximately equal to it in the CN and CS. In the SZ, the average of DR, is not statistically different from the dry period but the single peak value of DR22 (2nd dekad of August) is equal that of P1. This implies that the maximum rainfall amount is observed in the 2nd dekad of August (not shown).

To describe the seasonal cycles of rainfall, the 5-day cumulated rainfall of individual sites in each zone (10, 09, 07, and 05 sites in NZ, CN, CS, and SZ respectively) was area averaged and smoothed (3-point centered running mean) for each reference period. The smoothed signals are presented on Fig. 4 to depict the differences in between the zonal areal signals and the difference in between the reference periods over Senegal (cf. P1, P2, and P3). As for the seasonal cycle of 5-day rainfall (just like the 10-day rainfall), two opinions are to be made. In the Sudan and Sahel regions of the country (where annual total rainfall is less than 800 mm), the description is similar to that given by Lebel and Ali (2009) for the Sahel as depicted by Fig. 4a–c. The first break (appearing as a plateau on the graphs) around 10 July corresponds to the monsoon jump

Table 3 Output of the Student's–Fisher's tests scheme on total rainfall amount (1950–2008)

Sub-region	STY on AAV	AAV RPD1 (%)	AAV RPD2 (%)	AAV RPD[a] (70-08/50-69) (%)	Ratio of sig. p_{local}	Significantly affected sites (STY, RPD1, and RPD2)
NZ	1995	−32	+17	NA	2:5	Keb (1988, −29 and +28); Mat (1992, −22 and +26) Pod and StL (1993, −20 and +32)
CN	1992	−25	+10	NA	1:3	Bak and Bol (1988, −17 and +23)
CS	1998	−19	+12	NA	2:3	Kaf and NiR (1997, −16 and +16); Fnd (1995, −21 and +22)
SZ	NA	NA	NA	−23	2:9	Kld (1988, −23 and +5) Zig (1997, −16 and +16)

STY starting year of recovery, *AAV* area average value, *NZ* Northern zone, *CN* Central North, *CS* Central South, *SZ* Southern zone

[a] STY is not available (NA), and the RPD is statistically significant

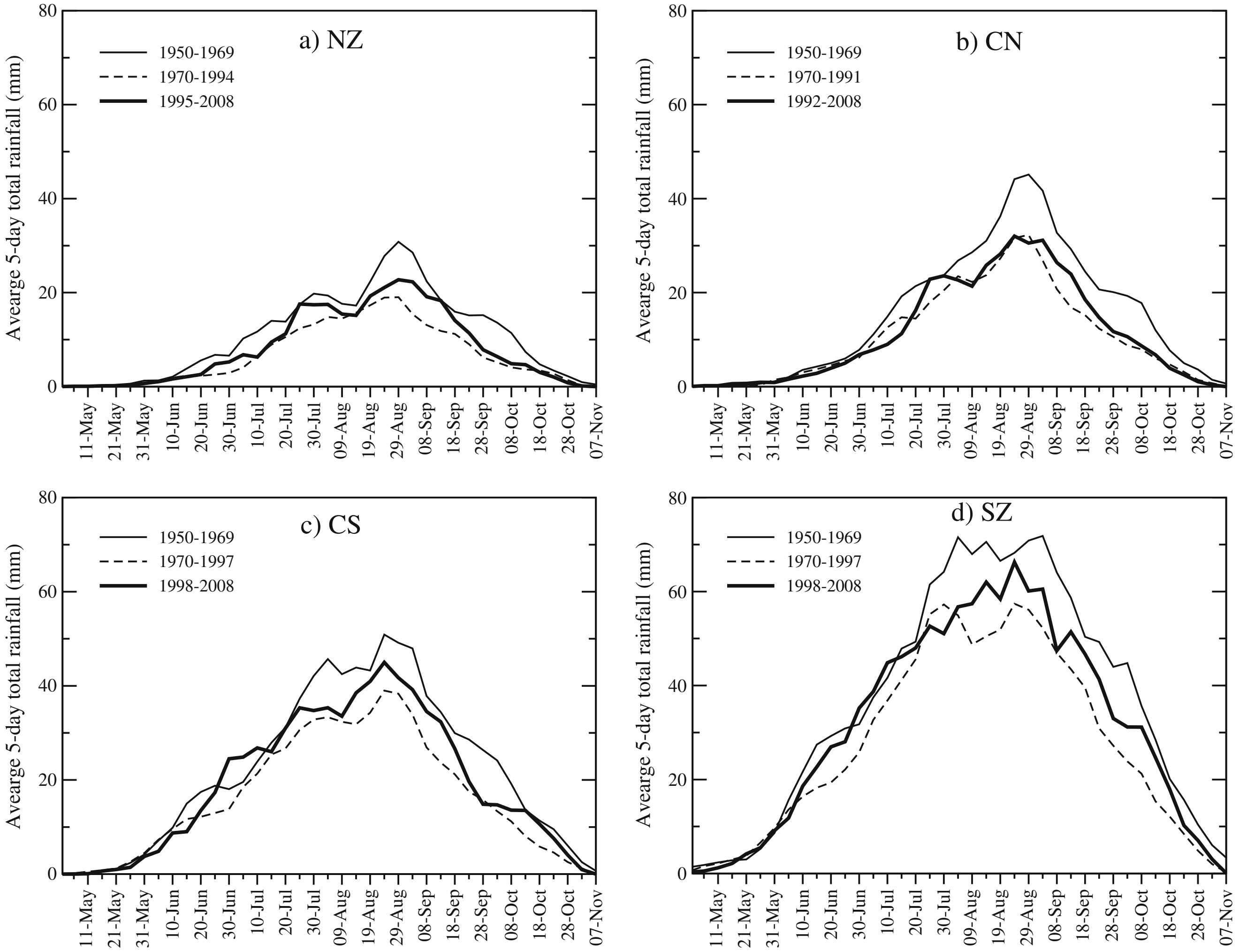


Fig. 4 A three-pt centered running mean of the average 5-day cumulated rainfall per zone over Senegal. An inter-comparison of the major periods and the reference zones. The peak of the rainy season experiences most of the increase in 5-day cumulated rainfall. The monsoon breaks (Sultan and Janicot 2004; Dieng et al. 2008) are clearly shown by the NZ, CN, and CS zones

(Sultan and Janicot 2004). The second break seen around 9 August is referred to as the monsoon dry spell (Dieng et al. 2008). It is a period of reduced rainfall intensity preceding the active phase of the monsoon in these regions. These two breaks are well pronounced in the recent recovery period. However, in the extreme south (SZ) where annual rainfall is above 800 mm (north Guinean rainfall-type regions of the country), the timing of the 5-day rainfall is as early May and lasts up to early November (Fig. 4d). The breaks (the monsoon jump and the monsoon dry spells) are missing in the last decade (1998–2008) just like in the humid period (1950–1969). Only a break in the early August is found in the 1970–1997 period (dry period). Although in this zone, no statistically significant change was found on areal rainfall values but the weak or absence of the major break of July is a key point to notify. The monsoon jump is very weak or quasi-inexistent in the extreme southern part of the country. This is justified by the fact that in summer, the settlement of the monsoon flux over Senegal starts from the SZ sub-region with a South/South–East progression toward the north of the country and majority of the meso-scale convective systems responsible for rainfall in the sub-region originate from the Fouta-Djalon mountains further south in the Guinean country.

4.2 Rainy days and dry spells

Particular results found on the number of rainy days (RD), the number of rain days of 50 mm or more (RD50) and dry spells DS1 are summarized in Table 5. Significant probabilities are also unevenly observed in the NZ, CN and the CS sub-regions. The periods usually include the sub-periods in which AR has shown some recovery. RPD1 is decreasing and RPD2 is increasing from the first year of recovery (STY) to the end of statistical checkup. The increase of RD with respect to the dry period shown by

RPD2 in the NZ is supported by its intra-seasonal distribution. It is seen on Fig. 5 that the mean 10-day cumulated number of rainy days of 1995–2008 (P3) is above that of 1970–1994 (P2) but is less than that of 1950–1969 period (P1). When subjected to a classical Student's *t* test, the DR21–DR26 mean of P3 is significantly greater than that of P1. In the CN and the CS, the case is a little different. Both the intraseasonal (DR21–DR26) average of RD and RD50 are greater than the P2 period and statistically significant. In the SZ, no changes are found in both seasonal and intra-seasonal cycles of RD and RD50. Other important finding includes the shift in the position of the peak frequency of RDs from the 25th dekad in the 1950–1969 period back to the 24th dekad (2nd dekad of August) in the recent periods. This peak coincides with the shift in the peak of rainfall amount unveiled by Lebel and Ali (2009) for the Western Sahel.

The average number of some seasonal threshold classes of daily rainfall values has also changed (Fig. 6). It appears there that the number of high daily rainfall values has increased in the Sudan–Sahel and Sahel regions of the country. Evidence can be taken from the results of a classical Student's *t* test shown on Table 4. They are derived from a comparison between the periods of recovery and the periods of drought, suggesting the "*return*" of some high daily cumulated rainfall. The frequency of occurrence of short dry spell category has also increased. In fact, DS1 (1–7 days) is +40% of P2 (against −45% with respect to P1). As stated earlier, the short dry spell category is dominated at ~60% by the 1–3 days sub-class. The rate of prevalence of 1–3 days dry spells in the northern regions is lesser compared with the southern regions (Sane et al. 2008; Salack et al. 2009a, 2009b) due to the difference in rainfall frequency in those regions. An increase in DS1 category of dry spells in the northern regions is synonymous to increase in rainfall frequency. Therefore the increase in annual rainfall amount is explained by the increase of both the frequency and amounts of rainfall. The

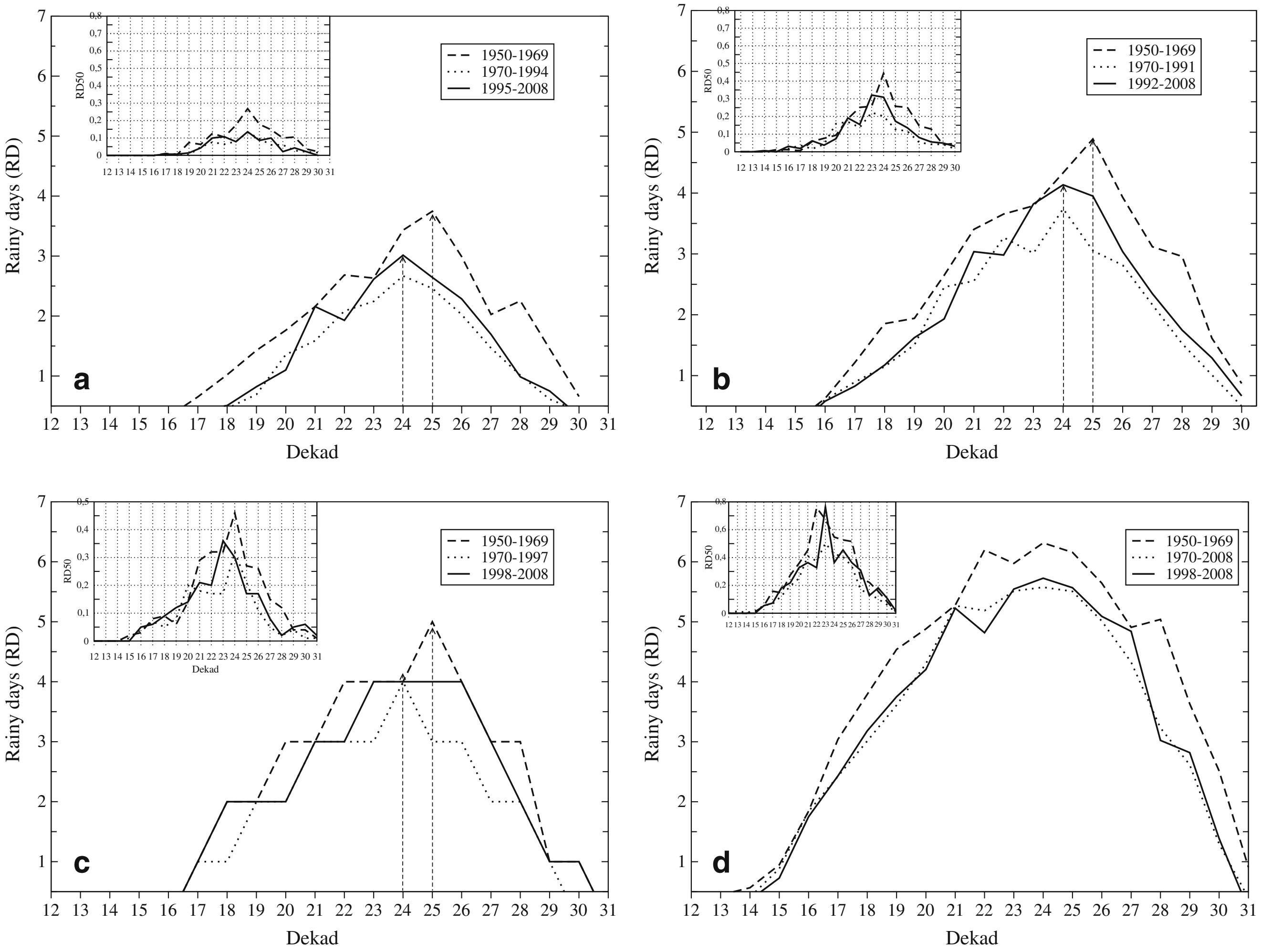


Fig. 5 Average 10-day (dekad) cumulated number of rainy days in the reference rainfall zones. The windows depict the average number of rainy days having rainfall ≥50 mm/day in the NZ (**a**), CN (**b**), CS (**c**), and SZ (**d**)

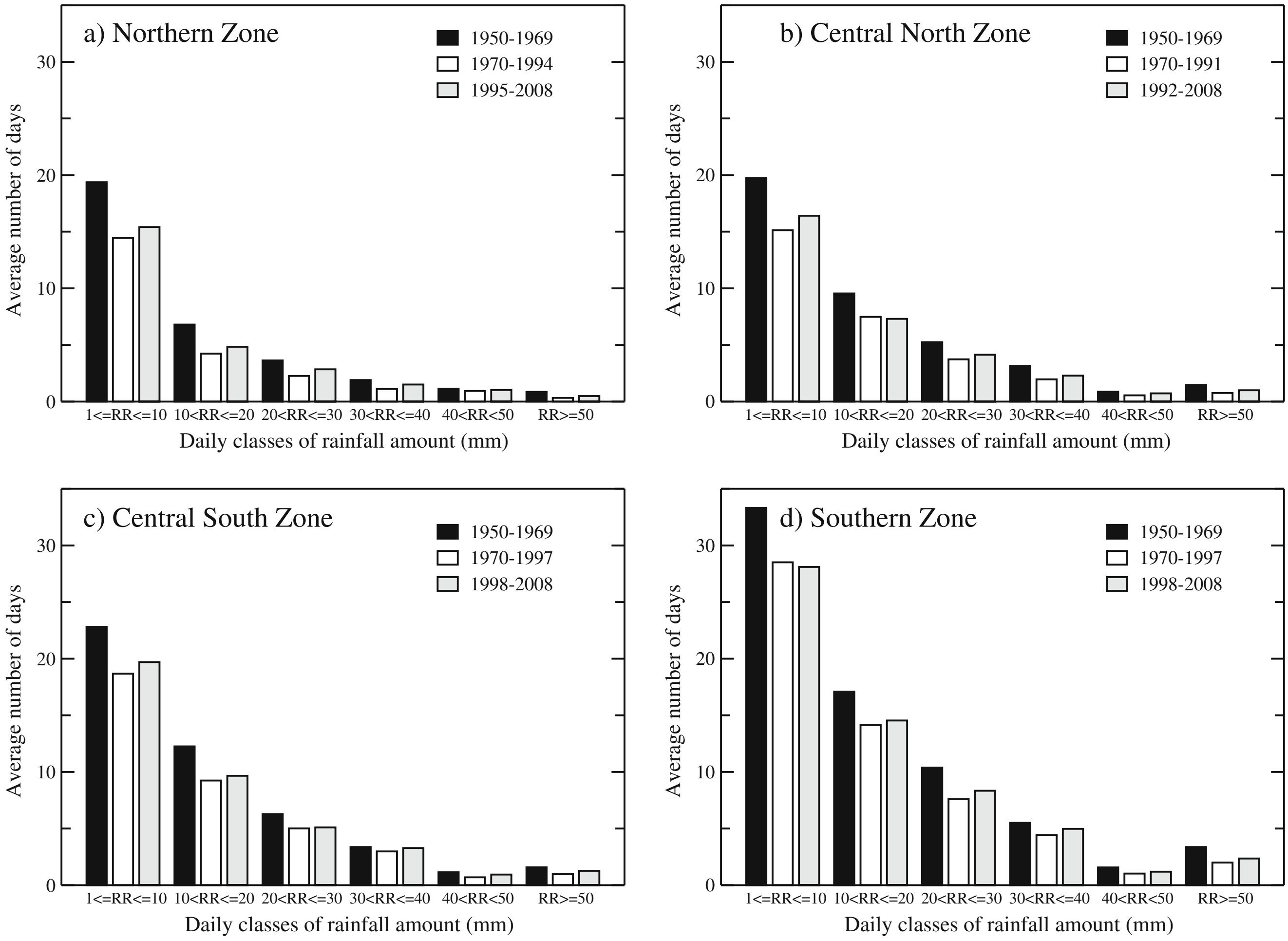


Fig. 6 Average seasonal number of daily classes of rainfall amounts. An inter-comparison of the humid (*black*), dry (*white*), and recovery (*grey*) periods per reference zone in Senegal. The *p* values are given in Table 4

other categories of dry spells such as DS2 (8–14 days), DS3 (15–21 days), and DS4 (>21 days) have shown no significant changes in the short term assessments considering the periods post-1990. Only significant F-test results were found, especially at local scales, suggesting high variability. However, DS2 and DS4 tend to show abrupt shifts in the long term assessment of the 1970–2008 time series (Table 5).

4.3 Onset/cessation and seasons' length

Onset of CS_b, successful CS_a, CE, CL_b, and cropping season length (CL_a) are the most stable factors in the short term statistical assessments (Table 6). On the zonal AAV, no significant changes are observed in the period post-1990 using the Student's–Fisher's tests scheme. Therefore RPD1 and RPD2 are NA. A further assessment considering the entire 1970–2008 period with respect to the 1950–1969 period (P1) reveals different rates of abrupt shifts. The results of the percent rates are directly converted into "days" for easy reading and are reported on Table 6. A positive RPD implies a late onset date for both CS_a, and CS_b. A negative RPD signifies an early cessation date and reduced season lengths. The results found in the CS and the SZ are not statistically significant for CS_b. Therefore, the onset of rainy season did not change from its previous 1950–1969 (P1) values in these zones. On the other hand, a 7-day late onset is found in the CN and the NZ. This is equivalent to 9–20 days lateness at local scale in the same sub-regions. Likewise, on the AAV, the average successful sowing dates, CS_a of the 1970–2008, are significantly different from the humid P1 dates, by 8–10 days, in all reference zones. The particular sites that are significantly affected by these changes include Tambacounda (Tam), Ous, and Vel Cas.

There is a statistically significant decrease in season lengths on zonal AAV, as a result of shifts in onset/cessation dates. This is in accordance with previous studies (Camberlin and Diop 2003). The highest local rate of significant, $p_{local,}$ is found in the SZ and CN zones (100% and 50% respectively) and the lowest (30%) is found in the CS and the NZ. Most of the time, this rate is the contribution of the same sites where

Table 4 *p* values of a classical Student's *t* test applied on daily classes of rainfall amounts (RR), comparing the differences between the "recovery" periods (P3) and the dry periods (P2) over Senegal

Class of rainfall (mm/day)	Northern zone	Central North zone	Central South zone	Southern zone
$1 \leq RR \leq 10$	0.14	0.08	0.14	0.35
$10 < RR \leq 20$	0.04	0.33	0.23	0.29
$20 < RR \leq 30$	0.004	0.04	0.34	0.13
$30 < RR \leq 40$	0.01	0.03	0.28	0.14
$40 < RR < 50$	0.22	0.03	0.04	0.14
$RR \geq 50$	0.02	0.02	0.04	0.12

The average values are given in Fig. 6. The significant *p* values are underlined ($\alpha=5\%$) identifying higher values in P3

a relative recovery is found for rainy days (RD and RD50), except in the SZ where all the analyzed sites are concerned. These results show that the recovery perception on rainfall amount and number of rainy days is embedded with shorter cropping season durations.

4.4 Reviews and updates

From the late 1960s, there is a well-known decrease in annual rainfall amount (AR) across the Sahel (Dai et al. 2004; Ali and Lebel 2009), Senegal being no exception. In terms of changes in the seasonal cycle of rainfall and rain events distribution at local scale, new features need to be taken into consideration starting from the beginning of the 1990s. An analysis of the seasonal rain events reveals high correlations between AR, RD, and daily rainfall intensity (RR) (Moron et al. 2006; Lebel and Ali 2009). There are high negative correlations between onset dates and rainfall amount (Gueye and Sivakumar 1992). Other important patterns include the seasonal (intra-seasonal) north–south gradients in rainfall events influencing crops development and yield (Salack 2007; this issue). Even in a small area, thought climatologically homogeneous, spatial rainfall coherence is exceptionally missing in the intra-seasonal time scale.

For more than one and half decade, rainfall totals (annual and intra-seasonal), the total number RD, high daily rainfall types and the frequency of short duration dry spells (DS1) have known some significant changes in the recent years. The +10% to +17% area average recoveries of AR, found in the regions recording less than 800 mm/year from the 1990s, is on the increase up to date and includes an intra-seasonal August–September (21st to 26th dekad) higher frequency of daily rainfall. The average threshold values that are more frequent include the 20–40 mm/day and some extreme cases beyond 50 mm/day, in the northern and central parts of the country. The onset of the rainy season is followed by extreme dry spell events (e.g., more than 15 days) especially in the May–June–July intra-seasonal time period all over the country. This suggests frequent "*false starts*" of season that contribute to dry up the top soil and cause seed abortion. The 1.5 frequency isopleth, which represents the average frequency of DS4, has shifted southward from its 1950–1969 position (as seen on Fig. 7) in the center and Central–West. This feature is putting the regions north of the 14° latitude under high agro-climatic risks. The 1991–2008 average seasonal dry spells typology and spatial distribution can be seen on Fig. 8. DS1 and DS4 categories have an opposite sign of N–S gradient and DS3 has an E–W pattern. Only DS2 exhibits no particular distribution pattern countrywide.

Figure 9 depicts the nowadays intra-seasonal distribution of potential successful CS_a at all reference zones (full line), compared with the humid period 1950–1969 (dotted line). The mean CS_a appears not later than June 25th (±16.2 days) in the SZ with a 14-day inter-zonal time lag. Late successful sowing dates are generally observed all over the country with a high inter-seasonal variability; leading to a shortening of the cropping season. A state-of-matter is provided, on Fig. 10, for the 1991–2008 period. The dashed contour lines are the empirical 3^{rd} quartile successful sowing dates (contours) associated with the corresponding cropping season length (colors). A synopsis of rain-based factors essential to agricultural applications is provided in Table 7 for historical reviews and updates. It provides the area average values and standard deviations of the variables at some reference periods including the most recent. This is a provision in the perspectives of impact assessments and research applications for agronomists in the local network.

The differences in the frequency of occurrence, amount of daily rainfall and types of rainy days found between the recent decades and previous dry decades may be justified by the increase in the size and organization of the meso-scale convective systems after the mid 1980s. The evidence can be taken from Bell and Lamb (2006) . These authors assessed station and Satellite rainfall data, for Niger, Burkina-Faso, Mali, and Senegal, using some statistical indices that define the ground imprint of DL trajectories in summer. They noticed an increase of the size/organization and intensity of these systems after the mid-1980s over Senegal. These systems are responsible for more than 90% of rainfall in this

Table 5 Output of the Student's–Fisher's tests scheme on total rainy days and dry spell categories (1950–2008)

Parameter	Sub-region	STY in AAV	AAV RPD1 (%)	AAV RPD2 (%)	AAV RPD[a] (70–08/50–69 (%))	Ratio of sig. p_{local}	Significantly affected sites (STY, RPD1, and RPD2)
Total rainy days/season	NZ	1995	−30	+12	NA	2:5	Keb (1988, −25 and +12); Mat (1994, −25 and +11); Pod and StL (1993, −20, +32)
	CN	1993	−20	+10	NA	1:4	Bol (1998, −26 and +14); Kid (1988, +13 and +30)
	CS	1998	−15	+10	NA	1:3	Fnd (1998, −15 and +17); Kaff (1998, −5 and +17)
	SZ	NA	NA	NA	−17	1:5	Zig (1993, −15 and +11)
Number of rainy days With less than 10 mm/day (RD10)	NZ	NA	NA	NA	−23	0	NA
	CN	NA	NA	NA	−20	1:9	Kid (1993, +75 and +45)
	CS	NA	NA	NA	−16	0	NA
	SZ	NA	NA	NA	−14	0	NA
Number of rainy days greater/equal 50 mm/day (RD50)	NZ	1993	−49	34	NA	2:7	Dag (1993, −61 and +320); Lug (1993, +17 and +171)
	CN	1998	−36	26	NA	1:3	Bak (1998, +47 and +250); Bol (1998, +8 and +48)
	CS	1998	−34	18	NA	2:3	Fnd (1998, +17 and +119); Kaf (1998, −20 and +64); Kng (1998, −9 and +41)
	SZ	NA	NA	NA	−37	0	NA
Short dry spells category (DS1, 1–7 days)	NZ	1998	−45	40	NA	2:9	Dag (1992, −36 and +72); Mat (1990, −31 and +50)
	CN	NA	NA	NA	−17	0	NA
	CS	1998	−15	+10	NA	1:3	Fnd (1998, −15 and +17); Kaff (1998, −5 and +17)
	SZ	NA	NA	NA		1:5	Zig (1993, −15 and +11)
Medium dry spells category (DS2, 8–14 days)	NZ	NA	NA	NA	00	0	NA
	CN	NA	NA	NA	+15	0	NA
	CS	NA	NA	NA	+07	0	NA
	SZ	NA	NA	NA	−11	0	NA
long dry spells category (DS3, 15–20 days)	NZ	NA	NA	NA	−05[b]	0	NA
	CN	NA	NA	NA	−07[b]	0	NA
	CS	NA	NA	NA	−07[b]	0	NA
	SZ	NA	NA	NA	+05[b]	0	NA
Very long dry spells category (DS4, ≥21 days)	NZ	NA	NA	NA	00	0	NA
	CN	1997	+16	+2	NA	0	Fat (1993, +12 and +14); Kao (1996, −02 and −05)
	CS	NA	NA	NA	+07	0	NA
	SZ	NA	NA	NA	−11	0	NA

[a] STY is not available (NA) and the RPD is statistically significant

[b] Not statistically significant

region (Gaye et al. 2005). Nevertheless, there are other complex factors associated with the local/regional dynamics which coupling with the atmospheric DLs is not well understood. Additional to the form of its terrain (no major orography), the weather over Senegal is influenced by factors such as Saharan Air Layer from the northern borders with Mauritania, ocean-content-atmosphere interface on the West, the Fouta-Djalon orography (in Guinea) where originate most of the squall lines from the South/South–East and the long lived meso-scale convective systems that come from the Central Sahel (Smith et al. 2011). Therefore, the dynamical and environmental mechanisms (both internal and external) controlling these new and locally important changes of the rainfall regime are still opened questions.

Table 6 Same as Table 5. For onset/cessation/successful sowing dates and seasons' duration

Parameter	Sub-region	STY on AAV	AAV RPD1 (days)	AAV RPD2 (days)	AAV RPD[a] (70–08/50–69 (days))	Ratio of sig. p_{local}	Significantly affected sites (STY, RPD1, and RPD2)
Onset of rainy season (CS_b)	NZ	NA	NA	NA	+7	2:7	Dar (1970, +18 and –); Mat (1970, +14 and –); Tiv (1970, +11 and –)
	CN	NA	NA	NA	+7	4:9	Bol (1970, +10 and –); Dor (1970, +20 and –); Kao (1970, +9 and –); Mba (1970, +17 and –);
	CS	NA	NA	NA	+2[b]	0	NA
	SZ	NA	NA	NA	+4[b]	1:5	Ous (1970, +8 and –)
Successful sowing date (CS_a)	NZ	NA	NA	NA	+10	0	NA
	CN	NA	NA	NA	+5[b]	0	NA
	CS	NA	NA	NA	+10	1:6	Tam (1970, +14 and –)
	SZ	NA	NA	NA	+8	2:5	Ous (1970, +9 and –); Vel Cas (1970, +14 and –)
Cessation date (CE)	NZ	NA	NA	NA	−6	1:9	Dag (1970, −10 and –)
	CN	NA	NA	NA	−7	2:9	Fat (1970, −8 and –); Kao (1970, −14 and –)
	CS	NA	NA	NA	−7	2:6	Gou (1970, −15 and –); Kon (1970, −10 and –)
	SZ	NA	NA	NA	−5[b]	4:5	Ked (1970, −12 and –); Kld (1970, −11 and –); Ous (1970, −8 and –); Zig (1970, −13 and –)
Length of rainy season (CL_b)	NZ	NA	NA	NA	−10	1:3	Dar (1970, −25 and –); Lin (1970, −15 and –); Mat (1970, −19 and –)
	CN	NA	NA	NA	−14	4:8	Fat (1970, −18 and –); Kao (1970, −25 and –); Mba (1970, −23 and –); Thi (1970, −20 and –)
	CS	NA	NA	NA	−9	2:6	Gou (1970, −15 and –); Kon (1970, −15 and –)
	SZ	NA	NA	NA	−16	3:5	Kld (1970, −12 and –); Ous (1970, −16 and –); Zig (1970, −15 and –)
Cropping season (CL_a)	NZ	NA	NA	NA	−11	0	NA
	CS	NA	NA	NA	−12	1:2	Dor (1970, −17 and –); Koa (1970, −25 and –); Mba (1970, −14 and –)
	CS	NA	NA	NA	−14	0	NA
	SZ	NA	NA	NA	−18	1:1	NA

STY starting year of recovery, *AAV* area average value, *NZ* Northern zone, *CN* Central North, *CS* Central South, *SZ* Southern zone

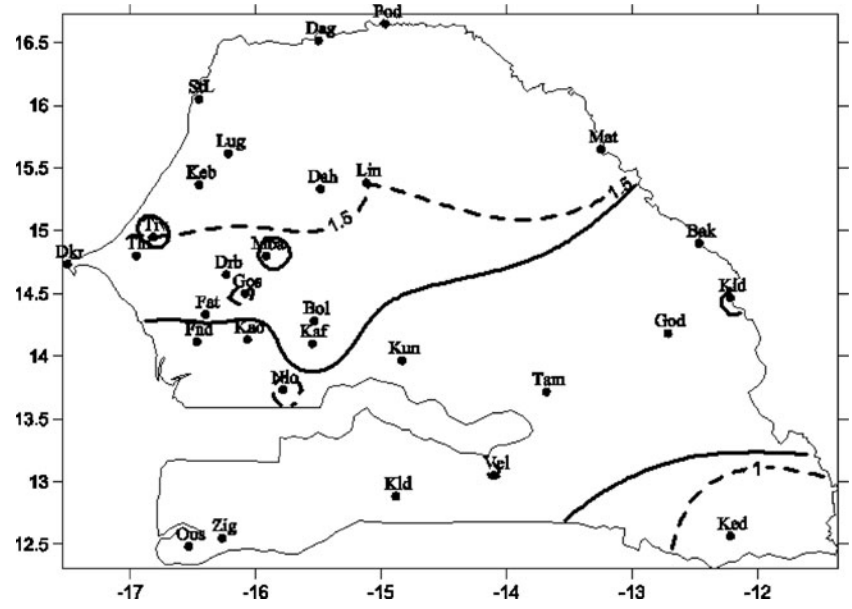
[a] STY is not available (NA) and the RPD is statistically significant

[b] Not statistically significant

5 Concluding remarks and perspectives

Knowing the internal variability of sub-periods prior to trend detection provides a strong basis for rating the significant shifts in the records of rainfall components. By a systematic exploration in the mean, the variance and the relative percent difference, the SFS led to the identification of three sub-periods of different rainfall characteristics over the last 59 years over Senegal. The first is the 1950–1969 period, humid at all scales, all over the country. The dry and recovery periods are unevenly distributed. In the Sudan-Sahel regions of the country (regions recording less than

Fig. 7 Spatial drift of dry spells. Here is an inter-comparison of dry spells category DS4 (DS≥21 days) at different periods. The 1950–1969 isopleths is shown by the dashed contours and the 1970–2008 by the *line contour*



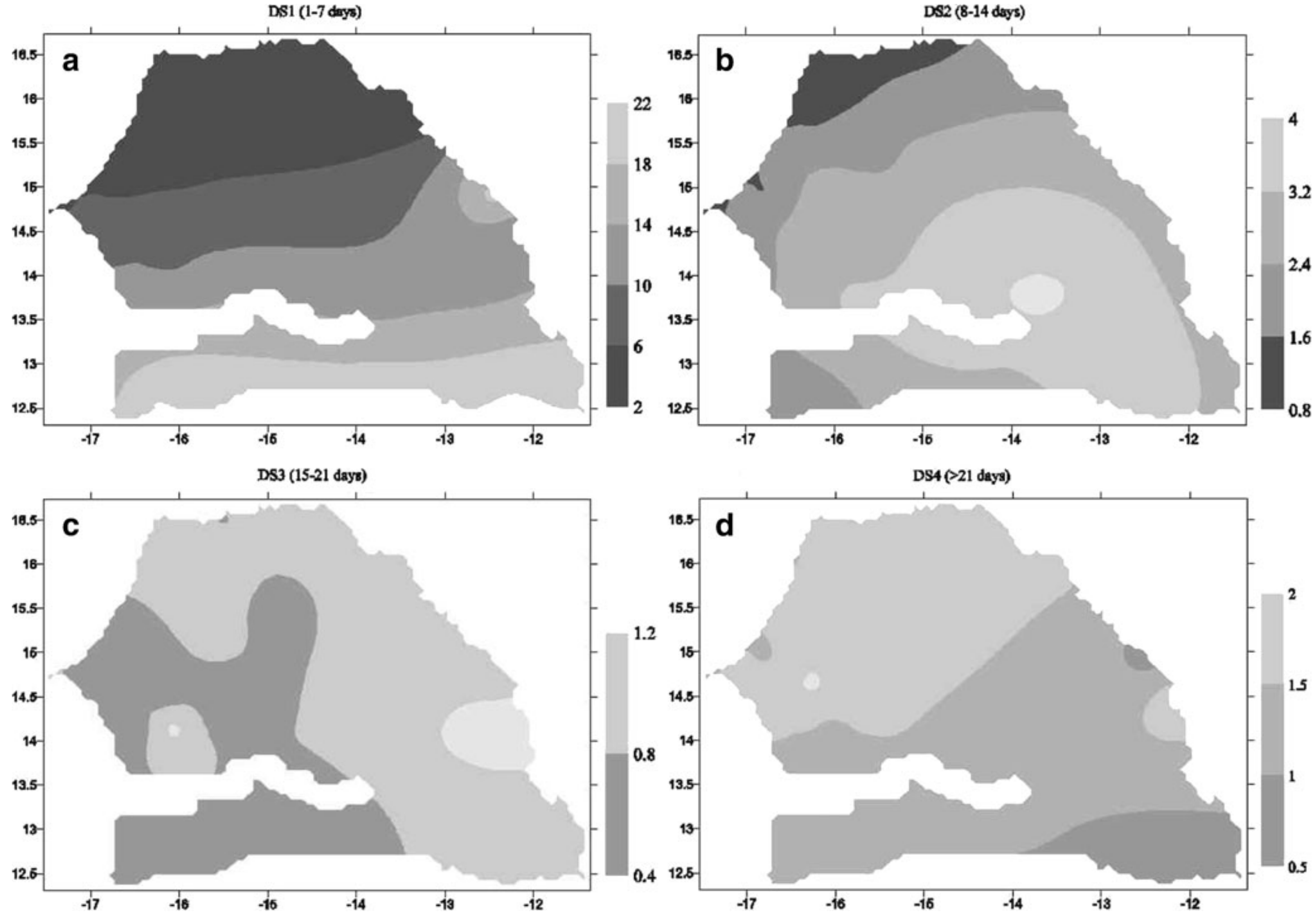


Fig. 8 Average absolute frequency distribution of the observed dry spell categories in 1991–2008 period. The DS1 category has about 60–80% of 1–3 days sub-class and are correlated to N–S rainfall gradients (Sane et al. 2008; Salack et al. 2009b)

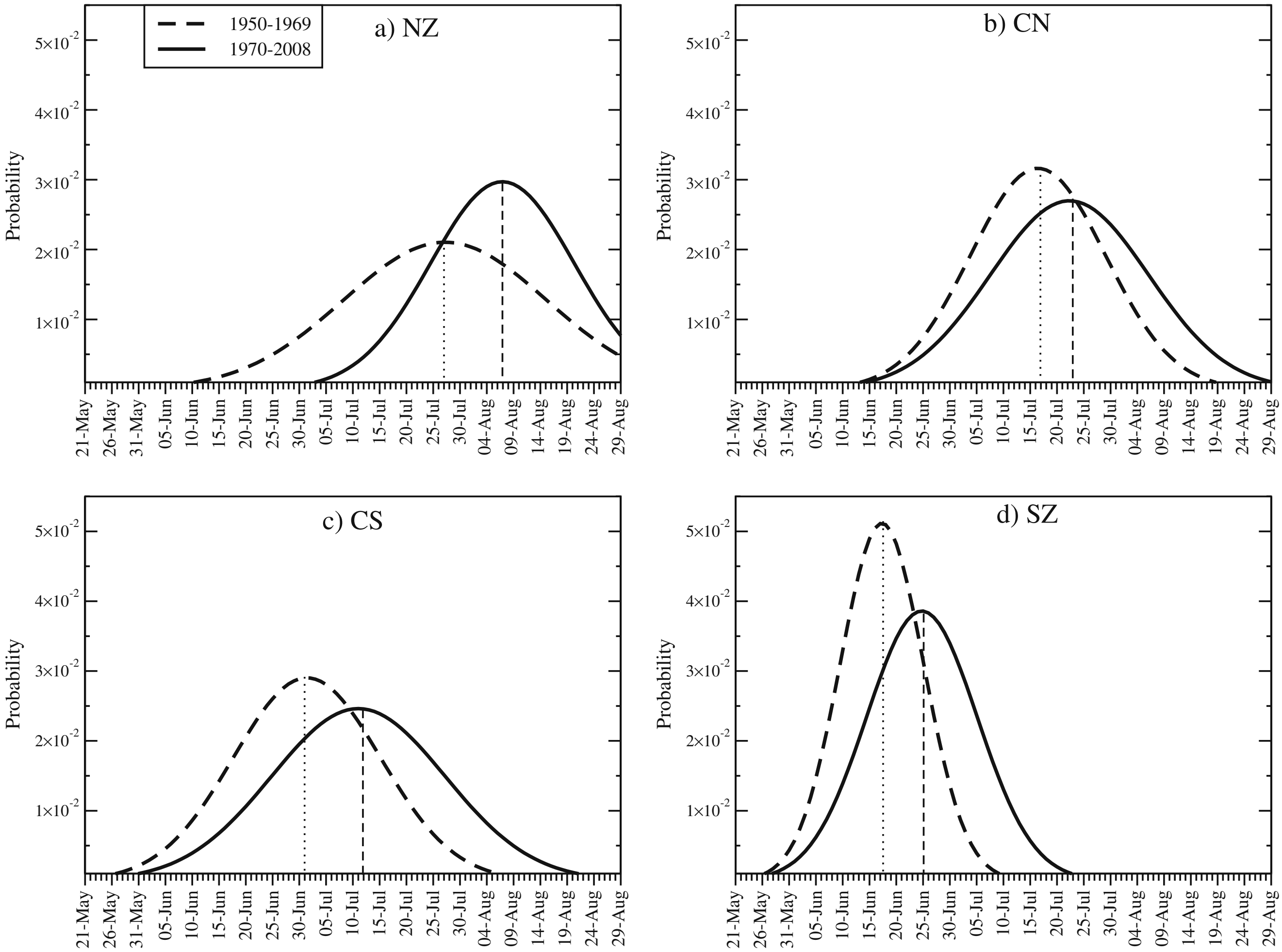


Fig. 9 Observed shifts in the Average successful sowing dates. An inter-comparison between 1970 and 2008 (*full line*) and the humid 1950–1969 (*dashed line*)

Fig. 10 Distribution of the 3rd quartile successful sowing dates (*contours*) computed using the classical *Sivakumar method* and the length of the cropping season (*colored bands*) as observed in the 1991–2008 period. The cropping season is quoted in "days after sowing" (*DAS*)

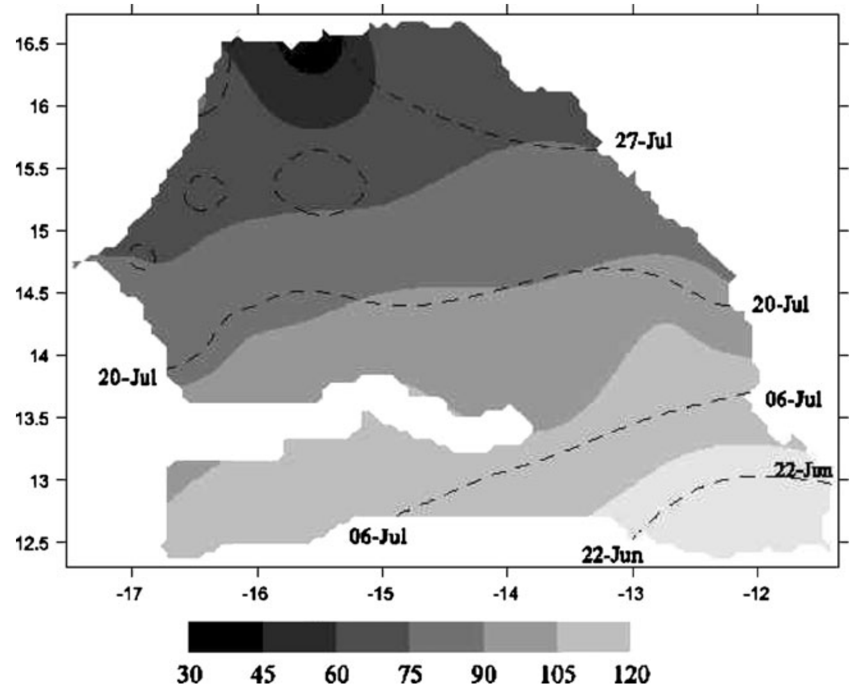


Table 7 Reviews and updates of factors affecting crops development and yield

Parameter	1950–1969 (humid period)		1970–1989 (dry period)[a]		1961–1990 (baseline)[b]		1971–2000 (WMO update)		1979–2008 (actual)		1995–2008 (recovery period)	
	Mean	STD deviation	$\bar{P}$	σ	$\bar{P}$	σ	$\bar{P}$	σ	$\bar{P}$	σ	$\bar{P}$	σ
For the Northern Zone												
Tot rainfall (mm/seas.)	477.3	142.6	290.8	16.2	333.3	79.5	291.0	100.7	301.6	67.3	312.7	110.4
Rainy days (#/seas.)	31	7	21	1	23	7	20	5	21	6	23	6
Short dry sp (#/seas.)	7.1	3.5	3.6	2.4	4.3	2.9	3.6	2.4	4.0	2.8	4.3	2.8
Med dry sp. (#/seas.)	2.4	1.3	1.6	1.3	1.8	1.3	1.6	1.3	1.6	1.3	1.8	1.3
Lon. dry sp. (#/seas.)	0.8	0.9	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.9
V. l. dry sp. (#/seas.)	1.7	0.8	1.7	0.9	1.7	0.9	1.7	0.9	1.6	0.9	1.7	0.8
Sowing date (day, Mon.)	29 Jul	25	14 Au	23	7 Aug	27	9 Aug	22	7 Aug	20	3 Aug	17
Cessation (day, Mon.)	10 Oct	14	8 Oct	16	8 Oct	14	4 Oct	22	30 Sept	17	29 Sept	19
Crop. period (DAS)	89	27	77	32	78	30	76	32	73	27	76	25
For the Central North zone												
Tot rainfall (mm/seas.)	717.3	193.7	490.8	22.9	538.8	166.6	498.0	128.2	512.0	132.7	536.2	135.2
Rainy days (#/seas.)	42	8	31	1	34	8	32	6	32	7	34	6
Short dry sp (#/seas.)	13.6	4.7	9.0	3.8	10.0	4.1	9.1	3.5	9.4	3.6	10.0	3.3
Med dry sp. (#/seas.)	3.0	1.6	2.2	1.5	2.4	1.6	2.3	1.5	2.5	1.6	2.7	1.6
Lon. dry sp. (#/seas.)	0.8	0.8	0.7	0.8	0.7	0.8	0.8	0.9	0.7	0.8	0.8	0.9
V. l. dry sp. (#/seas.)	1.3	0.6	1.4	0.8	1.4	0.8	1.5	0.9	1.5	0.9	1.6	0.9
Sowing date (day, Mon.)	16 Jul	15	23 Jul	21	21 Jul	20	23 Jul	21	23 Jul	21	22 Jul	21
Cessation (day, Mon.)	14 Oct	15	10 Oct	14	9 Oct	13	8 Oct	13	3 Oct	14	2 Oct	14
Crop. period (DAS)	94	24	88	25	88	24	84	24	78	29	74	28
For the Central South zone												
Tot rainfall (mm/seas.)	853.2	177.3	632.2	24.7	673.6	166.0	636.0	141.6	649.0	155.1	665.0	158.3
Rainy days (#/seas.)	50	8	40	1.0	42	8.0	40	8.0	40	8.0	41	8.0
Short dry sp (#/seas.)	15.7	4.5	11.2	4.3	12.4	4.4	11.2	4.4	11.4	4.4	11.8	4.1
Med dry sp. (#/seas.)	2.8	1.4	2.4	1.6	2.6	1.6	2.8	1.7	3.0	1.8	3.4	1.7
on. dry sp. (#/seas.)	0.9	0.9	0.7	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.9	0.8
V. l. dry sp. (#/seas.)	1.3	0.6	1.4	0.8	1.3	0.7	1.3	0.8	1.4	0.8	1.4	0.7
Sowing date (day, Mon.)	01 Jul	22	8 Jul	21	6 Jul	23	10 Jul	24	9 Jul	25	10 Jul	25
Cessation (day, Mon.)	15 Oct	15	9 Oct	15	10 Oct	14	9 Oct	13	6 Oct	8	6 Oct	8
Crop. period (DAS)	104	23	90	27	93	26	88	26	85	25	84	23
For the Southern zone												
Tot rainfall (mm/seas.)	1390.6	275.5	1055.8	572.0	1129.6	262.5	1,073.0	219.5	1,060.0	225.5	1,094.2	233.8
Rainy days (#/seas.)	75	10	62	4	64	10	62	8	61	8	62	9
Short dry sp (#/seas.)	23.6	4.6	19.2	4.6	20.2	4.8	19.5	4.6	19.7	4.8	20.4	4.5
Med dry sp. (#/seas.)	2.7	1.4	2.4	1.6	2.5	1.5	2.5	1.5	2.7	1.5	2.8	1.4
Lon. dry sp. (#/seas.)	0.6	0.7	0.7	0.8	0.7	0.7	0.7	0.8	0.6	0.8	0.6	0.8
V. l. dry sp. (#/seas.)	1.1	0.6	1.0	0.6	1.0	0.6	1.0	0.6	1.0	0.6	1.1	0.6
Sowing date (day, Mon.)	15 Jun	13	21 Jun	16	19 Jun	15	22 Jun	15	23 Jun	16	23 Jun	15
Cessation (day, Mon.)	22 Oct	14	15 Oct	14	16 Oct	14	13 Oct	12	11 Oct	8	10 Oct	6
Crop. period (DAS)	141	19	131	20	132	20	128	20	126	17	125	15

DAS days after sowing

[a] Dry period relative to the Western Sahel (Lebel and Ali 2009)

[b] Baseline relative to climate change assessment studies (Sarr et al. 2006; Ben Mohamed 2010)

800 mm/year), rainfall amount has recovered +10% to +17% from the previous dry decades as proven by the areal zonal values. This started in 1992–1998, at sub-regional scale (cf. NZ, CN, CS zones). It is statistically significant and is on the increase until recent but still below the humid period (1950–1969) in confirmation of previous studies. Mostly at local scale larger changes are found (about 16–32%) which started as early as 1988 at some individual sites (e.g. Bakel, Boulel and Kebemer). Beside the 1950–1969 major breaks in the rainfall regime, these are also important internal variability patterns of rainfall to consider in a multi-decadal work over the 1970–2008 period for this region at both local and sub-region scales.

The new perceptions include the increase in the frequency of daily heavy rainfall types, shift in the peak number of rainy days and the frequency of short dry spells (especially in the North). In the extreme south (regions recording more than 800 mm/year) drought state still prevalent in the past one and half decade according to the tested area average values. The suggests a North–south “dipole” of rainfall evolution over the country. Significant trends on agricultural calendar such as onset of rainy season, successful sowing dates and cropping periods are only found on the 1970–2008 time series and have shifted by more than a week from their 1950–1969 levels. These factors did not show statistical significant trends over the periods post-1990. They are rather embedded with an increased spatio-temporal variability in a larger portion of the northern and central zones of Senegal. Each time significant changes are observed, their magnitude on the areal values is not less than 10%. In most cases, a relatively small sub-regional scale change implies a more severe local perception in the same direction (negative or positive). This observation is true for at least one third fraction of the observation network. This is evidence that area average or aggregated analyses of trends and variability may underrate the locally significant and relevant patterns. These scale issues are very important in linking crop and climate models for in situ, short and/or long term climate impact assessments. The detailed results of this work contribute to complement previous analyses of rainfall regime over this region. They foster a strong background evidence of local and sub-regional recovery in this region. Even though their signal is weak, the new tendencies at the sub-regional scales are important internal variability to take into consideration in a multi-decadal model validation, impact and vulnerability assessments on traditional agriculture. The periodic reviews and updates (included in the synopsis) provided with these analyses are provisions for operational research and applications.

The updates especially show that the rainy season has become potentially hazardous (significant variability) with higher frequency of extreme dry spells. The highest number of rainy days in the season has shifted by a dekad. Shorter cropping seasons are also persistent. The implications of these changes to local agriculture are relevant and challenging questions to address for a better understanding and decision making.

Acknowledgments The authors are indebted to *Centre Régional pour l’Amélioration de l’Adapatation à la Sécheresse* (CERAAS) and *Agence Nationale de la Météorologie du Sénégal*, (ANAMS) for providing rainguage data. Special regards to the various persons who manage and update the CERAAS database: Moustapha Fall, Couna Sylla, Cheikh Dramé, Benoit Sarr, Mbaye Diop, and Ndongo Ngom.

The first author acknowledges the German Academic Exchange Service (DAAD) for the In-Regions Scholarship through CERAAS (#A/09/04677). Fruitful discussions were held with Frédéric Hourdin. Comments and suggestions from Serge Janicot and an anonymous reviewer helped greatly improve the quality of this paper. Financial support was also provided by CIRAD and AMMA-EU in the framework of the AMMA project. Based on a French initiative, AMMA was built by an international scientific group and is currently funded by a large number of agencies, especially from France, UK, US, and Africa. It has been the beneficiary of a major financial contribution from the European Community’s Sixth Framework Research Program. Detailed information on scientific coordination and funding is available on the AMMA International web site. http://www.ammainternational.org.

References

Abdi H, Molin P (2007) Lilliefors/Van Soet's test of normality. In: Neil Salkind (Ed.) (2007), Encyclopedia of Measurement and Statistics. Available at: http://www.utdallas.edu/~herve/Abdi-Lillie2007-pretty.pdf

AGRHYMET (1996) Méthodologie de suivi des zones à risque. AGRHYMET FLASH, Bulletin de Suivi de la Campagne Agricole au Sahel. Centre Régional Agrhymet, B.P. 11011, Niamey, Niger, vol. 2, No. 0/96. p. 2

Ali A, Lebel T (2009) The Sahelian standardized rainfall index revisited. Int J Climatol 29(12):1705–1714. doi:10.1002/joc.1832

Balme M, Galle S, Lebel T (2004) Démarrage de la saison des pluies au Sahel: variabilité aux échelles hydrologique et agronomique, analysée à partir des données EPSAT-Niger. Sécheresse 16(1):15–22

Baron C, Sultan B, Balme M, Sarr B, Traore S, Lebel T, Janicot S, Dingkuhn M (2005) From GCM grid cell to agricultural plot: scale issues affecting modeling of climate impact. Phil Trans R Soc B 360(1463):2095–2108. doi:10.1098/rstb.2005.1741

Bell MA, Lamb PJ (2006) Integration of weather system variability to multidecadal regional climate change: the West African Sudan–Sahel Zone, 1951–98. J Climat 19:5343–5365

Ben Mohamed A (2010) Climate change risks in Sahelian Africa. Reg Environ Change. doi: 10.1007/s10113-010-0172-y

Box GEP, Cox DR (1964) An Analysis of Transformations. J Royal Stat Society 127:211-252

Camberlin P, Diop M (2003) Application of daily principal component analysis to the assessment of the rainy season characteristics in Senegal. Clim Res 23:159–169

Catherinet MD, Dumont S, Mayaki AA (1963) Millet and sorghum in Niger. Cultivation water requirements, soil and climate, limiting factors. L’Agronomie Tropicale 18:108–113

Cochemé J, Franquin P (1967) An agroclimatological survey of a semi-arid area in Africa south of the Sahara. *Technical note* No. 86. World Meteorological Organization, Geneva

Dai A, Lamb PJ, Trenberth KE, Hulme M, Jones PD, Xie P (2004) The recent Sahel drought is real. Int J Climatol 24:1323–1331

Der Megreditchian G (1992) Le traitement statistique des donnée Multidimensionnelles. Application à la météorologie. *Cours et Manuel* No 8. Tome 1. Météo France, France. p. 287

Diedhiou A, Janicot S, Viltard A, de Felice P, Laurent H (1999) Easterly wave regimes and associated convection over West Africa and the tropical Atlantic: results from NCEP/NCAR and ECMWF reanalyses. Clim Dyn 15:795–822

Dieng O, Roucou P, Louvet S (2008) Variabilité intra-saisonnière des précipitations au Sénégal (1951-1996). Sécheresse, 19 (2):87-93

Easterling RD, Alexander LV, Mokssit A, Determmerman V (2003) CCI/CLIVAR workshop to develop priority climate indices. Bull Am Meteorol Soc 8:1403–1407

Fall S, Niyogi D, Semazzi FHM (2006) Analysis of mean climate conditions in Senegal (1971–1998). Earth Interact 10(5):1–40

FAO (Food and Agriculture Organization) (1978) Report on the agroecological zones project. *World Soil Resource Report* N° 48. Rome. FAO.

Frappart F et al (2009) Rainfall regime across the Sahel band in the Gourma region, Mali. J Hydrol. doi:10.1016/j.jhydrol.2009.03.007

Gaye A, Viltard A, De Félice P (2005) Lignes de grains et pluies en Afrique de l'Ouest: part des lignes de grains à la pluie totale des étés 1986 et 1987. Sécheresse 16(4):269–273

Grist PJ, Nicholson ES (2001) A study of the dynamical factors influencing rainfall variability in the West African Sahel. J Clim 14:1337–1359

Gueye M, Sivakumar MVK (1992) Analyse de la longueur de la saison culturale en fonction de la date de début des pluies au Sénégal. *Compte rendu des travaux* No 2. Niamey (Niger) : Centre sahélien de l'ICRISAT, 1992. Available at: http://library.wur.nl/isric/fulltext/ISRIC_13235.pdf

Hachigonta S, Reason CJC, Tadross M (2008) An analysis of onset date and rainy season duration over Zambia. Theor Appl Climatol 91:229–243. doi:10.1007/s00704-007-0306-4

Hirsch RM, Helsel DR, Cohn TA, Gilroy EJ (1993) Statistical analysis of hydrologic data. In: Maidment DR (ed) Handbook of hydrology. McGraw-Hill, New York, pp 17.1–17.55

IPCC (2007) Climate change: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge. p. 996

Janicot S, Mounier F, Diedhiou A (2008) Les ondes atmosphériques d'échelle synoptique dans la mousson d'Afrique de l'Ouest et centrale: ondes d'est et ondes de Kelvin. Sécheresse 19(1):13–22. doi:10.1684/sec.2008.0115

Katz RW, Glantz MH (1986) Anatomy of a rainfall index. Mon Weather Rev 114:764–771

L'Hôte Y, Mahé G, Somé B, Triboulet JP (2002) Analysis of Sahelian rainfall index from 1896 to 2000; the drought continues. J Hydrol Sci 47(4):563–572

Lanà X, Martinez MD, Burgueno A, Serra C, Martin-Vide J, Gomez L (2008) Spatial and temporal patterns of dry spell lengths in the Iberian peninsula for the second half of the twentieth century. Theor Appl Climatol 91:99-116

Laurent H, D'Amato N, Lebel T (1998) How important is the contribution of the mesoscale convective complexes to the Sahelian rainfall? Phys Chem Earth 23(5-6):629–633. doi:10.1016/S0079-1946(98)00099-8

Le Barbé L, Lebel T, Tapsoba D (2002) Rainfall variability in West Africa during the years 1950–90. J Climate 15(2):187–202

Le Houerou HN (1992) Relations entre la variabilité des précipitations et celle des productions primaires et secondaires en zone aride. In: L'aridité, une contrainte au développement. Didactiques. Orstom editions, Paris

Lebel T, Ali A (2009) Recent trends in the Central and Western Sahel rainfall regime (1990–2007). J Hydrol. doi:10.1016/j.jhydrol.2008.11.030

Lebel T, Parker D J, C Flamant et al. (2009) The AMMA field campaigns: Multiscale and multidisciplinary observations in the West African region. Q J R Meteorol Soc. doi: 10.1002/qj.486

Lilliefors H (1967) On the Kolmogorov-Smirnov test for normality with mean and variance unknown. J Am Stat Assoc 62:399–402

Misra AN, Misra M (1991) Physiological responses of pearl millet to agroclimatic conditions determining grain formation and yield. *Environmental Contamination and Hygiene* 165–175

Moron V, Robertson, Ward MN (2006) Seasonal Predictability and spatial coherence of rainfall characteristics in the tropical setting of Senegal. Mon Weather Rev 134:3248–3262

Mounier F, Kiladis G, Janicot S (2007) Analysis of the dominant mode of convectively coupled Kelvin waves in the West African Monsoon. J clim 20:1487–14503

New M, Hewitson B, Stephenson DB 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 SE (1983) Sub-Sahara rainfall in the year 1976–1980: evidence of Continued drought. Mon Weather Rev 3:1646–1654

Nicholson SE (2005) On the question of the "recovery" of the rains in the West African Sahel. J Arid Environ 63:615–641

Nicholson SE (2009) On the factors modulating the intensity of the tropical rainbelt over West Africa. Int J Climatol 29:673–689

Nzeukou A, Sauvageot H (2002) Distribution of rainfall parameters near the coasts of France and Senegal. J Appl Meteorol 41:69–82

Oladipo EO, Kyari JD (1993) Fluctuations in the onset, termination, and length of the growing season in northern Nigeria. Theor Appl Climatol 47:241–250

Ozer P, Erpicum M, Demarée G, Vandiepenbeeck M (2003) The Sahelian drought may have ended during the 1990s. Hydro Sci J 48:489–492

Ozer P, Bodart C, Tychon B (2005) Climatic analysis of the Gouré area, eastern Niger: recent changes and environmental impacts. *Cybergeo, Environnement, Nature, Paysage*, article 308. Available at: http://www.cybergeo.eu/index3338.html.

Redelsperger J-L, Thorncroft C, Diedhiou A, Lebel T, Parker D, Polcher J (2006) African monsoon, multidisciplinary analysis (AMMA): an International research project and field campaign. Bull Am Meteorol Soc 87(12):1739–1746

Reed RJ, Norquist DC, Recker EE (1977) The structure and characteristics of African easterly wave disturbances as observed during Phase III of Gate. Mon Weather Rev 105:317–333

Salack S (2007) Intra-seasonal to seasonal variability of simulated rainfall in the perspectives of agricultural impact assessment studies for the Sahel. M. Sc. Research Dissertation, University Cheikh Anta Diop of Dakar, Senegal. p. 60

Salack S, Muller B, Gaye A T, Sylla C, Fall M (2009a) Updated space-time rainfall regimes and agro-climatological features in Senegal. Work presented at the 3rd International AMMA Conference, Ouagadougou, 20–24 July 2009

Salack S, Muller B, Gaye A T, Hourdin F (2009b) Multi-scale intra-seasonal characterization of dry spells in Senegal and their implication in the rainy season attributes. Work presented at the 3rd International AMMA Conference, Ouagadougou, 20–24 July 2009

Sane T, Diop M, Sagna P (2008) Etude de la variabilité de la saison pluvieuse au Sud en Haute-Casamance (Sud-Sénégal). Sécheresse 19(1):23–28

Sarr B, Traoré S, Salack S (2006) Evaluation de l'incidence des changements climatiques sur les rendements des cultures céréalières en Afrique soudano sahélienne. *Centre Régional Agrhymet, CILSS, Niamey.* p. 100

Segele ZT, Lamb PJ (2005) Characterization and variability of Kiremt rainy season over Ethiopia. Meteorol Atmos Phys 89:153–180

Sene S, Ozer P (2002) Evolution pluviométrique et relation inondations—évènements pluvieux au Sénégal. Bull-Soc geÂogr LieÁge 42:27–33

Sivakumar MVK (1988) Predicting rainy season potential from the onset of rains in Southern Sahelian and Sudanian climatic zones of West Africa. Agric Fores Meteor 42:295–305

Sivakumar MVK (1992) Empirical analysis of dry-spells for agricultural applications in West Africa. J Climate 5:532–539

Sivakumar MVK, Valentin C (1997) Agroecological zones and the assessment of crop production potential. Phil Trans R Soc Lond B 352:907–916

Smith JW, Reynolds AE, Pratt AS, Salack S et al (2011) Observations of an 11 September Sahelian Squall Line and Saharan Air Layer Outbreak during NAMMA-06. Atmos Chem Phys (in press)

Stern R, Rijks D, Dale I, Knock J (2006) Instat Climatic Guide. University of Reading, Reading, p 330

Sultan B, Janicot S (2004) La variabilité climatique en Afrique de l'Ouest aux échelles intrasaisonnières. I: mise en place de la mousson et variabilité intra-saisonnière de la convection. Sécheresse 15:321–330

Sultan B, Baron C, Dingkhun M, Sarr B, Janicot (2005) Agricultural impacts of large-scale variability of the West African monsoon. Agric For Meteorol 128(1–2):93–110

Viltard A, de Félice P (1979) Statistical analysis of wind velocity in an easterly wave over West Africa. Mon Weather Rev 107:1320–1327

Ward MN (1998) Diagnosis and short-lead time prediction of summer rainfall in tropical North Africa at interannual and multi-decadal time scales. J Climate 11:3167–3191

Yue S, Pilon P (2004) A comparison of the power of the t test, Mann–Kendall and bootstrap tests for trend detection. Hydrol Sci J 49 (1):21–36